INTEGRATED REMOTE SENSING AND GIS TECHNIQUES FOR GROUNDWATER STUDIES IN PART OF BETWA BASIN

A THESIS

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By

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CANDIDATE'S DECLARATION

I, hereby, certify that the work which is being presented in this thesis, entitled **"INTEGRATED REMOTE SENSING AND GIS TECHNIQUES FOR GROUNDWATER STUDIES IN PART OF BETWA BASIN"** in fulfilment of the requirement for the award of the degree of **DOCTOR OF PHILOSOPHY** and submitted in the **Department of Earth Sciences** of the University of Roorkee, is an authentic record of my own work carried out during a period from march 1994 to June 1999 under the supervision of **Dr. A. K. Saraf**.

The matter embodied in this thesis has not been submitted by me for the award of any other degree of this or any other University.

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Date: 28/06/99

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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		9.6.2000
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ABSTRACT

Groundwater is a precious resource of limited extent in hard rock areas. In order to ensure a judicious use of groundwater, proper evaluation has to be performed. A groundwater development program needs a large volume of multidisciplinary data from various sources. Integrated remote sensing and GIS can provide the appropriate platform for convergent analysis of diverse data sets and for decision making for groundwater management planning.

In the present study, an integrated remote sensing and GIS based methodology has been developed and tested for the evaluation of groundwater resources of a hard rock area in a part of the Betwa basin, in the state of Madhya Pradesh, India. Two sub-basins, namely, the Kethan and the Narayan, have been studied. There are three components of this study – demarcation of groundwater potential zones, identification of artificial recharge provided by the existing reservoirs and suitability analysis for future artificial recharge sites.

The area mainly comprises Deccan Trap basalt and a small part is underlain by Vindhyan rocks. Groundwater occurrence in basalt is restricted to the weathered and fractured parts. In this area, monsoon groundwater recharge can not meet the demands for groundwater throughout the year. As a result there is water scarcity in the dry season. Although artificial recharge structures at suitable locations in the area can appreciably improve the groundwater conditions, much thought has not been given to utilize this. In this work, the present status of artificial recharge has been evaluated and suitable sites for future artificial recharge structures have been suggested through integrated remote sensing and GIS technique.

Three types of data have been used for the present study, namely, remote sensing data e.g. IRS-LISS-II and LISS-III data, field data e.g. depth to water level, rainfall data and the existing maps e.g. topographic, geological, soil and landuse maps. In order to bring these into a single spatial georeferencing

scheme, all the data have been registered to the base map, prepared from the Survey of India topographic maps.

Thematic information layers on geology, geomorphology, lineament and soil have been prepared from processed remote sensing data, supported by ancillary information. Digital elevation model (DEM) has been generated from elevation contours which provide a wealth of hydrogeologic information. Information layers on water level and rainfall have been produced through interpolation.

Drainage network has been extracted from DEM, assuming the surface to be insulated. From the comparative study of the two, it is inferred that areas showing misfit between the two indicate recharge areas. These areas are the areas covered by weathered basalt, having channel fills, having high lineament density and having deeper soil. Based on information derived from integrated analysis and field checks, information layers on geology, geomorphology, lineament density, slope and soil depth have been assigned appropriate weightage. Weighted index overlay has been performed to delineate groundwater prospective zones. The result shows that channel fills hold the highest potential for groundwater. Recharge estimation also supports this.

Remote sensing images of the area show that irrigation tanks are also augmenting groundwater recharge, as indicated by good growth of dry season vegetation downstream from the tanks. Tanks situated on a gentle slope provide better recharge due to the hydraulic gradient provided by the gentle slope. The weathered and fractured basalts permit a high intake of water, as well as help to maintain the required rate of recharge. Presence of yellow clay, however, hinders the flow of water. On the basis of this observation and field checks, suitable sites for artificial recharge have been suggested through a combination of Boolean logic and weighted index overlay methods. Slope has been assigned the highest weightage followed by geomorphology, lineament, geology, soil depth and depth to water level. Then, the most suitable zone from the output of weighted index method has been integrated with stream order, lineament buffer zone and landuse through Boolean logic model, and suitable sites for artificial recharge have been selected.

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Puspita Roy Choudhury

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CHAPTER 1

INTRODUCTION

1.0 PREFACE

Integrated Geographic Information System (GIS) and Remote Sensing is attracting increasing attention in natural resources studies. Remote sensing provides multispectral, multi-temporal, multi-sensor and multivariate data of the earth's surface. GIS has emerged as a decision support system with capabilities of efficient data storage and convergent analysis of spatial data from diverse sources. There is a strong synergy between remote sensing and GIS, as remote sensing data is a major source of spatial information in GIS analysis, and GIS data can be used as an ancillary information to support remote sensing data interpretation. The synergism between two technologies is a major advantage in the use of an integrated approach (Star et al. 1991; Trotter 1991).

Groundwater is an important part of the hydrologic cycle as it sustains life. It is used as a source of domestic water supply, agricultural practices, and in industries also. Although groundwater is a dynamic and replenishable natural resource in a hard rock terrain, it is a precious resource of limited extent. In such rocks, groundwater occurrence is essentially confined to fractured and weathered horizons. In India, 65% of the geographical area is covered by hard rock formations. Groundwater development in these areas needs special attention. Due to population explosion in the last 50 years and rapid industrialization, ground water resource has become further important for any developmental activity.

In general, water resources in India are very unevenly distributed, both spatially and temporally. Idiosyncrasies of monsoon and diverse physiographic conditions give rise to unequal distribution of water. Over the years, increasing population, urbanization and expansion in agriculture has accentuated the situation. The aftermath of unscientific exploitation of groundwater is that we are moving towards a water stress condition. Even now, some areas are facing acute water crisis. Despite being a very important part of the nation's growth, water resources analysis has been fragmentary. An integrated study covering all aspects of groundwater development is a crucial requirement of the present day. Especially in hard rock areas, it is very essential to have proper assessment of groundwater resources potential and to adopt appropriate water management plan in order to ensure availability of groundwater throughout the year. Integrated remote sensing and GIS has immense potential to provide platform for appropriate analysis of groundwater resources for development planning. The present work is an attempt towards this direction. The study focuses on developing an integrated remote sensing and GIS based methodology for evaluation of groundwater resources in a hard rock area, mainly covered by Deccan Trap basalt, and suggesting suitable sites for artificial recharge of groundwater in order to augment groundwater recharge. The study area forms a part of the Betwa river basin situated in the state of Madhya Pradesh and partly in the state of Uttar Pradesh.

1.1 THE BACKDROP

There have been considerable imbalances in the quantity of water resources available to the Indian population and their use. This has led to the falling ground water table, followed by declining per capita availability (Figure 1.1) and, wasteful and inefficient use of water. Despite a national average of 2464 m^3 of the water per capita per year, parts of India face water scarcity due to uneven availability of water (Pachauri and Sridharan,1998). The pressure on groundwater is gradually increasing as modern technology is replacing traditional farming. The increasing share of groundwater in an irrigated area can be visualized from the declining share of tanks in the net irrigated area (Figure 1.2). The larger share of groundwater can be explained in terms of higher

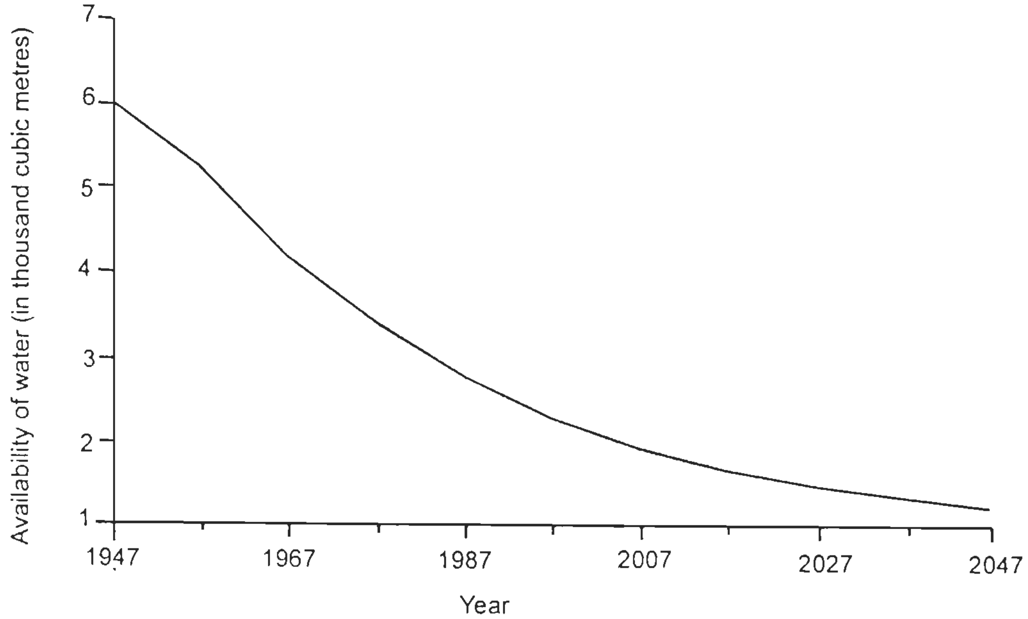


Figure 1.1: Declining availability of water per capita - from the past towards the future (Pachauri and Sridharan, 1998)

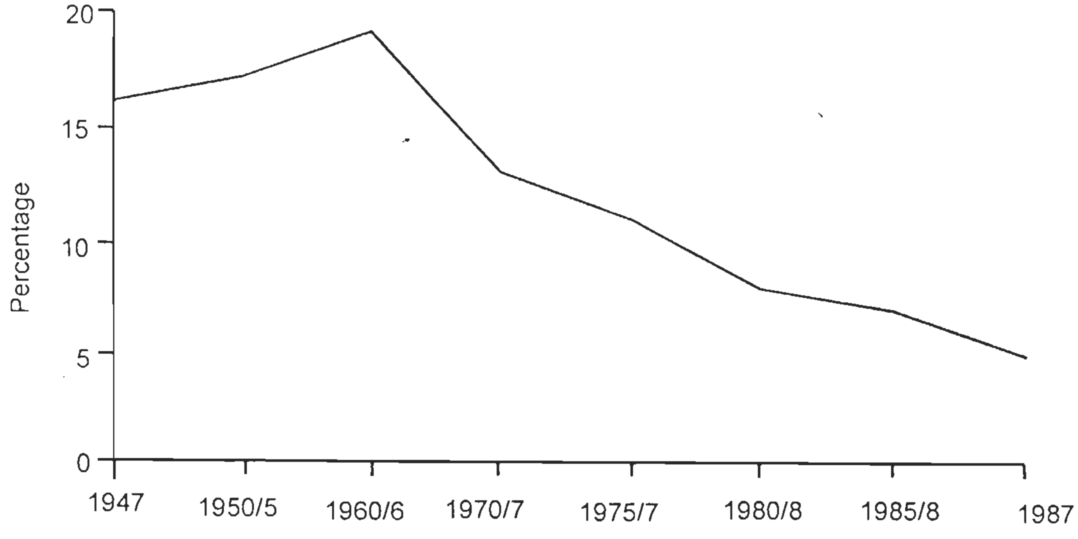


Figure 1.2: Declining share of tanks in net irrigated area (Pauchauri and Sridharan, 1998

productivity of groundwater irrigation compared to canal irrigation. Groundwater is preferred to surface water because farmers have greater control over it. Consequently, pressure on groundwater is increasing. The last five decades have witnessed a phenomenal increase in the number of groundwater abstraction structures (Table 1.1).

Thus, on the eve of the twenty first century, the critical situation calls for a well organized investigation, evaluation and management planning of groundwater in order to avoid any detrimental effect on the groundwater regime, and to provide sustainability to the groundwater development process. National water policy (1987) emphasizes setting up of a water information system with a network of databases. The major stress is laid on maximizing the availability of water, and developing groundwater recharge projects for augmenting the available supplies. Multi-disciplinary approach is to be adopted for project planning. Integrated remote sensing and GIS has tremendous potential to depict

Year	Dug wells (millions)	Private shallow tube wells (thousands)	Deep tube wells (thousands)
1947	3.51	1	1.7
1950/51	3.86	3	2.4
1968/69	6.11	360	14.6
1973/74	6.94	1000	22.0
1978/79	7.69	1960	32.6
1984/85	8.74	3360	46.2
1993/94	10.20	5040	69.4
1997	10.92	6020	83.2

Table 1.1: Progressive increase in groundwater structures: 1947 to 1997 (Pachauri and Sridharan,1998)

the actual scenario and suggest remedial measures. GIS transforms information into knowledge through the concoction of physical or mathematical models and human judgement. The present study has been undertaken keeping in pace with the national scenario of groundwater. The study area represents a typical hard rock terrain comprising mainly Deccan Trap basalt, with a small part being covered by sandstone and shale of the Vindhyan Supergroup of rocks. Bundelkhand Granite forms the basement in this area. A major part of the study area lies in the Vidisha district of Madhya Pradesh, India, which is under medium stress condition of water (Pachauri and Sridharan, 1998). The rainfall intensity gradually decreases from the southern to the northern end. There is a tendency of occurrence of moderate to severe droughts in this area once in every six years on an average (CGWB,1984).

This area was investigated by Central Ground Water Board (CGWB) under the Indo British Betwa Ground Water Project in Upper Betwa Basin during 1975-1980 in collaboration with the Government of United Kingdom (CGWB, 1984). The project studies were taken up by a multidisciplinary approach using traditional groundwater studies techniques. The project findings throw light upon the hydrogeological condition of the area.

1.2 OBJECTIVES AND SCOPE OF THE STUDY

The main objectives of the present work are:

- to develop and test an integrated remote sensing and GIS technique for evaluation of groundwater resources in a hard rock terrain,
- to identify the interrelationship of recharge areas with geology, geomorphology and structure of the area,
- to delineate the groundwater potential zones in the area,
- to have qualitative and quantitative assessment of groundwater recharge, and
- to suggest suitable sites and methods for artificial recharge to augment groundwater recharge in the area.

The methodology developed can be very useful at an early stage of groundwater development programme in a hard rock terrain. GIS can assimilate divergent sources of spatial and non-spatial data into a convergent analysis. Remote sensing is moving from a descriptive towards a quantitative technology. Various input parameters for hydrological modelling can be estimated to some extent. Remote sensing provides aerial information in contrast to point measurement obtained by conventional method of hydrogeological survey. This information is utilized in GIS analysis or in hydrological modelling in GIS which requires continuous spatial information. 3D-viewing capability helps greatly in depicting the complex subsurface hydrogeological system. 3D GIS can be very useful for impact assessment of groundwater development and the future scenario can be generated based on GIS analysis. Finally, this study can be applied to similar terrain conditions in groundwater resources evaluation directly or with appropriate modification.

1.3 THE STUDY AREA

The study area is bounded by longitudes of 77°20' E and 78°22' E and latitudes of 23°55' N and 24°28' N (Figure 1.3). The major part of the area lies in the Vidisha district of Madhya Pradesh state, the remaining part being in the Guna and Sagar districts, Madhya Pradesh and a very small part is in Uttar Pradesh state. The important town in the area is Sironj, which is 149 km north of Bhopal. The Betwa is the main perennial river in the area. Two sub-basins of the Betwa, namely the Kethan and the Narayan have been studied in this work.

1.3.1 GEOLOGY

A major part of the study area is covered by Deccan trap basalt (Figure 1.4). Rest of the area is covered by the Vindhyan Group of rocks and small patches of laterite. The regional geological succession is shown in Table 1.2.

	Group	Lithology	Age
Laterite			Pleistocene to Recent
Deccan Trap	Malwa	Basalt flows (Fine to medium grained moderately porphyritic and fine grained sparsely porphyritic)	Upper Cretaceous to Lower Eocene
Lameta Beds		Fluviatile and estuarine facies	Upper Cretaceous
Vindhyan Supergroup (Upper Vindhyan)	Bhander	Sandstone, shale, limestone	Upper Proterozoic
	Rewa	Sandstone ≈ shale	
	Kaimur	Sandstone > shale	

Table 1.2: A concise regional geological succession of the area (GSI Quadrangle Maps: 54H, 1977; 54L, 1985)

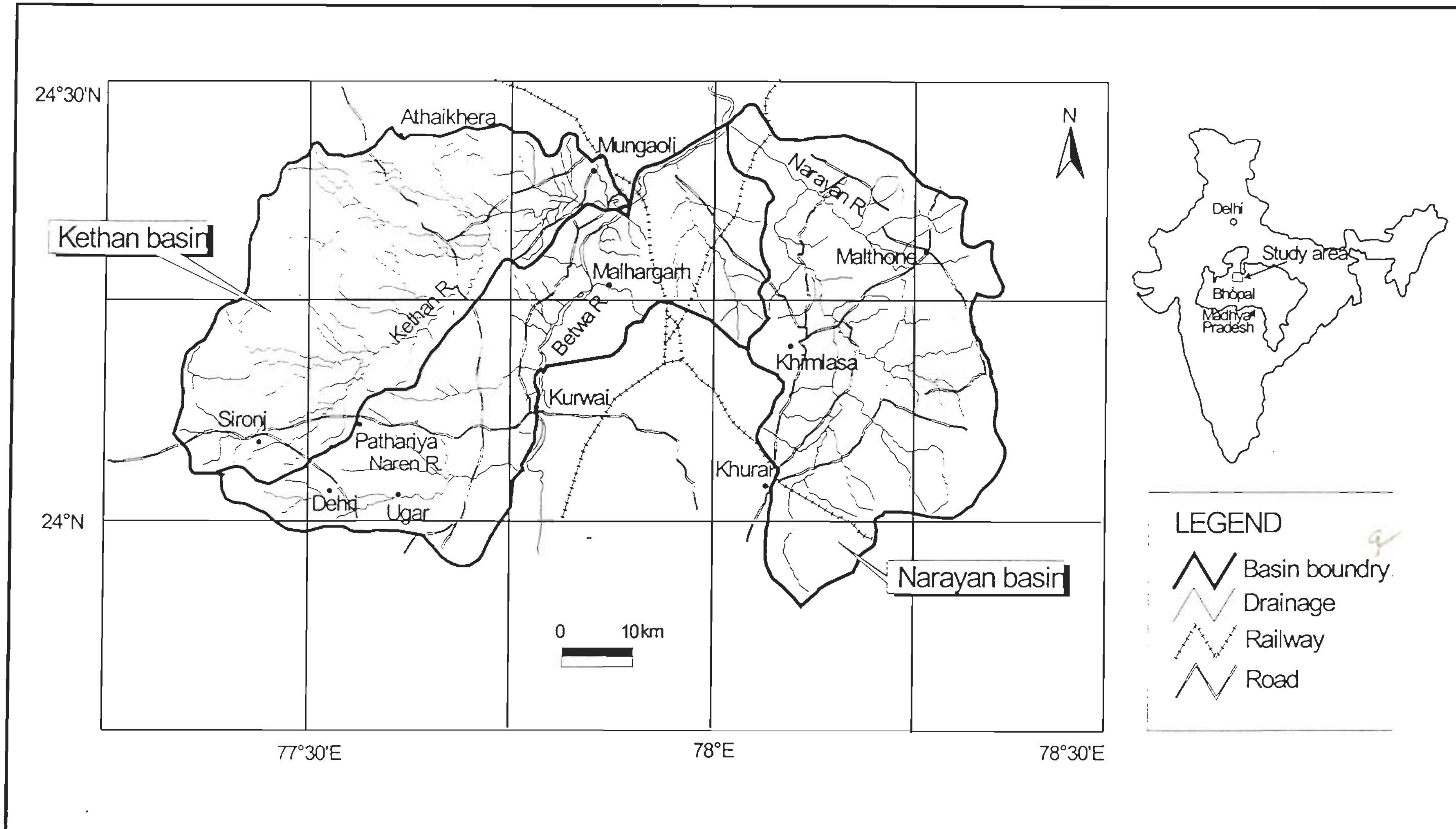


Figure 1.3: Location map of the study area showing drainage, road and railway network.

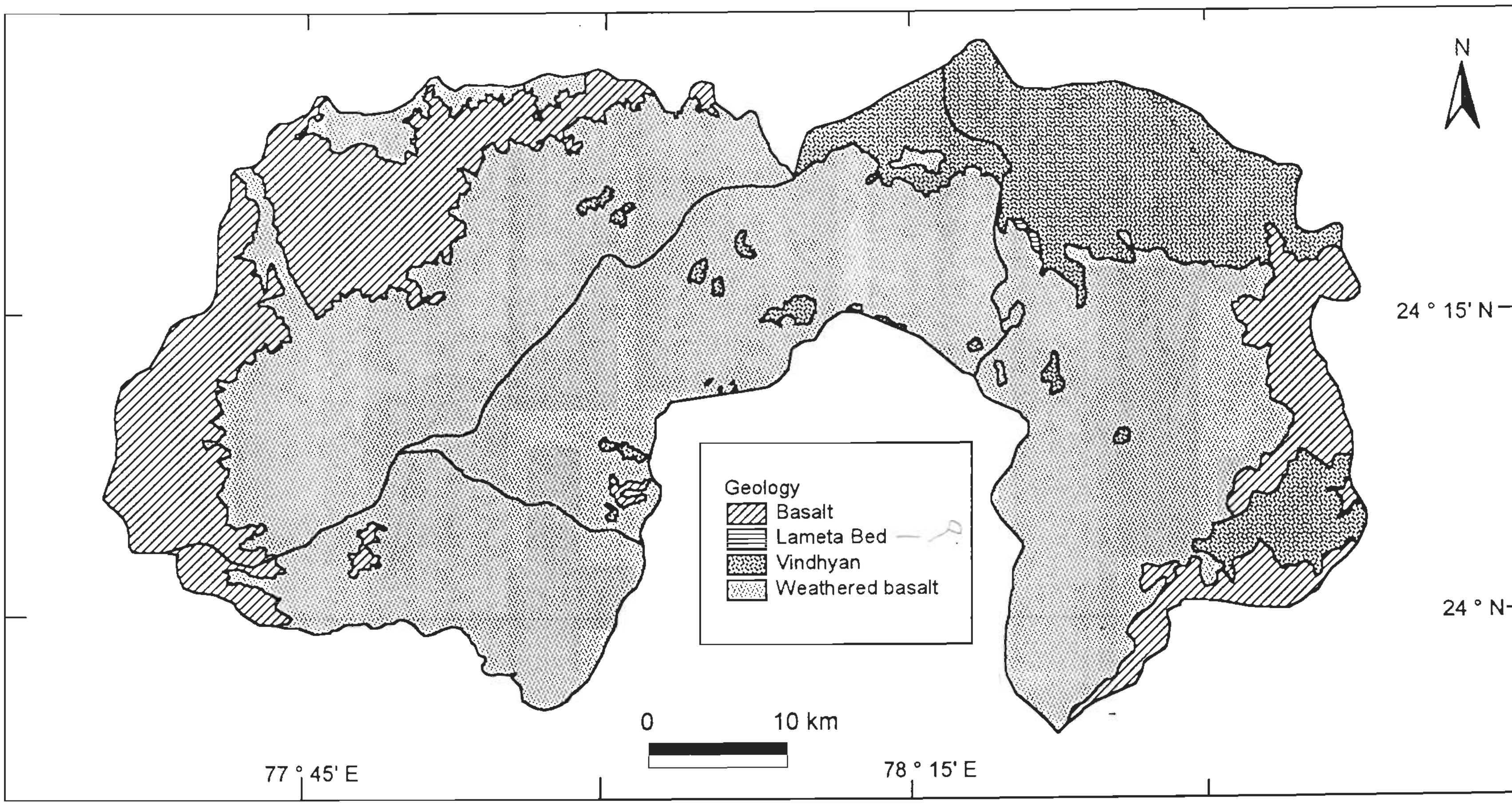


Figure 1.4. Geological map of the study area (Modified from GSI Quadrangle map 54 L, 1985 & 54H, 1977; CGWB, 1984).

1. **Laterite**: Laterite, occurring as capping over the basalts has localised developments. It varies in thickness from 1 to 5 m. Al_2O_3 content is less than 20% and it is mostly ferruginous in nature.

2. **Deccan trap**: It covers a vast area along the entire western and northwestern margin and some parts of the southeastern border. It occurs as hills or dissected plateaus. A total of 14 flows have been delineated in a vertical column of 175m. These are generally 'aa' type horizontal flows and are classified into three divisions namely Indore Formation, Kankariya Piru Kheri formation and Kalisindh Formation, on the basis of marker horizons like intertrappean beds, megacryst flows etc.

The flows at the bottom, termed the Basoda flows, are fine grained and sparsely porphyritic. The next younger group of flows, named Narsinghgarh flows, are dark grey, fine to medium grained and occasionally porphyritic. The lower and upper contacts of these flows are marked by intertrappean beds. The youngest group of flow, named as Sehore flow which are medium grained, non-porphyritic to moderately porphyritic. 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 that contains 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.

Few isolated outliers of Deccan Trap are also seen in the areas occupied by Vindhyans. This indicates the wide extent it covered in the geological past (CGWB, 1984). In the central part of the area, there is vast stretch of weathered basalt overlain by variable thickness of soil cover. The weathered basalt and the basalt exposures are differentiated (Figure 1.4) based on their different spectral signature on remote sensing images.

3. **Lameta Beds**: A small outcrop of the Lameta Beds occurs in the northeastern portion of the study area. It consists of fluviatile to estuarine rock facies of Cretaceous age. These beds occur below the Deccan Traps.

4. **Vindhyans**: Rocks of Vindhyan Supergroup are exposed in the northeastern ridge extending up to Malthone. There are some inliers in the central and eastern part occurring as monoliths forming isolated hills. These are shallow water sediments of Proterozoic age and are represented by alternating sequence of sandstone and shale. Of the three Groups of the Upper Vindhyans, only rocks of the Kaimur Group are present in the study area:

<u>Kaimur Group</u>: This is the oldest unit in the area, exposed in the northern and northeastern part of the area and also in patches around Vidisha. This consists of coarse to fine grained sandstones with intercalation of silt and sandstone in the upper part. It exhibits low dip towards SW. In the northern part it forms well developed scarps.

1.3.2 STRUCTURE

The Vindhyans form a broad synform with its axial trace in an arcuate shape. A series of synforms and antiforms are present in the region from north to south, with the axial traces trending WNW-ESE. The northern limb of the Vindhyan basin is comparatively undisturbed, whereas the southern limb was subjected to greater degree of structural disturbance (CGWB, 1984). Numerous joints have developed in the basalts, the prominent direction being NE-SW and NW-SE.

1.3.3 PHYSIOGRAPHY

Physiographically, there are two broad divisions in the area: (a) Plateaus and hillocks of basalt and (b) Low lying valley plains. The northern, northeastern and northwestern parts are bounded by plateaus and hills. The central part is mostly plain land with occasional intervenial plateaus and residual hills.

1.3.4 SOIL

The entire area is covered by black cotton soil. 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.

1.3.5 CLIMATE

The area is fed by southwestern monsoon rainfall from middle of June to September under the influence of monsoon depression originating from Bay of Bengal and travelling from east to west. The area comes under sub-humid to humid type of climate in the Thornthwaite's climatic classification. In general, the southern side of the area receives higher rainfall than the northern side. The average annual rainfall of the area is about 1040 mm. Most of the total rainfall is received during the monsoon months, i.e. June to September, and this is the period of ground water recharge. There is occasional rainfall in the period from October to March, which practically does not contribute to ground water recharge.

The area does not show much variation in the mean annual temperature. The maximum monthly temperature is about 40^{0}C in May, which is the hottest month. January is the coldest month with a minimum temperature ranging 3^{0}C to 10^{0}C. The rainy season gets maximum relative humidity in the month of August (around 98%) and the minimum relative humidity is observed in the month of April due to dry air and high temperature.

1.3.6 DRAINAGE

The Betwa river is the major perennial river draining the present area flowing from SW to NE and S to N in some parts. Kethan and Naren are the left-hand tributaries of the Betwa, and Narayan and Bina are the right hand tributaries. The right hand tributaries are aligned NW-SE parallel to the strike direction of basalt flows. Generally, drainage is sub-dendritic to dendritic in the areas covered by basalts and its weathered products, whereas trellis drainage is developed in areas covered by Vindhyans, as in the Narayan sub-basin. At places, drainage is structurally controlled.

1.3.7 LANDUSE

The hills and plateaus of Basalt and Vindhyan support dry deciduous mixed forests, covering the western and eastern boundary. In some parts, plateaus and pediments have patches of mixed forests with agricultural land. The cultivated area is mostly confined to alluvial plains and some parts of intervenial plateau. Grazing land and scrubs are found along the banks of the stream and along roads. Large agricultural lands are developed downstream from the reservoirs. Approximately 90% of the area are used for Rabi (winter crops) and only 10% area is used for double crops, that is, Rabi and Kharif (monsoon crops). The main crops are wheat, gram (various pulses, lentils, peas) and oilseed which are grown in Rabi season. The Kharif crops are mainly soyabean, sugarcane, millets and groundnuts. Thus, most of the cultivated land lies fallow from end of Rabi season to start of next season.

1.4 ORGANIZATION OF CHAPTERS

Chapter 2 gives a review of the application of remote sensing and GIS in groundwater studies.

Chapter 3 provides a general outline of the methodology developed.

Remote sensing data and ancillary information are integrated through GIS analysis.

Chapter 4 describes qualitative and quantitative assessment of the groundwater resources in the area.

Chapter 5 evaluates the status of artificial recharge conditions in the area through remote sensing and GIS techniques. Based on this observation and ground truth information, suitable locations for future artificial recharge are suggested.

Chapter 6 summarizes the work done and conclusions are drawn.

CHAPTER 2

REMOTE SENSING AND GIS IN GROUNDWATER STUDIES

2.0 INTRODUCTION

Remote sensing has established itself as a valuable tool for hydrologists to understand the groundwater regime of an area. The upper boundary of shallow groundwater is strongly influenced by features at or near the surface, information about which is provided by remote sensing (Meijerink, 1996). Groundwater is, by definition, subterranean. It is not available for direct observation. Hence, behaviour of groundwater is to be inferred from hydrogeologic clues, i.e. surface expressions of subsurface geological formations comprising the aquifer. Most remote sensing techniques, except airborne geophysical and radar, have no penetrating capabilities. Even long wave radar can sometimes detect groundwater levels only up to depths of a few meters. Therefore, information on hydrological indicators of groundwater is extracted from satellite images. These include structures (shear zones, faults, joints, folds etc.), consolidated and unconsolidated lithology, geomorphology (landform, erosion surfaces etc.), present and palaeo drainage patterns, vegetation vigour and areas of preserved soil moisture during dry season (Waters et al., 1990). Remote sensing investigation certainly narrows down the detailed hydrogeologic and geophysical investigation and thus minimises field work and overall cost. Remote sensing based hydrogeologic studies may be regional surveys involving understanding the general groundwater condition of a large area or local surveys for site selection of a borehole or dug well. In most of the cases, local surveys follow regional surveys.

Various remote sensing techniques are used in groundwater studies, e.g. aerial photographs, multispectral scanner images, radar images operating in different parts of the electromagnetic spectrum, airborne geophysical methods etc.

The concept of integrating remote sensing and GIS is relatively new. Probably, the fullest utilization of the potential of the two technologies can be realised only when an integrated approach is adopted. Blending of the two technologies has proved to be an efficient tool in groundwater studies. Remote sensing data provide the most accurate spatial information and it can be economically utilised 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 analysis of large volumes of multi-disciplinary data, both spatial and non-spatial, within the same georeferencing scheme.

In this chapter, an attempt has been made to portray, in brief, the route starting from remote sensing application with the help of visual interpretation through digital image processing in groundwater studies towards the integrated GIS approach.

2.1 HYDROGEOLOGICAL INDICATORS DERIVED FROM REMOTE SENSING

This section concentrates mainly on the hydrogeological application of remote sensing in the reflected and emitted electromagnetic radiation by satellite or airborne sensors in the visible and infrared region of the electromagnetic spectrum. Some selected works are discussed under different headings.

Use of photogeology contributed much to hydrogeological mapping in the past and it is in use till now (Meijerink, 1974). Photogeology reached a state of maturity during 1960s. A new era in natural resources studies dawned with the launch of ERTS (Earth Resources Satellite Technology) on 23 July, 1972 by NASA (National Aeronautic and Space Administration). ERTS imagery offered the first opportunity to apply moderately high resolution satellite data for nation-wide study of water resources. It proved to be suitable for broad regional survey and reduced fieldwork. The potential uses of ERTS imagery include locating new aquifers, to study aquifer recharge and discharge, estimation of pumpage for irrigation, to predict the location and type of water management (Moore and Deutsch, 1975). Identification of hydrologically significant lineaments is another important application, especially in hard rock terrains where large amount of groundwater can be obtained from wells along fractures. These imageries have advantage over low altitude, high resolution aerial photographs in detecting regionally extensive faults due to their synoptic view.

Application of remote sensing in groundwater has been reviewed by many (Sharma, 1983; Gupta and Ganesha Raj, 1986; Waters et al., 1990; Engman and Gurney, 1991; Sahai et al., 1991; Meijerink et al., 1994; Meijerink, 1996; Reddy et al., 1996; Rao and Gupta, 1998). Basically there have been two approaches to the use of remote sensing in groundwater exploration. The first is generally applied to basement and carbonate aquifers, where fracture flow is the characteristic mode of water movement and some linear features correspond to fractures that correlate with the occurrence of groundwater. The second approach integrates remote sensing data with other sources of information to create hydrogeological thematic maps for groundwater exploration (Waters et al., 1990).

Remote sensing has been successfully used in conjunction with other regional information for groundwater investigations (Gurney et al., 1982; Salman, 1983; Sahai et al., 1985; Chaturvedi et al., 1983; Farnsworth et al., 1984; Kaufman et al., 1986; Ramasamy et al., 1989; Kruck, 1981 & 1990). Two aspects of hydrologic variables can be derived from remote sensing. The qualitative aspect comprises understanding of groundwater regime of an area. The quantitative approach attempts to quantify the hydrological indicators e.g. precipitation, evaporation, soil moisture etc. from remote sensing data. Detailed discussion on these is beyond the scope of this chapter. Discussion on the estimation of hydrologic variables can be found in Schultz (1993a), Kite and

Pietroniro (1996).

The hydrogeologic clues that can be extracted from remote sensing are as follows:

a) Geology

b) Geomorphology

c) Structures (lineaments, fault zones etc.)

d) Vegetation

e) Drainage (density and pattern)

f) Surface water bodies

g) Landuse

h) Soil properties

i) Soil moisture

j) Recharge and discharge areas

In order to detect the clues for groundwater occurrence and movement from remote sensing data, spectral properties of the earth surface features are to be understood. The following section gives a brief description of the behaviour of these materials in the visible and infrared region of the electro-magnetic (EM) spectrum.

2.1.1 SPECTRAL PROPERTIES OF VEGETATION, SOIL AND WATER

Electromagnetic radiation incident on an object is either reflected, absorbed or transmitted, the proportion of the three being different for different objects as well as the sensors. The spectral properties of the materials depend on the physical and physiological nature. The most important are vegetation and soil properties. The spectral reflectance properties of leaf which is the simplest component of vegetation in the visible and infrared region is a function of the leaf pigments, the leaf cell morphology, internal refractive index discontinuities and the water content (Raines and Canny, 1980). The factors responsible for reflectance properties of vegetation canopy in the visible and near infrared region are different cell structures, proportions of chlorophyll and other pigments, surface morphology and water content. A plant leaf typically has a low reflectance in the visible spectral region because of strong absorption by chlorophyll, a relatively high reflectance in the near-infrared because of internal scattering and a relatively low reflectance in the infrared beyond 1.3μm because of strong absorption by water (Knipling, 1970). Figure 2.1 shows a typical spectral reflectance curve of vegetation. Since organisms have life cycle of various duration, spectral properties change in response to temporal changes. Towards the end of the functional life of a plant, the tissues deteriorate and chlorophyll breaks down. This leads to a marked increase in reflectance at the end of the visible region (0.6-0.7 μm) as the chlorophyll absorption reduces. During senescence, near infrared reflectance falls. In general, lower the water content of a plant the higher the reflectance in the middle infrared, with reflectance peak between moisture absorption band at around 1.6 μm and 2.2 μm (Belward, 1991).

In case of soil, all the incident energy is either reflected or absorbed. There is increase in reflectance from visible to infrared but the moisture content in the soil upsets this. Figure 2.2 shows the reflectance curve for sandy and clayey soils. The soils with small particle size and, therefore, large surface area hold a large amount of water. The reflectance curve for clay dips at 2.2μm corresponding to hydroxyl absorption band. Presence of organic matter and high iron content lowers down the reflectance.

The reflectance of pure water generally decreases uniformly from visible to near infrared with a peak in the 0.55μm (Figure 2.3). Presence of organic and inorganic materials in water effects the reflectance. It also depends on the nature of bottom material. Water with high inorganic sediments has higher reflectance in the visible region. This helps in detecting sediment load in water and monitoring water quality from remote sensing data.

2.1.2 HYDROGEOMORPHIC INFORMATION

Visual interpretation of aerial photographs and photographic products of multispectral remote sensing data has been extensively used for deciphering

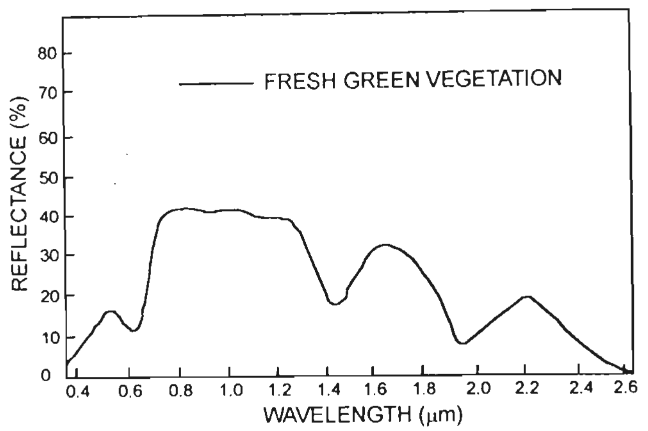


Figure 2.1: Spectral reflectance curve of fresh green vegetation

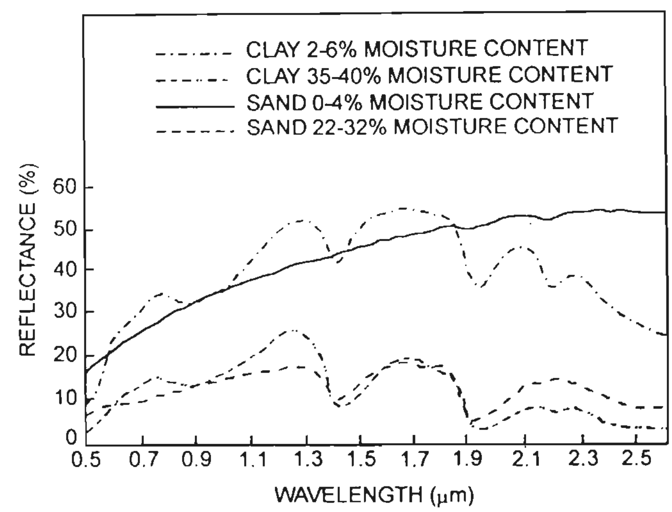


Figure 2.2 :Spectral reflectance curves for bare soil.

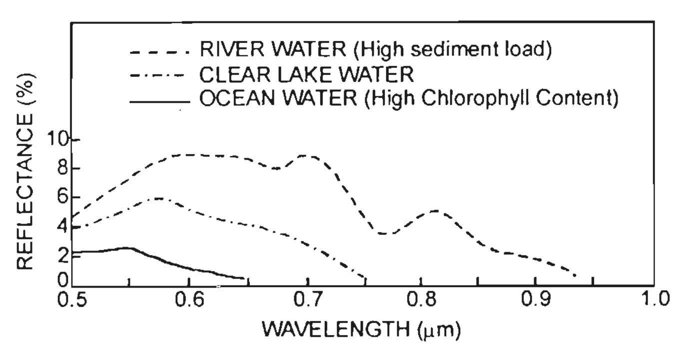


Figure 2.3 : Spectral reflectance curves for water. River and lake water

hydrogeomorphic conditions (Perumal and Roy, 1983; Anjaneyulu, 1983; Ramasamy and Bakliwal,1983; Balasubramaniam et al., 1983; Srinivasan, 1988; Agarwal and Mishra, 1992). Sharma (1983) described an overview of aerial and satellite remote sensing based mapping of geomorphic features. In hard rocks there are two types of aquifers, namely granular aquifer and fractured rock aquifer (Raju, 1985). The weathered zone constitutes the former type and the latter is formed by the development of secondary permeability due to fractures. Hydrogeomorphic maps are prepared by combining information on drainage characteristics, landforms, geology, structural features and soil types. Identification of these from remote sensing data helps greatly in selection of drill targets and also to have an understanding of the groundwater circulation system by delineation of recharge and discharge areas.

Drainage is one of the simplest parameter, which can be extracted through remote sensing. It gives the most recent and accurate information and the seasonal changes can also be mapped using multi date data. The near infra red (NIR) band reveals the most contrast between land and water features due to very low to almost zero reflectance of water in this region. Drainage network has been mapped from FCC photo prints as well as from digital data. Astaras (1985) used Landsat imagery for mapping of drainage features for quantitative analysis in the Olympus-Pieria mountain area. Astaras et al. (1990) performed a multi-sensor analysis using Landsat-3, RBV, TM images and SPOT PLA stereo pairs in Central Macedonia for drainage extraction. Drainage pattern and texture reflect the permeability of the underlying lithology and provide an important indication of groundwater condition (Charon, 1974, Salman, 1983). High drainage density is the result of impervious lithology at or near the surface. Some drainage patterns are associated with particular type of rocks e.g. dendritic pattern is usually developed in granitic or other hard rock terrain. Drainage pattern indicates how much water can percolate into the groundwater and thus the recharge conditions can be inferred. Generally, in hard rocks, the drainage density is high except in the weathered areas.

Drainage pattern can be correlated with lineaments and the direction of movement of groundwater can be deciphered where groundwater movement is fracture controlled. Ahmed et al. (1984) prepared lineament intensity and drainage density contours using Landsat data and groundwater target areas were selected where high lineament intensity and low drainage intensity overlap. El Shazly et al. (1983) described a similar approach in Wadi Araba area of Egypt. Geomorphic features, land cover, vegetation, structural lineaments and drainage were interpreted from Landsat MSS imagery. These information along with ancillary information were analysed with respect to the pre-existing well sites; lineament intersection in combination with low to medium drainage density appeared to favour groundwater occurrence. However, this combination of low drainage density and high lineament density may not favour groundwater movement in all areas. Seelan (1983) identified potential groundwater zones from remote sensing data of Karnataka, India based on lithological and morphological factors, which control groundwater occurrence and, soil and landuse factors, which affect groundwater recharge. In this case, there is a good groundwater potential in Deccan Trap in areas showing high lineament density and good surface drainage. There is good groundwater potential also in alluvium where lineament density is low and surface drainage is moderate. This is because lineament in alluvium is not related to fracturing of bedrock and can not be compared to lineaments in bedrock. Thus, the interdependence of all the parameters are to be considered.

Surface manifestation of paleochannels can be identified from remote sensing data. Usually these are potential sites for groundwater (Dhinwa and Majumdar, 1983; Chaturvedi et al., 1983; Ramasamy and Bakliwal 1983). Chaturvedi et al. (1983) performed an integrated study of remote sensing and conventional techniques in the Bundelkhand region of Uttar Pradesh, India. They delineated a circular feature near the Betwa river, which is interpreted to be a paleochannel. This is confirmed by geoelectrical sounding and a number of potential well sites were marked in this area. Ramasamy and Bakliwal (1983) also detected buried channels in a part of Banded Gneissic Complex, Rajasthan, which form potential sites for groundwater. Balasubramaniam et al. (1983) mapped hydrogeomorphic features from Landsat imagery in North Arcot district, Tamil Nadu, India. The area is mainly covered by gneisses and charnockites.

The alluvial plains and bajadas hold good groundwater prospects. Perumal and Roy (1983) performed a similar study in parts of the Vagai, the Manimuthar and the Pambar basins of Tamil Nadu. The valley fills, buried pediments and alluvial plains were the potential sites for groundwater. Ravindran and Jeyaram (1997) performed a study in the Shahbad tehsil, Rajasthan, covered by Vindhyan sandstones. Groundwater potential was evaluated based on geomorphology, drainage, springs, lineaments derived from IRS-LISS-II imagery, and depth to water level data. Only the valley fill and buried pediments in sandstone form very good prospects for groundwater. The groundwater resource can be augmented by inducing artificial recharge through infiltration tube wells.

Vegetation bears an important role in groundwater studies. Vegetation intensity and types can be identified from remote sensing data. Kruck (1990) described some examples using Landsat and TM data in six different test sites having different lithology. In a sandstone area of Yemen Arab Republic, TM data taken during the final stage of dry season revealed vegetation anomalies. FCC of bands 4, 3, 2 and 7, 4, 1 were particularly useful in understanding of hydrogeological conditions. The interrelation of vegetation with lineament is noteworthy in a hard rock terrain. Dry season healthy vegetation is a possible indicator of groundwater. Taranik and Trautwein (1977) performed an integrated study using remote sensing data supported by ancillary information or facts namely geology, geomorphology, climate, drainage, soil and hydrology. Satellite data provided information on landform, vegetation, drainage, relief and lineaments. They noticed correlation between spatial pattern of vegetation with the derived lineaments. Lineaments were assumed to represent joints and faults. Based on the interpretation, hydrogeological map was prepared and site for test wells were selected. Kruck (1990) noticed vegetation anomalies interrelated to lineaments. MSS data of Burkino Faso were used to produce pedologic map, population density map (based on landuse density) and lineament map. Geologically, the area is underlain by crystalline basement and hence, fractures are of great importance for groundwater prospecting. Linearly arranged vegetation accumulations can indicate fracture zones beneath a cover of weathered zone. In another study in the Republic of Mali, hydrography and lineaments with active vegetation on the Bandiagara sandstone were delineated on FCC. It was noticed that shorter distance to lineaments give higher borehole yields. Vincent et al. (1978) tried to correlate fracture density with other information. Fracture density related to truncated vegetation pattern indicating infilling of residual soils on downthrown blocks of a normal fault was found to be the best target site. Gustafsson (1993) used SPOT data in southwestern Botswana in a sandstone area where primary porosity is low. The fractures serve as conduits for groundwater movement. Superimposition of classified vegetation index image with lineament map showed that spatial distribution of vegetation matches with the direction of lineaments.

Remote sensing data provides information on soil moisture conditions. In general, wet soil surfaces have less reflectance values, both in visible and infra-red regions than dry surfaces (Figure 2.3). Soil reflectance is not only dependent on moisture content but also on many other factors. Microwave remote sensing can provide a direct measurement of soil moisture (discussed under section 2.1.5).

Digital image processing of satellite data facilitates better discrimination of terrain features. Various digital image processing techniques are applied to enhance the hydrogeomorphic features. Deekshatulu (1983) reviewed various digital image processing technique employed in water resources management. Most commonly used were contrast stretching, filtering, band ratioing and principal component analysis (PCA). Statistical methods are frequently applied in remote sensing analysis. The basis of statistical method is that various objects at the surface of the earth are reflecting, absorbing and emitting radiation depending upon their type. An object is not represented by a single reflectance or emission value but is characterized by a cluster of values with a specific range in each spectral band. Statistical methods classify each pixel according to its specific spectral properties into a class using an algorithm (Baumgartner and Apfl, 1996).

Basappa Reddy and Gaikwad (1985) found that linear stretching, band ratio and their FCC are very useful for groundwater targeting in fractured crystalline rocks mainly granite gneiss and schists. Krishnamurthy et al. (1992) used various combinations of FCC generated from principal component analysis to highlight landforms, and directional filtering to extract lineaments in a hard rock area in Karnataka, India using Landsat TM data. They found infrared bands to be more useful in enhancing the geological features. Subtraction of band 3 from band 4 enhanced the moisture bearing lineaments. These were found to be promising sites for shallow groundwater occurrence in the area. In general, the valley fills provide excellent prospects for groundwater. Pediplains over granite and gneiss also have good prospects. Jeyaram et al.(1992) found principal component analysis and NDVI quite useful for demarcation of geomorphic features. Further, they used local optimization technique to identify individual basalt flows and intertrappean beds of Nagpur district, Maharashtra, India. Fractures and intertrappean beds are indicative of moderately good potential of groundwater. Pediplains of basalt or granite have fairly good to moderate groundwater potential. Three different sites in Karnataka, India, representing typical geological setup were selected to compare and evaluate the various factors that affect groundwater occurrence by Krishnamurthy and Srinivas (1995). Linear stretched FCC and principal component composite highlight the lithounits and the landforms. The filtered products bring out the lineaments. The integration of details on geology, structures and landforms derived from digitally enhanced IRS data with morphometric parameters obtained from drainage maps along with ground truth data has enabled assessment of groundwater condition. The valley fill, lineament intersection, lineament controlled valley floor and pediplains are the promising sites for groundwater exploration. Groundwater occurrence in similar landforms varies considerably with the variation in lithology. Perumal (1990) showed that digital image processing of MSS and IRS data could enhance the subdued structural features and landforms in mapping groundwater prospect in a hard rock terrain (Athur valley, Karnataka, India). He found that hybrid FCC of PC-3 components and brightness index of Bands 4 and 6, and, 5 and 7 (MSS) are particularly useful for demarcating different geomorphic units, like denudational hills, shallow or buried pediment, piedmont area and valley fills. Field data e.g. pumping test data and depth to water level data were also used. Hybrid false colour composite of brightness index images of bands 4,5 and 5, 7 of Landsat TM and the PC1 proved quite useful in differentiating between hills, buried pediments and valley in parts of Orissa, India (Das et al. 1997). The area is covered by granite, quartzite, metavolcanics and iron ore deposits. Directional filtered images helped delineation of lineaments. From the lineament map and exploratory drilling, it was concluded that lineaments traversing intermontane valley and pediments are ideal locations for occurrence and exploitation of groundwater through bore wells.

Legg (1989) has used an integrated approach for groundwater targeting using image processing. TM and Seasat SAR data were processed to extract lineament and geological information. Three information layers were combined using IHS transformation. Lineament map has been assigned to the intensity layer, geological map to the hue and DEM (digital elevation model) to the saturation and reverse transform to RGB has been performed. On the basis of this combined information, test sites for detailed geophysical survey have been selected.

With the advent of high resolution sensors, e.g. IRS-LISS-III PAN, interest of hydrogeologists is increasing. The main advantage of PAN data is the proper identification of groundwater zones on the ground. Well-defined fractures can be identified accurately on ground. Minor slips, offsets and dislocation in the linear ridges and intrusive like dykes can be mapped. Parts of Andhra Pradesh, India, covered by granite gneisses were studied for groundwater prospects. IRS-1C LISS-III data facilitate mapping of dolerite dykes, which are acting as a barrier for groundwater movement. Merged image prepared by merging of high resolution of IRS-1C PAN and spectral resolution of LISS-III provides further detail of the terrain. Individual agricultural fields, small stream courses and minor fractures can be delineated (Reddy et. al., 1996).

2.1.3 LINEAMENT ANALYSIS

The surface expressions of subsurface structures appearing on remote sensing data are in the form of lineaments. These linear features or lineaments are of great interest to hydrogeologists in locating groundwater zones. The correlation of lineament with groundwater depends on the geological nature of the lineament. In hard rock terrains, the primary porosity is practically zero and groundwater occurrence is primarily a function of fracture-induced secondary permeability. The fractures either provide water circulation channels or act as impervious barriers (Vincent et al. 1978). In these areas, surface drainage is also mostly aligned along the fracture system. Recognition of surface expressions of the structural features is, therefore, an important task in groundwater exploration.

O'Leary et al. (1976) defined lineament as "a mappable, simple or composite linear feature whose parts are aligned in rectilinear or slightly curvilinear relationship, which differs distinctly from the patterns of adjacent features and which presumably reflects a subsurface phenomenon." This term, however, is used in a wider sense. A lithological boundary, vegetal or soil boundary, or topographic discontinuity may appear as lineaments on satellite imageries. There are also cultural lineaments. The definition given by Gold (1980) covers a wider perspective as it defines lineament as "any straight or slightly curved feature or alignment of discontinuous features that are apparent on a map." Large lineaments observed on satellite image are often surface expressions of major fracture zones, whereas photolineaments tend to be discrete fracture traces marked by linear drainage or changes in soil tone and vegetation (Waters et al., 1990).

All lineaments are not necessarily traces of fractures. It is very important to have an understanding of rock stress and deformation in order to determine the possible hydrogeological significance. Remote sensing may show the prominent fracture trends correlated to the movement of groundwater. Waters et al. (1990) and Waters (1990) have given a detailed discussion on the hydrologic behaviour of lineaments. There is a general agreement that lineaments associated with brittle deformation caused by tensional stress related to normal and strike slip faulting provide the most promising water bearing zone (Greenbaum, 1986).

Lineaments are extensively used as a guide for groundwater exploration in hard rocks. Deolankar et al. (1980) interpreted photolineaments in Deccan Trap basalt, and groundwater flow direction was inferred. On the basis of this, new well sites were suggested. Ramasamy and Bakliwal (1983) identified lineaments from remote sensing data, correlated them to major structural features, and prepared lineament intersection density map. The maximum values were inferred to be potential areas of groundwater accumulation. Further, lineament intersection density map is combined with geomorphology. Ramasamy et al. (1989) mapped structural pattern in part of south India on the basis of relief, drainage, soil tone and vegetation linearities from satellite imagery. These data were integrated by multivariate analysis with water level, transmissivity and yield data, and regional groundwater characteristics were mapped. Rao (1983) applied an integrated deformation model put forward by Larsson, 1972 (in Rao, 1983) for groundwater targeting in an area around Hyderabad, India, covered by Peninsular gneisses. Landsat MSS image was interpreted to prepare lineament map and non-tectonic and tectonic lineaments were identified. Three major brittle deformation periods are identified. The fractures in N-S direction, parallel to the dykes are open tensile fractures and are not suitable for groundwater occurrence. NW-SE fractures are generally shear fractures associated with faults. Though they are close fractures, in some parts they yield good quantity of groundwater. E-W tensile fractures correlate to dykes and are not suitable for groundwater occurrence. However, in several places in the upstream, where E-W dykes cut across drainage, good yield is found. Usha et al. (1989) mapped lineaments from TM data and inferred subsurface configuration of the folded structure. Fracture density map was prepared, and after interfacing with water level maps, groundwater movement direction was identified.

Spatial filtering is widely used to define lineaments on digital images (Chavez et al., 1977; Schowengerdt et al., 1981; Moore and Waltz, 1986; Drury, 1987). Rampal and Rao (1989) used Landsat MSS data in a part of Chitraduraga greenschist belt in Karnataka, India. They found high pass filtering to be very useful for extraction of fracture zones and for groundwater targeting. Suzen and Toprak (1998) have developed a methodology for geological lineament analyses applied in a fault zone, Central Turkey. They used stretched TM band 7 and PCA images to detect lineaments. Further, through the combined use of large smoothening filter and gradient filter, in order to remove artefacts, they prepared the final lineament map.

Basappa Reddy and Gaikwad (1985) have used MSS data for groundwater targeting in fractured crystalline rocks comprising granitic gneiss and schists in Karnataka, India. They concluded that linear stretching, band ratioing and their FCC were very useful for identification of lineaments and targeting of groundwater development areas. Krishnamurthy et al. (1992) used colour composites of vertical, diagonal and horizontal filtered products of Landsat TM bands 4,5 and 7 to highlight the linear features in a hard rock area of Karnataka, India. Combination of spectral and spatial enhancement greatly enhances lineaments. Gustafsson (1993) tested different combinations of image processing and the ideal combination for lineament interpretation was merging of SPOT multispectral from dry season in RGB with SPOT panchromatic as an intensity layer.

Moore and Waltz (1986) developed a five step digital convolution procedure to extract edges and linear features using Landsat MSS band 7 image. This method has been found to be useful in groundwater studies (Saraf and Choudhury, 1997 and 1998). Specialised operators such as Hough transforms are also attempted for automated lineament detection (Gurney and Williamson, 1981; Cross and Wadge, 1988; Wadge and Cross, 1989; Wang and Howarth, 1990).

Hardcastle (1995) used a new approach to facilitate ranking of discrete areas about their potential ability to store and transmit groundwater. The normalised sum of three photolineament parameters, namely, 1) the number of photolineaments, 2) the number of directional photolineament families and 3) total length of photolineament within an area of defined radius is defined as photolineament factor value. Further, contour map of the value is generated, which facilitates rapid quantitative ranking.

Mahmood (1996) carried out a study using Landsat MSS data in a granitic terrain of Morocco in conjunction with slope analysis. The study concerns with a prominent lineament that was found to be due to a major dip slip fault. Statistical slope analysis reveals strong topographic and hydrographic influence of the fault, which coincides with the only perennial stream. The faults were giving pathways for groundwater movement. It was concluded that in crystalline basement terrains deep seated fractures with the weathered overburden provide favourable sites for groundwater circulation.

There have been many attempts to correlate lineaments with well yields. Many examples are cited by Waters et al. 1990. In most of the cases a positive correlation is found (Siddique and Parizek, 1971; Lattmen and Parizek, 1964; Woober, 1967; Alpay, 1973; LaRiccia and Rauch, 1976; Kareemuddin and Dharmaraj, 1979; Sarma and Babu, 1980; Yin and Brook, 1992). Fracture traces indicate zones of higher porosity and hydraulic conductivity. Some studies, however, hold contrary views. Rauch (1984) found inconsistent results of well yields near lineaments.

Lineament mapping from satellite images necessarily implies some limitations due to the characteristics of the sensors. The influence of scan line direction of the sensor and the azimuthal sun angle depending on the overpass time of the satellite are particularly noticeable. For example, on Landsat images, scan line direction may lead to more lineaments with a ESE-WNW strike. In this case, images were recorded with a 147° solar azimuth. They applied a multiangular derivative where the 54° derivative reduced the influence of solar azimuth (Zilioli and Antoninetti, 1987).

Geophysical methods are used to support remote sensing interpretation for identification of groundwater prospects (Mishra et al., 1990; Prakash and Mishra, 1993; Palanivel et al., 1996). Resistivity data helps in delineating properties of the water-bearing zone. Chaturvedi et al. (1983) used aerial photographs and satellite data in conjunction with geoelectrical sounding for selecting potential well sites in Bundelkhand Granite in India. Delineation of paleochannels helped in siting of wells. Palanivel et al. (1996) used an integrated approach of remote sensing, geophysical and well inventory data for hydrogeological evaluation in parts of Tamil Nadu. The shallow aquifer was found to be controlled by geomorphology and structural pattern, whereas at intermediate depth, fractures control the yield of groundwater. Das et al. (1997) carried out resistivity survey to reveal the different layers of weathered, fractured and massive formations and their hydraulic connection in parts of Orissa, India and corroborated the results with hydrogeomorphic information to understand the controls of groundwater occurrence in the area. Gustafsson (1993) attempted correlation of geophysical anomaly with lineaments. The number of anomalies decrease with distance from the lineaments. The authenticity of satellite lineament can also be examined through combination with geophysical data. Thilliagovindrajan and Andrawis (1978) selected some sites of linear features mapped from Landsat data for detailed geophysical survey and tried to recognize the geological lineaments. Dewangan and Udaya Shankar (1983) carried out a study in the Noyil basin, Tamil Nadu, covered by gneisses, granite, and charnockite. It was noticed that in most areas the stream frequency matches with lineament frequency. The inferred lineaments were correlated in the field through VES (vertical electro sounding) method.

2.1.4 GROUNDWATER CIRCULATION SYSTEM

Image processing helps in the delineation of groundwater recharge and discharge areas, and the flow system can be inferred. Salama et al. (1994)

performed an integrated study using aerial photographs and image processing of Landsat TM data supported by hydrogeological investigation to classify the geomorphic units which control the mechanism of recharge and discharge in the Salt river system, Western Australia. The area is formed of granite, gneisses and metasedimentary rocks. PCA images and directional filtering of first principal component highlighted the landforms and geological features. Recharge and discharge area map was prepared on the basis of interpretation from geomorphic, structural and hydrogeologic features and the groundwater flow system was conceptualized. Peters and Sturmann (1989) inferred flow system in an unconsolidated rock using classified Landsat TM data. In some areas, satellite images contain features that have a direct link to the groundwater discharges, such as the extent of the fresh water swamps in a saline lacustrine plain (South Kenya; Meijerink, 1996). A hydrometric survey showed that the groundwater discharge is approximately equal to the area of swamp vegetation times the potential evapo-transpiration. Size of the swamp area can be measured form remote sensing data and fluctuations in discharge in the past can be estimated (Meijerink ,1996). Hatton and Dincer (1979) also related discharge to the size of wet areas expressed by vegetation response, in Botswana. Such direct links are exceptional.

Bobba et al.(1992) identified areas with relatively warm groundwater on aircraft thermal imagery of Ontario, Canada, and related them to either shallow aquifers or discharge areas of deeper flow systems. From linear segmentation of feature space of MSS bands 7 (0.8 to 1.1 μm) and 5 (0.6 to 0.7 μm) of late March, recharge, transition and discharge areas could be mapped. PCA image was used to classify vegetation related groundwater exfiltration in an area in Belgium (Batelaan et al., 1993). PC1 image was in good agreement with the modelled discharge areas. The association of moist soil and low spectral brightness, however, hold true for only certain seasons; in others, the empirical relations may be different and other classification techniques may be used, depending on the knowledge of local vegetation responses (Meijerink, 1996).

2.1.5 THERMAL INFRARED DATA

Thermal infrared scanner records information of the emitted radiance, in the 8-14μm region. Thermal anomalies are the result of high heat capacity and may be a clue to shallow groundwater. A detailed discussion on the application of thermal infrared imagery can be found in Salomonson (1983). Heilmann and Moore (1982) used HCMM (Heat Capacity Mapping Mission) data to correlate surface temperature with shallow groundwater. Moore and Myers (1972) used thermal data to identify areas of artesian wells and natural springs in south Dakota. Bobba et al.(1992) used airborne thermal data to map the groundwater flow systems. Shih and Jordan (1993) indicated that TM thermal IR data can provide useful information for periodic monitoring of spatial distribution of soil moisture conditions. They found that day time surface temperature is inversely proportional to the soil moisture content. TM thermal data facilitated detection of soil moisture conditions under various landuse categories.

2.1.6 RADAR DATA

Radar is responsive to surface roughness and changes in topography. It is very useful in large scale mapping of terrain features because of its capability to penetrate cloud cover and vegetation. Radar application in hydrology has been reviewed by Harris et al. (1984). In groundwater studies, radar data has been used to extract soil moisture information (Jackson et al., 1996). Since the radar return signal is related to the dielectric properties of the surface it is possible to use this as an indication of soil moisture. It has good potential in perpetually cloud covered and tropical thick rain forests. SAR (Synthetic Aperture Radar) is useful in groundwater exploration in arid region. McCauley et al. (1982, 1986) demonstrated that SIR-A imagery revealed paleo-drainage channels, penetrating several metres thick cover of sand. Such channels can act as a storage site for groundwater. Ground penetrating radar is found to be valuable in initial assessment of hydrogeological conditions (Benson and Yuhr, 1987) and also in detecting water table depth (Shih et al. 1986). The penetration capability is dependent on not only the frequency of the antenna but also in the electric properties of the earth materials. Highly conductive material like clayey soil reduces the penetration depth (Strangland and Kuo, 1987). SIR-C data have been used by Rao (1999) in paleao-drainage study in north western India. L-band SAR data have provided the trace of river Saraswati that is buried under sand cover (Rao, 1999). Such data sets, however, have not been used in the present study.

2.2 GROUNDWATER RESOURCES ESTIMATION AND DEVELOPMENT THROUGH REMOTE SENSING

Availability of high resolution remote sensing data also enables the quantitative estimation of groundwater resources. Multi-date remote sensing data facilitates estimation of groundwater inflow and outflow components. Meijerink et al. (1994) identified irrigated areas in hard rock region in South India, comprising gneisses and granite traversed by dolerite dykes, through image processing. From this data, the total groundwater draft during the growing season was estimated by compiling the cropping calendar, and making a field check as to the water use for land preparation and the frequency of water application. Rao et al. (1993) used multi-date IRS-LISS-II and Landsat TM data to extract hydrogeomorphic features. Groundwater resources were estimated using conventional methods and sites for rain water harvesting structures were suggested in order to recharge the irrigated wells.

High resolution PAN data from IRS-1C provide details of the irrigated area which are very useful for estimating deep percolation losses from the irrigated field. Reddy et al. (1996) identified zones of over exploitation of groundwater from LISS-III and PAN data and found these data very useful for groundwater resource estimation and groundwater development planning. Reddy et al. (1998) estimated groundwater recharge, draft and balance of Sharada basin Andhra Pradesh, India using SPOT MLA data. The area is underlain by crystalline rocks and alluvial formations. Crop areas and geomorphic features were extracted from remote sensing data and respective values of infiltration factors were assigned to different geomorphic units.

Karale et al. (1990) carried out a study using IRS-LISS-I and II data in Nagpur district, Maharashtra to select site for artificial recharge structures to combat overdraft in the area. Geology and geomorphology maps were prepared from visual interpretation of digitally enhanced pre-monsoon LISS-II data. Landuse/ landcover map was generated from multi-date LISS-I data, of winter (Rabi) and summer (Kharif) crop seasons. Depth to water level and soil data were also incorporated. Based on hydrogeomorphic studies, suitable sites for artificial recharge were suggested.

The above discussion reveals that remote sensing data are to be used in conjunction with other ancillary information in groundwater studies. It can be realised that multi source multi thematic data are required in groundwater studies. The need for an efficient spatial information analysis system in natural resources studies was perceived by many authors. For optimisation of resources management, planning, merging and integrated analysis of information, layers from diverse sources are required. With the application of GIS technology, groundwater resources can be evaluated and monitored more efficiently and management plans can be designed based on the requirement.

The interest of hydrogeologists is shifting towards the dynamics of water balance and contamination. The appropriate tool is combination of image processing, GIS and numerical modelling. The real hydrologic value of remote sensing data depends on the transfer functions to transform reflectivity data to hydrologic variables.

2.3 GIS APPLICATIONS IN GROUNDWATER STUDIES

The hydrogeologic system in most areas is quite complex. In order to have a proper understanding of the groundwater regime, coherent analysis of all the influencing factors are to be performed. A large volume of data from various sources are required. Remote sensing data alone are not sufficient. Merging of remote sensing data with other ancillary information is of great value and GIS is the appropriate tool. GIS is an efficient tool for manipulating and storing large volumes of data, integrating spatial and non-spatial information within a single system, offering a consistent framework for analysing the spatial variation, allowing manipulation of geographic information, and allowing connections between entities based on geographic proximity (Moore et al. 1991). Further, 3D perspective visualization is extremely valuable for characterization of hydrogeologic framework. This is an unique feature provided in GIS.

In this section, the general utilities of GIS like the various analysis operations are not discussed in detail. Only the specific features applicable in groundwater studies are discussed.

2.3.1 DIGITAL TERRAIN MODEL (DTM)

Digital terrain models (DTM) are extremely valuable in understanding the properties of the terrain. Moore et al. (1991) have reviewed hydrological and geomorphological applications of DTM. DTM is an ordered arrays of numbers that represent the spatial distribution of terrain attributes. DEM is a subset of DTM which represent the spatial distribution of elevation above some arbitrary datum in a landscape. Topography plays a very important role in hydrogeologic system. GIS facilitates the generation of digital elevation model (DEM) to understand the variation in elevation in the terrain and its effect on the groundwater regime. There are two ways of information extraction from DTM: through visualization and by quantitative analysis of digital terrain data. The wealth of information generated in this way can be used directly for interpretation of groundwater conditions, or can be used as weighted parameter in ranking analysis, and as an input in models. There are many derivatives of DEM which are valuable in groundwater system analysis:

a) Slope
b) Aspect
c) Curvature
d) Shaded relief
e) Flow direction and flow accumulation
f) Drainage network and watershed delineation

g) Stream order

The most common use of DEM data is the generation of slope values. Slope is an important factor in understanding the groundwater movement and also in suggesting artificial recharge sites. Slope values are also used as input to models. Slope comprises two components namely *gradient*, the maximum rate of change of altitude, and *aspect*, the compass direction of this maximum rate of change (Burrough, 1986). A pseudo relief image of the terrain can be created from a DEM, which gives a more effective way of representing slope. Further, the amount of radiation received at various slope can be calculated (Meijerink et al., 1994). It provides a better perception of the landforms. The concept of DEM can also be used to represent groundwater table.

Curvature (convexity) is the rate of change of slope and is often used in geomorphological analysis. It has two components: *plan convexity* or the convexity of contours, and *profile convexity* or the rate of change of gradient. Sometimes concavity is used to denote negative convexity. Convexity is measured in degrees per unit distance. A number of other parameters may be extracted: drainage density, hypsometric integral, statistics of slope and convexity. Drainage density is of real use in groundwater studies, especially in hard rocks, as discussed in earlier sections.

DTMs are very useful for automated terrain analysis (Mark, 1984; Mark et al. 1984; O'Callaghan and Mark, 1984; Jenson and Domingue, 1988; Riazanoff et al. 1988; Moore et al., 1991; Weibel and Heller, 1991; Donker, 1992; Dymond and Harmsworth, 1994; Dymond et al. 1995). Extraction of topographic structure from DEM is a multi-step procedure. DEM always contain some depression, which hinders the flow routing. A depressionless DEM is created through neighbourhood analysis. The flow direction is the direction in which water flows out of individual pixel (or cells). The maximum downward slope is selected from eight neighbours. The flow direction data set is used to create a flow accumulation data set where each cell is assigned a value equal to the number of cells that flow to it (O'Callaghan and Mark, 1984). The cells having a flow accumulation value of 0 represent ridge, where no other cells flow. Flow accumulation data set can be used to produce a drainage network depending on a particular threshold value. As the threshold decreases the density of the drainage increases (Jenson and Domingue, 1988). There will always be some degree of mismatch between synthetic drainage network and surveyed drainage. This may not always be related to the accuracy and resolution of DEM data. This mismatch information may be utilized to infer about the permeability of the underlying geology. Where surveyed drainage, corresponding to the DEM derived drainage, is absent, water is probably percolating down, and these may act as recharge areas (Saraf et al., under preparation). Automated channel segment ordering can be done from drainage network matrix and flow direction data (Donker, 1992). Details on this aspect have been discussed in Chapter 4.

Water level information is extremely valuable in groundwater analysis. GIS facilitates reconstruction of groundwater surface from point heights as measured in wells through suitable interpolation method. The three dimensional distribution of the groundwater surface can be simulated. This information can be interfaced with other information layers in a GIS framework. Subtraction from the DEM yields the spatial distribution of unsaturated thickness. This map can be combined with a soil map, reclassified for texture information, and a vegetation cover map to map the areas where the root zone is in the capillary fringe or above it. This may be used for estimates of actual evapotranspiration (Meijerink et al., 1994). Interpolated grid of variables: rainfall, evaporation, weathered thickness, soil depth, soil properties, permeability, chemical quality etc can be generated for further analysis and as input in groundwater models.

2.3.2 THREE DIMENSIONAL VISUALIZATION

Characterization of surface and subsurface hydrogeologic system needs three dimensional visualization. The 3D-perspective display helps in simulating the feel of the terrain. A surface can be viewed from a different perspective other than the vertical. This is very useful for visual interpretation and a better understanding of spatial relation between entities. 3D view is closer to our natural way of visualizing objects. By exaggerating the vertical scale, the features can be emphasized (Meijerink et al. 1994). Some systems allow draping of another mapped feature on the DEM to simulate near natural view. This is particularly useful in geomorphological mapping. 3D perspective view generated by FCC draped on DEM gives a better understanding of the terrain. It depicts the role of topography in groundwater movement, and the direction of maximum hydraulic gradient can be inferred. It has been utilized to study the artificial recharge provided by reservoirs/ tanks in the present area. It has been inferred that tanks constructed over gentle slope provide better than the ones in a flat area due to sufficient hydraulic gradient (Saraf and Choudhury, 1998). Real 3D processing is very important in groundwater resources assessment. The ability to rapidly create and manipulate 3D images can speed up a geoscientist's understanding of the subsurface environment (Turner, 1989).

2.4 INTEGRATED REMOTE SENSING AND GIS IN GROUNDWATER STUDIES

Remote sensing and GIS are now established tools for natural resources and environmental studies. During the last few years, research has been going on to integrate both the tools. As the demand for spatial information grows there is an ever increasing synergy between remote sensing and geographical information systems. There are three main ways in which these two technologies are complementary to each other:

(a) Remote sensing data can be used as data set in GIS.

(b) GIS data sets can be used as ancillary information to support remote sensing data.

(c) Remote sensing data and GIS data sets can be used together in environmental modelling and analysis (Wilkinson, 1996).

Probably there is no universally accepted definition of "Integrated GIS". Ehlers et al. (1989) defined three levels of integration:

Level 1: Separate database and image processing system with facilities to transfer data between them.

Level 2: Two software modules (GIS and Remote sensing) with a common user interface.

Level 3: A single software with combined processing.

Trotter (1991) defined integration as the interchange of data between respective systems but also stated that full integration environment will be free of logistical consideration of moving data between two systems. However, in most of research, the integration revolves around the 'Level 2' of Ehlers et al. (1989). The potential bottleneck of full integration is the GIS data format and their conversion. Since remote sensing data are in raster format, the data format in GIS analysis i.e. raster or vector is to be decided in accordance with the requirement of a particular application. In most of the natural resources studies, raster processing is needed because the change in natural boundaries is often gradational and continuous information about the ground is required. However, Hinton (1996) argued that integrated GIS must not rely on data conversion for effective integration, and data flow between the images and the vector database must be two ways.

In most of the cases, either classified remote sensing data are converted to vector or vector data sets are converted to raster for analysis purpose. In groundwater studies, not much work has been done towards integrated approach. Analysis may be descriptive or prescriptive. Attempts have been made to use empirical or physical models embedded in GIS. Some advantages of integrated approach are listed:

a) Geometric and radiometric correction

b) Improvement of image classification using ancillary data

c) Use of knowledge base or expert system approach

d) Modelling dynamic natural processes

2.4 1 GIS ANALYSIS FUNCTIONS AND SPATIAL DECISION SUPPORT

Integrated spatial analysis is the most attractive part of GIS. Merging of image interpretation and GIS has proved quite useful in groundwater exploration and management programme. In groundwater studies, not many studies have been done to integrate all the controlling factors through GIS. Karanga et al. (1990) used this approach for groundwater development planning in a data scarce region in Kenya. Sharma and Anjaneyulu (1993) utilized an integrated GIS approach using SPOT and IRS-1A-LISS-II data for water resources evaluation in selected coastal alluvial and hard rock terrain of India. Attempt has been made to quantify waterlogged and salinised areas. Saraf and Jain (1996) used GIS overlay analysis for groundwater exploration in a granitic terrain of Lalitpur district, Uttar Pradesh. Geology and vegetation information derived from remote sensing data are interfaced with soil map and water level map. Groundwater recharge image has been prepared by multiplying water level fluctuation map by the respective specific yield.

Gustafsson (1993) demonstrated integrated approach of remote sensing data (SPOT data) along with geophysical and groundwater data to find out drill targets in a semi-arid area in southwestern Botswana. Lineaments and vegetation cover were mapped from SPOT data. Detailed correlation study between interpreted satellite data and field data was done. Buffer zones were created in 80m increments from the lineaments and proximity analysis was done. Correlation of lineament with geophysical anomalies and also with borehole yield shows that the lineaments were the sites of high groundwater potential.

The most important use of GIS is the spatial decision support. GIS is a powerful technique in suitability analysis (Burrough, 1986; Padmavathy et al., 1993). It facilitates integration of all parameters controlling groundwater through analysis functions like weighted index overlay and Boolean operation. Chi and Lee (1994) carried out a study in parts of Kochang area of Korea to map groundwater potential. Thematic layers of geology, slope, soil and landuse were rated on the basis of DRASTIC index. Groundwater potential zones were delineated through overlay analysis. Krishnamurthy et al. (1996) performed an integrated GIS analysis in order to find out groundwater prospect in Marudaiyar basin in Tamil Nadu, India. Various thematic information layers were generated from IRS-LISS-II photographic products along with field data. All the thematic layers were processed in vector and analysed using weighted aggregation and logical operation. The weight to different classes of any thematic layer was given according to its relative importance with respect to other classes and weight interval between successive classes was not uniform. Weighted overlay analysis has been used to identify recharge areas (CGWB, 1997; Ramalingam, 1998). IRS-LISS-III and PAN data are used to extract pertinent information on geology, geomorphology, soil, landuse. Groundwater level data, borehole lithology are also incorporated. Suitable weightage is given to each theme and respective classes. Suitable site for artificial recharge structures are also suggested based on overlay analysis (Ramalingam, 1998). Saraf and Choudhury (1997 and 1998) have identified areas of anomalous vegetation growth downstream the reservoirs using dry season IRS-LISS-II data and attributed this to artificial groundwater recharge from the reservoirs (Details in Chapter 5). Assigning appropriate weightage to various parameters and overlay analysis, suitable sites for artificial recharge are suggested.

GIS can be used to generate the input layers in groundwater models (discussed in Section 2.5.2). D'Agnese et al. (1996) generated the input layers of groundwater flow model using GIS analysis functions. Integration of geologic, hydrogeologic and climatological information facilitates visualization of 3D hydrogeologic framework. Regional recharge and discharge map, and potentiometric surface have been generated from various themes on surface and subsurface hydrogeologic conditions through GIS analysis and decision support. Regional flow system has been conceptualized for use in the numerical model.

A new approach was applied by Hansmann et al. (1992) in a hard rock area of Sri Lanka. In this, the factors affecting well yields are selected and combined using weights of evidence modelling which is based on a stochastic approach. Information on groundwater occurrence derived from existing tubewells expressed as an *a priori* probability and is improved by adding weights calculated from predictor map.

2.4.2. GROUNDWATER MODELLING USING GIS

Many attempts have been made to use hydrologic models within a GIS environment. In addition to data integration, GIS facilitates generation, storage and retrieval of large volume of input layers of information in a user defined map extent, projection and scale. There are many strategies for coupling GIS with models from loose coupling to tight coupling (Tim, 1996). Gupta et al. (1996) preferred a loose coupled GIS for groundwater system evaluation. Maidment (1993), Singh and Florentino (1996), Schultz (1993b), Zhang et al. (1990), have overview the status of hydrologic modelling coupled with GIS.

Models are metaphors for nature or reality. Models can be stochastic or deterministic (Chow, 1972). Both these model can be subdivided into lumped or distributed depending on the treatment of space. A lumped model represents a spatially homogeneous region and no account is taken of the spatial variability of the input parameters. Distributed parameter model assumes that physical system is made of discrete sub-regions, each characterized by a unique set of properties of input parameters (Tim, 1996). GIS facilitates use of distributed models. Some selected works are discussed in brief under this section. The purpose is not to present a review of groundwater modelling in GIS, which is beyond the scope of this chapter, but to have a glimpse of the current trends.

There are many examples of quantitative assessment of groundwater recharge using GIS. Drayton and Md. Said (1989) estimated recharge in the Worfe river basin in the Shropshire Groundwater Field. Empirical relation was established between rainfall and topography, and annual average rainfall was estimated from DTM. A groundwater model was run to simulate recharge using uniform rainfall and land cover. The model was then run with derived rainfall distribution and landcover mapped from remote sensing data. It was noticed that use of distributed data produced significant difference in spatial estimates of recharge. Drayton et al. (1991) developed an approach to model run-off for each pixel using SCS method in GIS with distributed data. Land cover map was generated from classification of TM data. SCS curve number map was prepared from hydrologic soil group and landcover. The run-off was then routed through the main drainage.

Statistical analysis in a GIS framework was used by Rogowski (1996) to predict spatial distribution of recharge contributing areas in a watershed in Pennsylvania. The input parameters were generated from field measurements. Detailed statistical analysis of the data set was carried out to verify field data values and their locations against other available information e.g. soil, geology, landuse etc. Mathematical operations on the overlays on hydrologic parameters were carried out to predict distribution of water flux from below root zone, travel time to groundwater and recharge flux pulse at the water table.

Meijerink et al. (1994) used the well defined Thornthwaite and Mather monthly soil moisture balanced method in a GIS environment to estimate the recharge in a mountainous catchment in Indonesia. Remote Sensing data provided information on soil units to obtain spatial distribution of water holding capacity and vegetation classes to estimate rooting depth. The application of the method when applied to a small catchment has a variable degree of accuracy. Van Dijk et al. (1996) applied a similar method to a semiarid area to prepare input for groundwater modelling. Van Deursen and Kwadijk (1993) have developed an integrated GIS water balance model for river Rhine using the Thornthwaite and Mather model (1957). They estimated total runoff in all calculated time steps and routed through the drainage. The results are able to describe monthly changes in water balance compartments for both the entire basin and its tributaries.

Batelaan et al. (1993) integrated one layer and multi-layer groundwater flow model in GIS. There are many examples of integrating groundwater models in GIS environment. Lieste et al. (1993) developed a groundwater model coupling a finite element groundwater program package with GIS. Biesheuvel and Hemker (1993) performed integration of finite element flow modelling with GIS. Nachtnebel et al. (1993) discussed the coupling of groundwater model with

GIS at various steps starting from the exchange of information, design of model, visualization and display of analytical results. MODFLOW model has been used in GIS environment by many (Hinaman, 1993; Orzol and McGrath, 1993; Watkins et al.,1996). Richards et al. (1993) integrated MODFLOW with GIS for groundwater resources assessment in Florida.

Baker et al. (1993) developed a strategy to delineate wellhead protection areas and prepare maps. Baker (1993) used GIS to develop an automated procedure for identifying primary aquifer supplying groundwater to individual wells in Arkansas. Flockhart et al. (1993) used GIS for groundwater protection planning in Masachussets, U.S.A.

2.5 SUMMARY

To summarize, it can be perceived that remote sensing provides an excellent source of data for groundwater resources evaluation, monitoring and development planning. Especially in developing countries like India, remote sensing data are the source of most accurate terrain information. The capabilities of remote sensing has been utilized to a larger extent than that of GIS in groundwater studies. A groundwater resources evaluation programme demands a huge database including water levels, lithologs, and geological characteristics of aquifer material, hydraulic properties, recharge-discharge relationship and chemical concentration. GIS is the appropriate tool for integration of data from diverse sources, scale and projection. Integrated approach certainly enhances the quality of the output because it allows a far broader perspective to answer a large range of questions in spatial context. With the availability of higher spatial and spectral resolution of remote sensing data, and advanced image processing and GIS systems, there is scope for increased utilization of the potential of GIS and improvement in the integrated approach. The handling of time, the fourth dimension is an important issue. The study of dynamic aspects of spatial entities and their properties become increasingly important as modelling of the spatial and temporal changes in the occurrence of natural resources becomes more and more vital for management purpose. Not only where and what, but also when is a valid question!

CHAPTER 3

METHODOLOGY

3.0 INTRODUCTION

The present study attempts the development of an integrated remote sensing and GIS technique for evaluation of groundwater resources in a hard rock terrain and selection of suitable sites for artificial recharge structures. Remote sensing data sets have been used to extract information on geologic and geomorphic features controlling groundwater occurrence and movement, and also to visualize the surface expressions of groundwater. Field data e.g., depth to water level data, form an integral part of the study. Thematic information from various sources and scales has been used to support remote sensing data interpretation. GIS provides the appropriate tool to converge this large volume of data into same spatial georeferencing system for integrated analysis and decision support.

A general outline of the methodology followed in the present study has been presented in this chapter. A detailed discussion is given in the succeeding chapters. The methodology is summarized in the following steps (Figure 3.1):

1. Data input
2. Preprocessing
3. Digital image processing of remote sensing data sets.
4. Processing of ancillary and field data to generate thematic information
5. Development of the spatial data base
6. Integrated analysis functions
6. Decision making and qualitative assessment of groundwater conditions
7. Selection of suitable site for artificial groundwater recharge

8. Computation of groundwater recharge using GIS
9. Ground truth check/collection
10. Generation of output

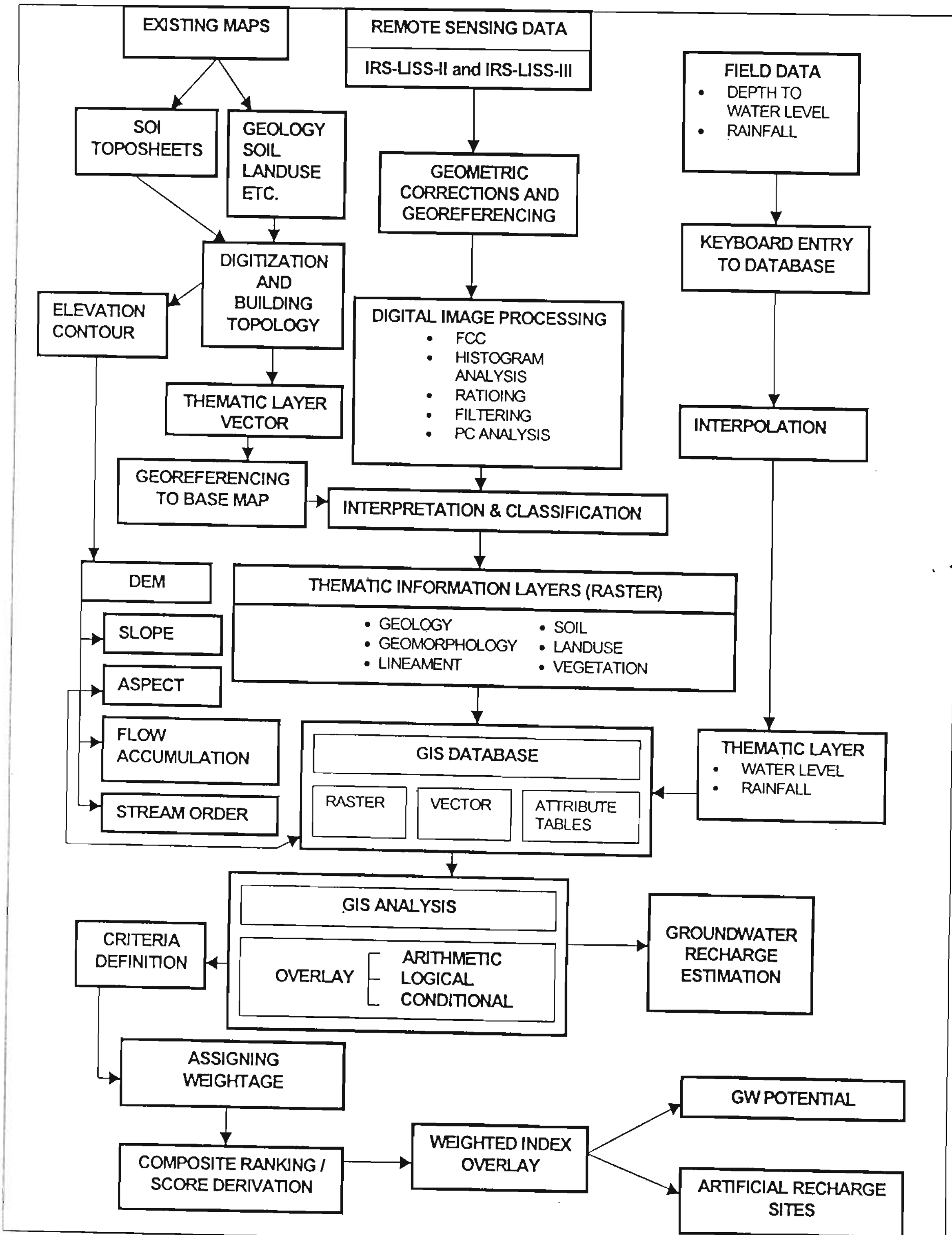


Figure 3.1 Flow chart showing data flow and different GIS analysis operations followed in the present study.

3.1 DATA USED

Three sets of data have been used for the present study:

a) Remote sensing digital data (Table 3.1).

b) Existing maps

c) Field data

Satellite	Sensor	Data format	Source	Details			Date of Acquisition
				Path	Row	Subscene	
IRS-1B	LISS-II	Band Interleaved by line (BIL)	National Remote Sensing Agency (NRSA)	27	51	A1 B1	21/03/95 & 27/02/95
IRS-1C	LISS-III	Band Interleaved by line (BIL)	National Remote Sensing Agency (NRSA)	98	55	Full scene	20/02/98

Table 3.1: Details of Remote Sensing data used.

The choice of time for acquisition of remote sensing data is very important for geohydrological studies. Immediately after the monsoon, spectral signature of vegetation dominates which suppresses geologic and geomorphic features. On the other hand, terrain will be more or less devoid of vegetal cover just before the onset of monsoon. Therefore, an intermediate time has been chosen before the harvesting of the winter crops in order to get the balanced response of vegetation, geologic and geomorphic features. The spectral characteristics and other properties of the sensors are summarised in Table 3.2.

Thematic maps are prepared by various organizations under different projects. Naturally, they are in different scales. These maps are mainly used to support the interpretation of remote sensing images. Field data are point information of the hydrologic and meteorological variables. Field data have been converted to aerial information in GIS for further use in GIS analysis. The details are given in Table 3.3. All the data were in analogue format.

Sensor	Spectral Band	Spectral Range (μm)	Spatial Resolution (m)	Application	Swath (km)	Orbital Altitude (km)	Repetitive Coverage (days)	Quanti-sation (bits)
LISS-II (Linear Imaging and Self Scanning Sensor)	B1	0.45-0.52	36.25	a. Coastal environmental studies b. Soil/ vegetation differentiation c. Coniferous/deciduous vegetation differentiation	141	904	22	7
	B2	0.52-0.56	36.25	a. Vegetation vigour b Rock/soil discrimination c. Turbidity and bathometry in shallow waters				
	B3	0.62-0.68	36.25	A strong chlorophyll absorption leading to discrimination of plant species				
	B4	0.77-0.86	36.25	a. Delineation of water features b. Landform/geomorphic studies				
LISS-III	B1	0.52-0.59	23.5	Same as B2 of LISS-II	141	817	24	7
	B2	0.62-0.68	23.5	Same as B3 of LISS-II	141			
	B3	0.77-0.86	23.5	Same as B4 of LISS-II	141			
	B4	1.55-1.70	70.5	a Leaf water content b Canopy water status c Forest and crop type mapping d Lithological studies	148			

Table 3.2: Details of the IRS-1B & 1C sensors (LISS-II and LISS-III)(after IRS-Data Users Handbook, 1989 & 1995)

In addition to all these data sets, some information, derived from existing hydrogeological investigation reports of the present area, have also been used to validate the modelled results. Monthly potential evapotranspiration data for 6 stations have been used from CGWB report (1984). Statistical data on dug wells, hand pumps, canal, different crops, landuse etc. have been collected from district statistical records published by the Statistical Department, Madhya Pradesh.

Type	Theme	Source	Details	Date/Time	Scale
Existing Maps	Toposheets	Survey of India (SOI)	54 H	1981	1:250,000
			54 L	1985	
			55 E	1982	
			55 I	1989	
			54H/11,12,16	1985	1:50,000
			54 H/15	1971	
			54 L/3,12	1977	
			54 L/4,7,8	1976	
			54 L/11	1986	
			55 I/5	1976	
			55 E/9	1976	
			55 E/13	1977	
	Geological Quadrangle Map	Geological Survey of India (GSI)	54 H, Guna Quadrangle	1977	1:250,000
			54 L, Tikamgarh Quadrangle	1985	
			55 E, Bhopal Quadrangle	1993-94	
	Soil Map	National Bureau of Soil Survey and Landuse Planning (NBSSLUP)	Madhya Pradesh Soils	1998	1:500,000
	Landuse Map	National Atlas for Thematic Mapping Organisation (NATMO)	Bhopal Plate	1981	1:1,000,000
			Nagpur Plate	1981	1:1,000,000
Field data	Hydrological Data	Central Ground Water Board (CGWB)	Depth to water level of hydrograph network stations (4 times in a year)	1976-98	
	Geochemical data	Do	Specific electrical conductance	May 1996	
	Borehole data	Do	Litholog	1976-1978	
	Meteorological data	Indian Meteorological Department (IMD), Bhopal	Monthly rainfall data	1976-96	
	Details of Reservoir	Irrigation Department, Bhopal		Culturable command area, Date of functioning, Estimated capacity etc.	

Table 3.3: Details of existing maps and field data used in the present study.

3.2 SOFTWARE AND HARDWARE USED

3.2.1 SOFTWARE

- Arc View 3.0a with Spatial Analyst 1.0 Extension (ESRI, U.S.A)
- ILWIS 1.41 and 2.1 (ITC, The Netherlands)
- MGE Advanced Imager 6.0 (Intergraph Corporation, U.S.A)
- Aldus Photostyler 2.0 Special Edition
- Microstation 95 (Bentley Systems, U.S.A)
- Surfer for Windows 5.1 (Golden Software)
- PC- ARC/INFO (ESRI, U.S.A.)

3.2.2 HARDWARE

Pentium II-300 Mhz, RAM-128MB, 5.5 GB HDD, 17" SVGA Monitor, Windows 95 environment

Input Devices: A0 size Summagraphics Digitizer

Output Devices: HP LaserJet Printer 5/5M
HP DeskJet Printer 1120C

3.3 DATA INPUT

The very first step is to bring all the data (except remote sensing data) into digital format. Conversion of the analogue maps has been done by manual digitization directly from the map on the digitizing tablet using ILWIS and Microstation. Base map for the study has been generated from SOI (Survey of India) toposheets at 1:50,000 scale, digitizing surface drainage features, transportation network, canals, reservoir and location of settlement areas. In case of linear features e.g. roads, railway line, drainage, elevation contour etc., the corresponding attribute is attached directly during digitization. Polygons digitized from the area features e.g. geological formation, forest cover, soil types, landuse classes etc. have been transformed to PC-ARC/INFO coverage and topology of the features have been built. The point observations comprising hydrologic and meteorologic variables have been entered manually through keyboard entry into the GIS database along with geographic coordinates in a tabular form and stored as a database file. Remote sensing data were available in cartridge tapes or in CDs. These data have been directly read off in the system through Image Translator module of Intergraph and separated into different spectral bands.

3.4 PREPROCESSING

The digitized layers of information as well as remote sensing data needs certain preprocessing. The topology for the vector polygons have been made in PC-ARC/INFO after cleaning the arcs and the respective attribute information was attached. As the data have been collected from diverse sources, the coordinate system was different. All these maps have been transformed to the geometry of the base map in PC-ARC/INFO. An affine transformation function was performed based on ground control points in both the layers. Care has been taken to minimise the root mean square (RMS) error.

In order to remove the geometric distortion and for use in GIS analysis, remote sensing data have been georeferenced to the base map. Ground control points have been taken at the junction of road, railway line, and drainage intersection. An affine transformation is performed and resampling was done using the nearest neighbour interpolation method. RMS error was within one pixel both in LISS-II and LISS-III data.

Data format conversion is another crucial issue. Most GIS systems allow raster-vector overlay operations. Raster data format is preferred for hydrogeological purposes because the boundaries of change in the hydrogeologic variables are often gradational. Hence, the thematic layers on geology, geomorphology, and soils have been rasterized for calculation and analysis. Overlay analysis in vector format has also been done to derive further information.

3.5 DIGITAL IMAGE PROCESSING OF REMOTE SENSING DATA

The next step involves digital image processing of remote sensing data for extraction of pertinent information through visual interpretation and classification for further use in GIS analysis. Various standard digital image processing techniques have been applied to remote sensing data to enhance and extract information on geology, geomorphology, land use, structural features and vegetation cover (Jensen, 1986; Drury, 1987). Enhancement in the spatial and spectral domain has been used in combination.

Contrast stretching of individual raw bands is one of the initial steps and is effective in improving interpretability of different features through increasing contrast. To have an idea of the frequency distribution of the data, image histogram of the bands has been studied. Histogram equalization stretch was very useful in increasing the contrast of image.

Band ratioing of various band combinations has been found to be quite useful, particularly for discrimination of vegetation and soil from geologic features. Vegetation index images, namely, ratio vegetation index (RVI) and normalized difference vegetation index (NDVI), were generated to map the intensity of vegetation cover.

Principal component analysis (PCA) on four bands has been performed to reproject highly correlated LISS-II and LISS-III data into statistically independent orthogonal axes and PCA images are generated. Principal component composite image from PC1, PC2 and PC3 has been found particularly useful for geomorpholgical mapping.

Spatial filtering was used to enhance the lineaments. Lineament detection method, developed by Moore and Waltz (1986), was applied on the near IR band and also on the PC1 image, which accounts for the maximum spectral variance. Compass directional filters in the eight direction have been used on a low pass filtered PC1. Later, smoothening filter was operated to reduce noise.

The directional component was extracted by rescaling the filtered product and adding to the original PC1 image. Lineaments have been visually interpreted and a lineament map has been generated through on screen digitization. Edge enhancement filters have also been used.

Various combinations of colour composites have been used. False Colour Composite (FCC) from bands 4, 3, 2 of LISS-II (3,2,1 in case of LISS-III) coded in red, green and blue colour scheme highlights the geomorphological features, land use, vegetation cover and soil types. Yellow clay soil can be readily recognized by its characteristic dark green colour due to its contrasting reflectance property with vegetation in the visible band (0.62-0.68μm) (Figure 4.5). Band combinations of 3, 4, 1 and 3, 2, 4 of LISS-III have been found to be useful for discrimination of geological formations, weathered areas and also yellow soils.

3.6 PROCESSING OF ANCILLARY INFORMATION AND FIELD DATA

GIS analysis needs spatial information of hydrologic variables, may it be rainfall, depth to water level or concentration of chemicals in groundwater. Point data are to be converted to aerial data. Various methods of interpolation are in use. Deterministic approach fits a surface through the observation point values, by some mathematical function. Statistical methods examine the spatial correlation of the data set. Choice of interpolation method depends on the nature of variation of the variable. Details about interpolation techniques used in the present study are given in the following sections.

3.6 1 RAINFALL

The first task in aerial rainfall estimation is the choice of interpolation method. The most familiar and simple method for estimation of aerial rainfall are isohyetal method and Theissen polygon method. These are based on simple linear interpolation. The most important factors to be considered are the accuracy of measurement and the gauge density. It is very difficult to measure rainfall even at a point with perfect accuracy. Rodda et al. (1976) after studying the capture of rainfall by different types of gauze environment, defined the true rainfall as "the amount of rain that would have reached the ground if the gauge have not been there".

In the present area, the gauge density rainfall measurement is poor. However, the general trend of monsoon rainfall does not show much variation within the area and a uniform pattern of distribution can be noticed. In this case, inverse distance weighing scheme has been used. In this scheme, the weight of an observation point diminishes as the distance from the point increases. The weights depend on the distance only. The value of intermediate points is calculated from the summation of the product of the observed values Z_{1k} and weights W_k, divided by the summation of the weights, within a given window of m reference points.

3.6.2 TOPOGRAPHY

Topography can not be considered as a true stochastic variable (Meijerink et al., 1994) and statistical methods are not suitable to represent the topographic surface. The present area does not show large variation in elevation. Various interpolation methods e.g. inverse distance weightage are tried. Linear interpolation is found to give good result in areas of dense contours at regular intervals, but areas where sampling density is low, this gives erroneous result. Spline interpolation has been found suitable for a gently varying surface like topographic surface. It fits a minimum curvature surface through the input values by polynomial functions. Spline interpolation gives a fairly good result in the area. Elevation contours have been digitized at 20m interval from SOI toposheets. Spot heights are also entered in the tabular form and subsequently using both contours and spot heights, DEM has been prepared. Calculating the local first derivative in x and y direction, slope map has been generated. Aspect map has also been generated by the direction of slope.

Further, various derivatives of DEM e.g. flow direction and flow accumulation, have been generated using the method presented by Jenson and Domingue (1988). Drainage network and also stream order are derived from flow accumulation grid (Discussed in Chapter 4).

3.6.3 GROUNDWATER

Groundwater surface is generally a subdued replica of the topographic surface. Usually, it has a gentle gradient. However, in hard rock terrain, the groundwater surface may be discontinuous due to variable weathered thickness. In the present area, density of observation wells is not very high. Linear kriging is used for interpolation of the water level data. The choice of method was decided based on comparative assessment of results from three different methods e.g. inverse distance weightage, spline and kriging. The advantage with kriging method is that it considers the spatial structure of the variable and it also preserves the measured value at the observation points. Specific electrical conductance data have been interpolated using kriging.

3.7 GIS DATABASE DEVELOPMENT

The GIS database was generated in ArcView GIS 3.0a. All the data were registered to the base map. Tabular database attached to the thematic information layer was continuously upgraded interactively. Many attributes have been attached to one point or polygon data. In ArcView, vector data, raster maps (grid) and image data can be handled simultaneously.

3.8 INTEGRATED ANALYSIS

The ultimate utility of GIS is in spatial decision-making and integrated analysis. There are two important aspects of integration (Rao et al., 1994). These are:

a. The criteria defining the logic of the analysis of composite information set.
b. The relative importance of weightage of each parameter.

GIS analysis operations have been performed in raster (grid) format. However raster-vector overlay and query generation can be performed in integrated GIS analysis. Various methods of combining multi-parameter data sets are in use. In the present study Boolean logic model and weighted index overlay method have been employed. Boolean logic model is the simplest method in GIS analysis. In case of weighted overlay analysis, weightage is assigned to the parameters on the basis of relative contribution towards the output. The strength of this method is that it is very straightforward and it allows incorporation of human judgement in the analysis. Further, weighted index overlay method takes into consideration the relative contribution of each parameter as well as their classes. Ground water potential zones have been mapped through weighted indexing. Suitable sites for artificial recharge structure have been selected through combination of weighted indexing and logical and conditional overlay analysis. For quantitative assessment of groundwater recharge, Thornthwhite and Mather (1957) model for water balance has been used in a GIS environment.

3.8.1 DEFINING THE CRITERION

Simple overlay analysis of DEM, geology, geomorphology and drainage layers in GIS provides a greater understanding of these in controlling the ground water regime of the area. The time of acquisition of remote sensing data was chosen carefully so that the geologic and geomorphic features can be discriminated from vegetation. Moreover dry season healthy vegetation are indicators of ground water. Pre- and post- monsoon water table and rainfall grids have been interfaced with geomorphic features in order to understand the response of various geomorphic features to rainfall as expressed by the rise in water table. Ground water recharge areas have been delineated from remote sensing data in conjunction with other datasets (discussed in Chapter 4).

On the basis of this analysis, criterion for ground water potential mapping has been defined. Further, LISS-II data of the area shows that the reservoirs are augmenting groundwater recharge in the area (discussed in Chapter 5). The criterion for suitability analysis of artificial recharge structure has been designed based on this observation.

3.8.2 DETERMINING WEIGHTS

There are various methods of assigning weights. The relative importance of parameters vis-a-vis the objective is represented by a set of weights. Sometimes these are called utility. In case of binary input maps, each map carries a single weight factor. Else weights may be of equal interval or unequal values. Although there is no standard unit of weightage, usually weights are expressed on a scale of 1 to 10. This is the most simple and straightforward method. In the present study, a 1 to 10 scale has been adopted with weightage of equal interval and weights are assigned to the parameters on the basis of diminishing influence towards the desired output for 1 to 10. Then different classes of each parameter are assigned again with weight 1 to 10. Finally, the weighted score for a pixel is calculated by the following formula (Bonham - Carter, 1996),

$$\overline{S} = \frac{\sum_{i}^{n} S_{ij} W_i}{\sum_{i}^{n} W_i}$$

where, $\overline{S}$ = weighted score

W_i = weight for i^{th} input map

S_{ij} = score for j^{th} class of i^{th} map

j = class occurring at the location.

This is a more flexible method of weighted analysis. The advantage of weighted index overlay method is that individual parameter and scores can be adjusted according to the judgement of an expert. Map scores can be chosen as positive integers or real number. The disadvantage of this method is its linear additive nature.

3.8.3 LOGICAL AND CONDITIONAL OPERATION

Logical overlay operation work with AND, OR, XOR, NOT. (Aronoff, 1990; Burrough, 1986). Conditional statements are constructed as the IF, THEN, ELSE format or using two-dimensional tables. Conditional statements have been used in selecting the artificial recharge sites. Queries have been generated across multiple themes.

3.8.4. WEIGHTED INDEX OVERLAY

Two cases of weighted overlay functions are performed : (a) binary weights and (b) weighted indexing. In case of binary weights, only one parameter has been given weightage. Thus, fulfilling this situation, the map gets a value of 1 else 0 (zero). 1 means suitable and 0 means not suitable. This is highly subjective and cannot be used in case of ground water prospects mapping. Weighted indexing is a more rational method. Here, weighted score is calculated by contributions of human judgement and mathematical functions. This method has been found to give the best results.

3.9 RECHARGE ESTIMATION USING WATER BALANCE MODEL IN GIS

A simple monthly water balance model developed by Thornthwaite and Mather (1957) has been computed in GIS. The input parameters for the model have been generated from remote sensing data and also from ancillary data and field data. The location of runoff gauging stations has been plotted on the drainage network and the modelling results have been matched with the gauged runoff data.

3.10 GROUND TRUTH CHECK

For ground truth checking of the interpreted results, limited sites were selected. In the Kethan basin, the Kethan tank and the Naren Reservoir and surrounding areas were visited in order to check the findings from remote sensing data, and the results match with real ground conditions. Field photographs were taken at various places to show different landuse practices upstream and downstream the reservoirs. The effect of ground water recharge from recharge ponds and basins was clearly visible in the field.

3.11 GENERATION OF OUTPUT

Finally the analysis results have been represented in the form of maps, graphs and tables. The results can be saved as ArcView projects for further use. Hard copies of the maps have been taken through the printers.

CHAPTER 4

GROUNDWATER RESOURCES EVALUATION

4.0 INTRODUCTION

In hard rock areas, primary porosity is practically zero, and groundwater occurrence and movement is largely controlled by the geology, geomorphology, structures, soil, topography, landuse practices and climatic conditions. Groundwater, being a subsurface phenomenon, can not be observed directly on the ground. As discussed in Chapter 2, a remote sensing and GIS based technique has immense potential in groundwater resources evaluation.

Deccan Trap basalts cover most of the present area, except for a small patch of Vindhyan sandstone in the northeastern part. In basalt, groundwater occurrence is mainly confined to (a) the fractures (especially joints) and weathered parts and (b) the flow contacts and the vesicular part. Massive basalt may yield water if fractures (especially joints) are developed. In these areas, groundwater is an extremely valuable resource of limited extent. Proper utilisation of groundwater and management planning demands a thorough understanding of the groundwater resources. Sironj and Sagar block cover a major part of the area, and the rest lies in Mungaoli, Basoda and Kurwai blocks. In the Sironj block itself there are 225 villages facing groundwater problems (District Statistical Booklet, Vidisha District, 1995). The monsoon recharge can not sustain groundwater levels till the end of dry season. Both qualitative and quantitative assessment of groundwater resources is required in order to facilitate groundwater utilisation and management planning. This chapter is an attempt to develop an integrated remote sensing and GIS technique to understand the interrelation of the influencing factors and their role in controlling the groundwater scenario of the area. Further, a quantitative estimation of groundwater recharge has been performed in a GIS environment.

4.1 HYDROGEOLOGIC SETTING

The study area is underlain by a thick pile of Deccan Trap basalt lava flows up to a thickness of about 300m. The average thickness of the flows is about 20m. A number of lava flows of varying thickness are stacked in a sub-horizontal disposition. Each flow unit consists of four parts, which differ, in their hydrogeologic properties, due to their inherent physical characteristics of collecting, storing and transmitting water. A layer of yellow clay follows the uppermost black cotton soil layer. The next layer is a weathered basalt layer and it consists of vesicular and amygdaloidal units that contribute to a high degree of porosity and permeability. The massive basalt is normally devoid of porosity and permeability except in the jointed part. The cooling joints, developed as columnar joints, facilitate groundwater storage and movement. The present zone of weathering is the most important aquifer in the area. It is a shallow aquifer and is a transition from fresh rock through partly broken, partly weathered to heavily weathered, into yellow clay. The broken rock is the most permeable part of the shallow aquifer (Versey and Singh, 1982). Rain water percolates through the weathered and jointed part and recharges the aquifer after meeting the soil moisture deficit. During dry season, the black cotton soil and yellow clay lose their water content and develop cracks. At the onset of monsoon, the soil is quickly saturated through these cracks and no storage space is left for further recharge. The amygdaloidal basalts are not water yielding, except for the jointed parts.

The deeper aquifer is beyond the range of present day weathering. It is found in the vesicular part at the base of the flow, immediately overlying the top of the underlying flow, within intertrappean layers, and also within the jointed basalt immediately underlying the clay at the flow top (Herbert et al. 1981). The base of the first massive basalt is identified as the deeper aquifer, which is at a depth of 30m.

The central part of the area is weathered to a depth of about 5-10 m. It is bordered by basalt and the Vindhyan hills along the northern, eastern and western margins. The channel fills form the most promising site for shallow groundwater, as expressed by the growth of vegetation in dry season, observed on the remote sensing images (Figures 4.1 & 4.3).

4.2 SCOPE OF THE WORK

In this chapter an attempt has been made to develop an integrated remote sensing and GIS based method for identifying prospective zones for groundwater and evaluation of groundwater resources in the area. The main objectives are:

a) To have an understanding of the interrelationship of various factors influencing groundwater occurrence and movement.
b) To develop an integrated remote sensing and GIS based model for identification of groundwater potential zones.
c) To estimate groundwater recharge.

The study has been undertaken for two sub-basins of the Betwa, namely the Kethan and the Narayan. Available subsurface information was not sufficient for the study of deeper aquifers. Litholog information for 13 boreholes was available in the surrounding area, out of which only three were within the study area. However, these provide information regarding the depth of weathering, and the depth of basalt-Vindhyan contact.

4.3 METHODOLOGY

The general outline of the methodology developed has been summarised in Chapter 3. The following steps have been followed to accomplish the above objectives (also Figure 3.1):
(a) IRS-LISS-II and LISS-III data have been enhanced through suitable digital image processing techniques and thematic maps on geology, lineaments,

geomorphology, vegetation, landuse, soil have been prepared, supported by ancillary information.

(b) Water level data have been analysed to study the long-term behaviour of water level in the area.

(c) Each information layer has been assigned with an appropriate weightage on the basis of its relative importance, and weighted index overlay operation have been performed to generate groundwater potential map.

(d) Groundwater recharge has been estimated by water level fluctuation and specific yield method, and using the soil moisture balance method of Thornthwaite and Mather (1957) in a GIS environment.

4.4 GENERATION OF THEMATIC INFORMATION LAYERS

4.4.1 GEOLOGY

The geological map has been prepared from remote sensing data supported by published geological maps of GSI. FCC 432 of LISS-II (Figure 4.1 & Figure 4.3) and 321of LISS-III (Figure 4.2 & Figure 4.4) help to distinguish different geological formations. A monotonous lithology of the Deccan Trap basalt covers almost the entire area. However, Vindhyan sandstone intercalated with shale is exposed over a linear ridge in the northeastern part and a small triangular patch in the southeastern corner of the Narayan basin. Exposure of basalt is noticed in the northern and northwestern hilly parts. Some residual hills of basalt are also scattered in the central part. The remaining part of the area comprises weathered basalt. Small isolated exposures of Vindhyan sedimentary rocks occur in the central part near the banks of the Betwa River. Basalt is identified on the FCC 432 of LISS-II (Figure 4.1 & Figure 4.3) and 321of LISS-III (Figure 4.2 & Figure 4.4) as green patches occupying the higher grounds. Weathering of basalt has led to the development of yellow clay soil over the basalt. It is seen as dark green patches due to its high reflectance in the visible band 0.62-0.68 μm in contrast to healthy vegetation (Figure 4.5). Weathered basalt is identified by the light greenish blue colour on the standard FCC; however, development of vegetation gives shades of red to the weathered area (Figure 4.1).

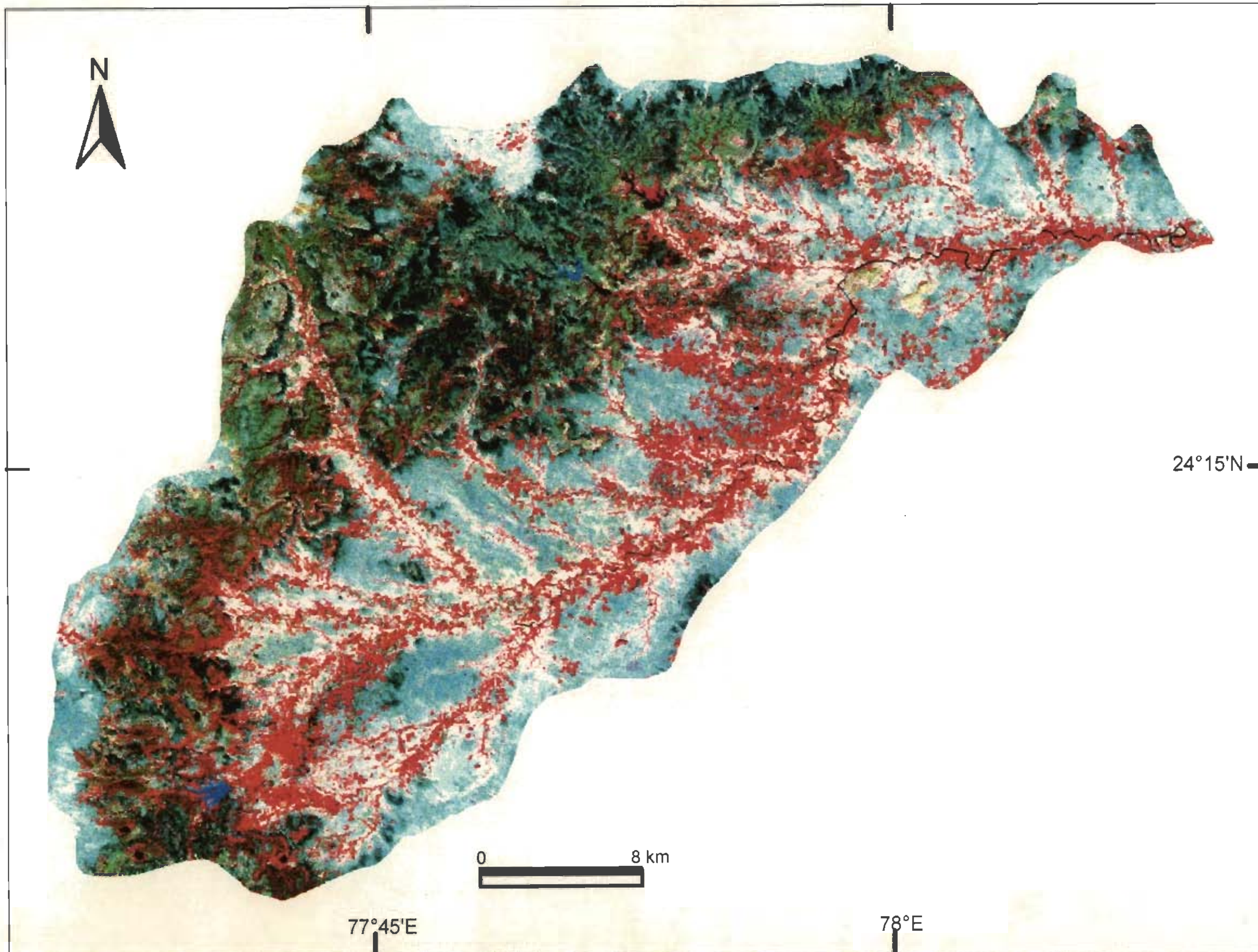


Figure 4.1. IRS-LISS-II FCC of 21st March,1995, of the Kethan basin (bands 4, 3, 2 in RGB) shows basalt in shades of green and yellow clay as dark green patches, due to its high reflectance in the band3. The alluvial plains are seen as light blue. Channel fills support vegetation and hence, in most of the areas, are seen as red.

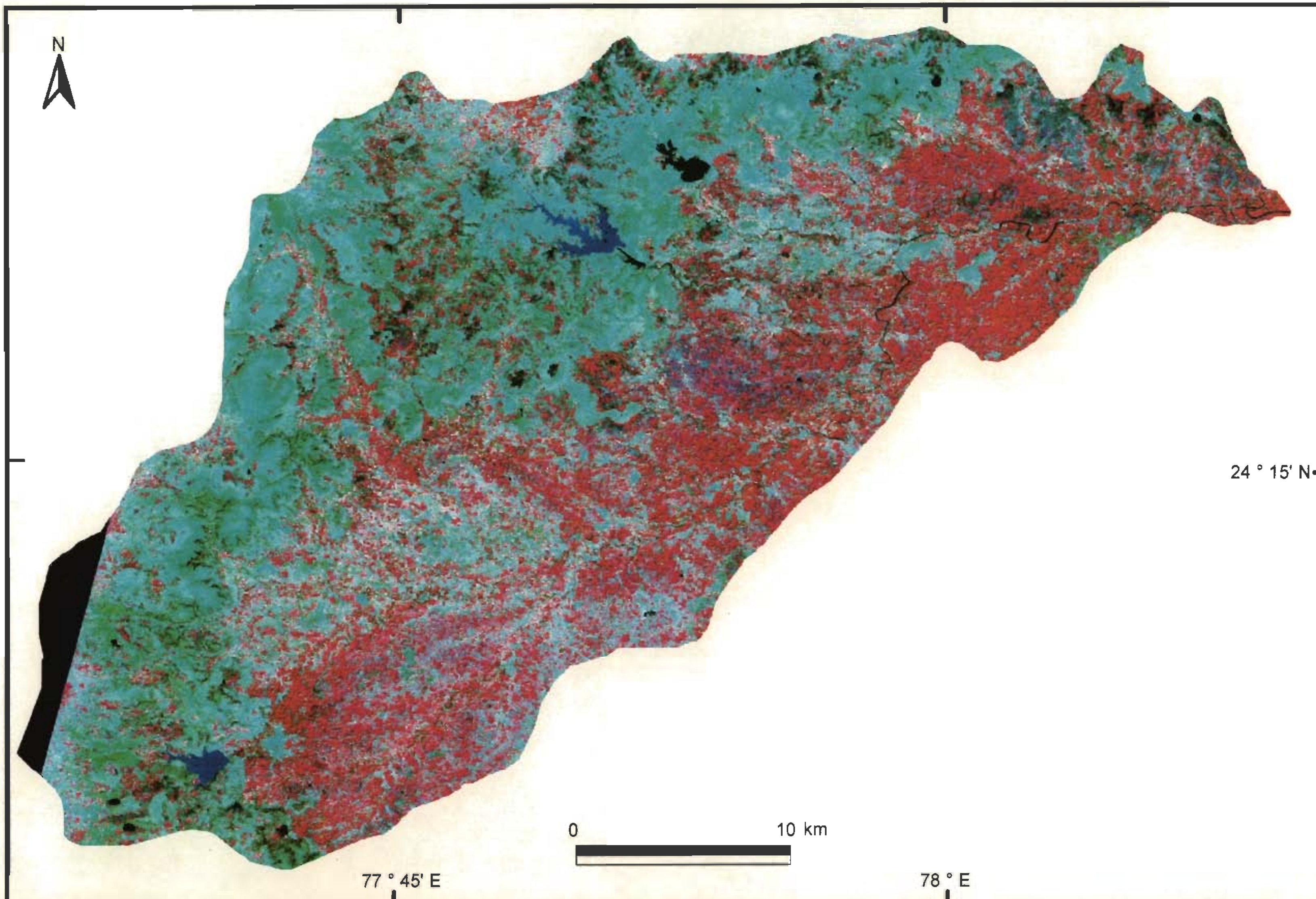


Figure 4.2. IRS-LISS-III FCC of the Kethan basin (bands 3,2,1 in RGB) of 20th February, 1998. Growth of vegetation is more compared to the Figure 4.1. This may be due to the variation in rainfall which is reflected by the shallow water level in January 1998 (5m b.g.l. in Sironj station in contrast to the average 6.5m b.g.l.).

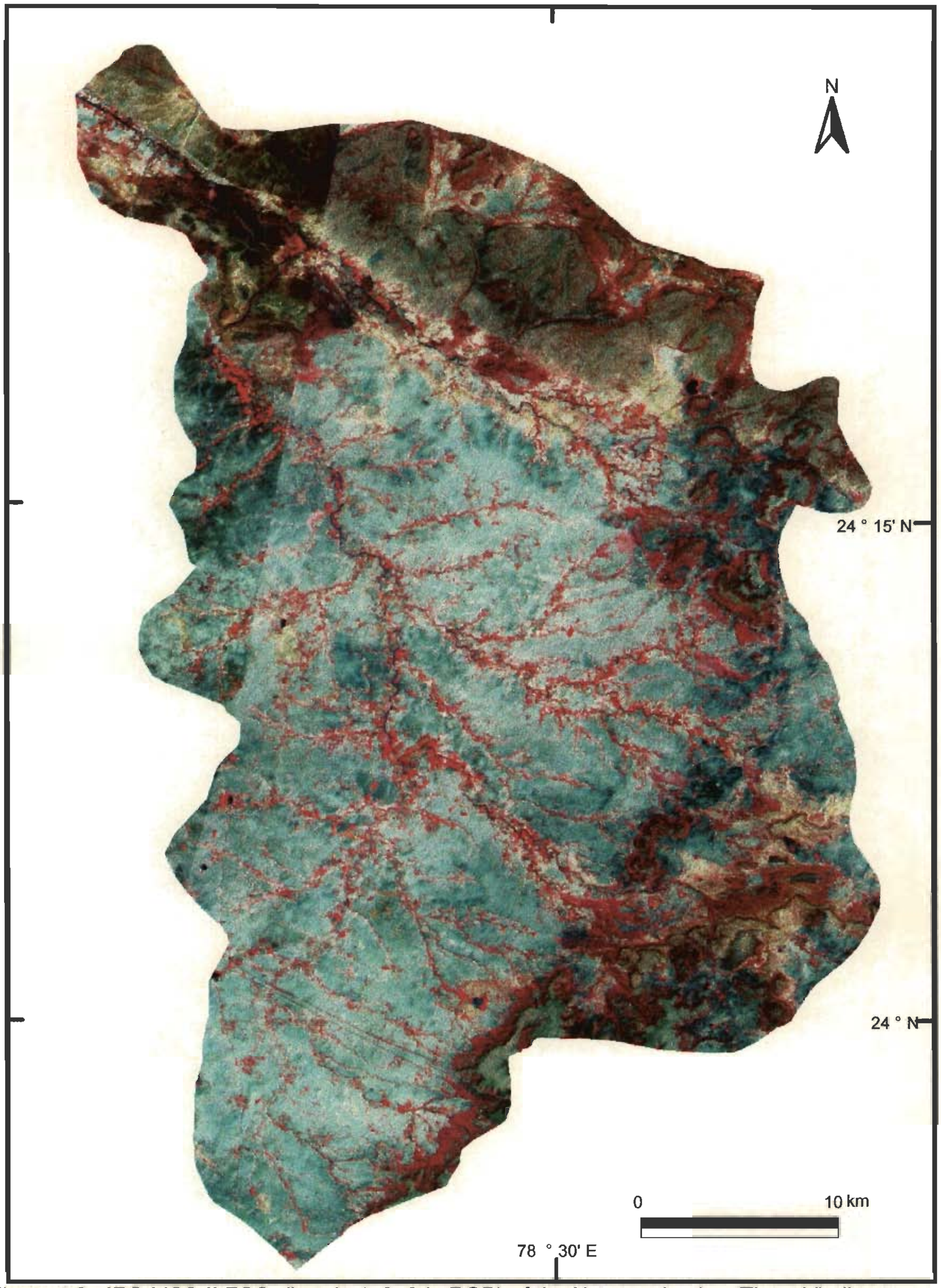


Figure 4.3. IRS-LISS-II FCC (bands 4, 3, 2 in RGB) of the Narayan basin. The Vindhyan upland is distinguished in brownish shade along the northeastern margin. Basalt hills are seen in shades of green in the southeastern corner. Weathered basalt shows light green shades occupying the valley portion. Channel fills of limited width are developed along the streams. In the alluvial plain, there are patches of yellow clay soil, seen in dark green colour. Probably because the image is of 21st March, vegetation growth is scanty, only along channel fills and the slopes of basalt and Vindhyan hills.

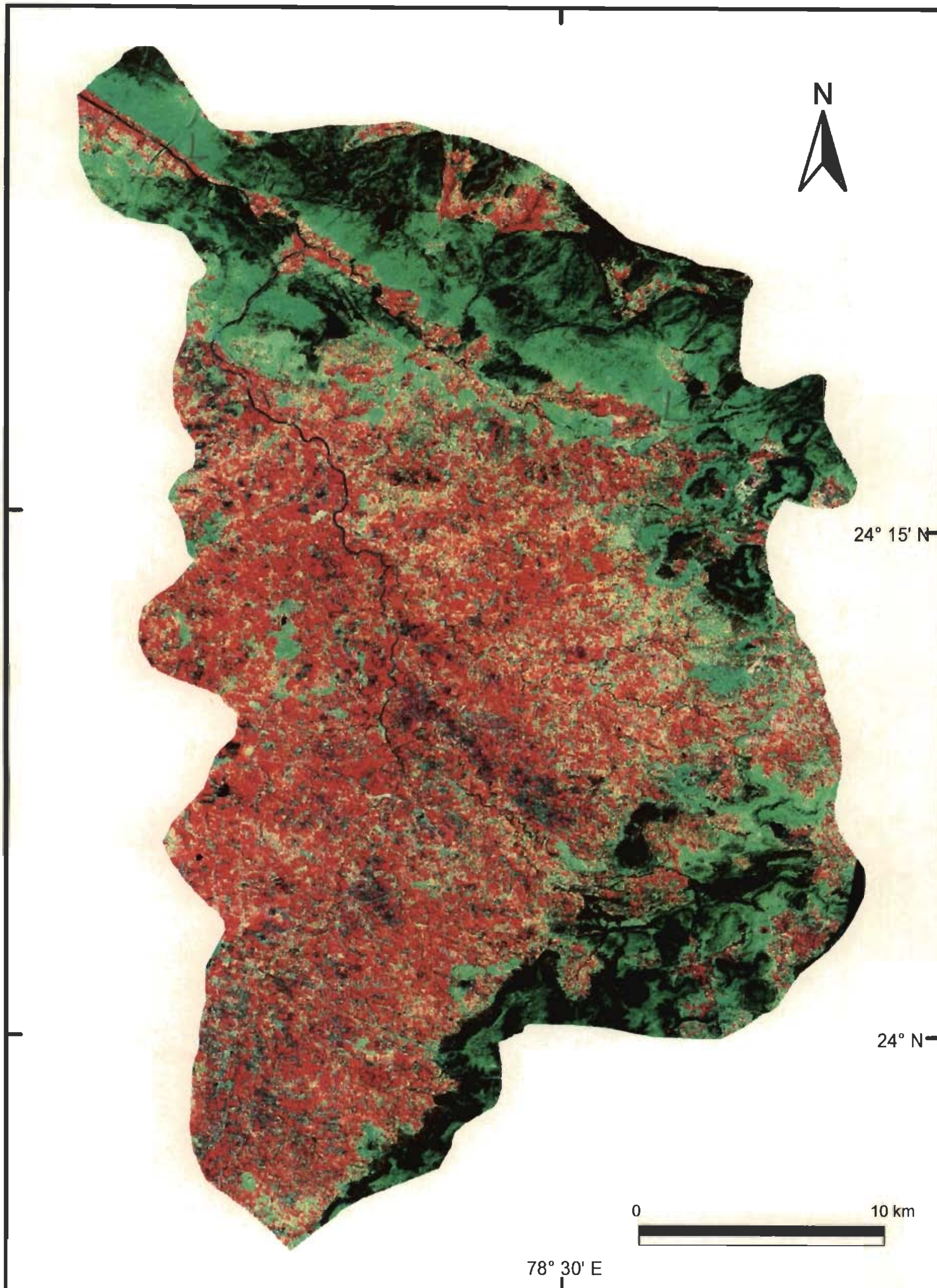


Figure 4.4. IRS - LISS - III FCC (bands 3,2,1 in RGB) of the Narayan basin. The Vindhyan hills are seen in dark green. The valley part is covered by vegetation. A very strong lineament is noticed, along the Narayan river from the joining with the Betwa river.

(L-L) can be shown on diagram

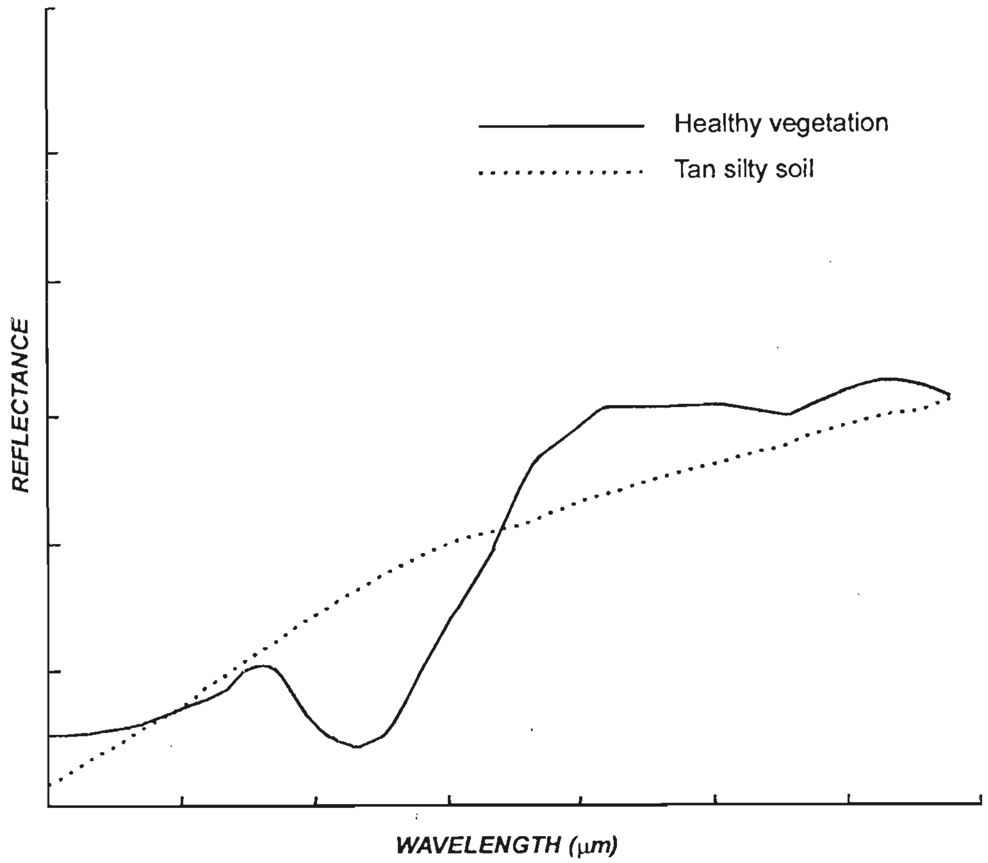


Figure 4.5. Spectral curves for average spectral responses from vegetation and soil, unscaled vertical axis (after Holz, 1984).

The entire northwestern margin of the Kethan basin is covered by basalt (Figure 4.6). Irregular shaped boundary of the basalt exposure in the hilly area presumably indicates basalt flow boundary that covered the older flows. Later, gradual weathering of the flows gave rise to the present configuration. Along the eastern boundary of the Kethan basin the linear patch of intervenial plateau is visible on the remote sensing data, almost parallel the basalt exposure in the northwestern margin. This probably indicates another flow, which was weathered. Further, the small patch of residual hills of basalt in the southeastern corner of the Narayan basin also follows the same linear trend as the basalt exposure in the northwestern margin of the Kethan basin (Figure 4.7). Probably the central part was weathered more rapidly, leaving the hard and compact part, which stands out as residual hills.

The Vindhyan rocks are exposed in the northeastern margin of the Narayan basin forming ridges. Some parts are covered by forest. The Vindhyans are differentiated from basalt by the dark brownish colour on the LISS-II FCC of 432 (Figure 4.3). These are readily recognised by the sub-horizontal disposition of the bedding. Various combinations of colour composite of LISS-III bands (e.g. 324 in RGB, 341 in RGB) have been useful in delineating different lithologic boundaries.

4.4.2 DIGITAL ELEVATION MODEL (DEM)

Topography plays an important role in the spatial distribution of groundwater. Water table generally follows the topography. The DEM has been generated from elevation contours at an interval of 20 m, digitised from SOI toposheets by interpolation. Spot heights have also been used wherever available. The area does not show much variation in relief. The maximum and minimum elevations are 670 m and 380 m above m.s.l. respectively. The central part of the area is nearly flat and rises to hills and plateaus along the western, northwestern and northeastern boundary. In the Kethan basin, the basalt hills occupy higher grounds in the northwestern part (Figure 4.8). In the Narayan basin, the basalt hills rise up to 670 m in the southwestern portion (Figure 4.10). DEM is quite useful in such studies as it provides various derivatives describing the terrain.

4.4.2.1 Slope Map

The slope map has been generated calculating local first derivative in X and Y directions. In order to facilitate interpretation and for further use as an input layer in integrated analysis, slope has been classified to a number of classes. Histogram statistics shows that 0°-1° class has the highest frequency. Nearly 80 % of the area comes under this class. Equal interval (arithmetic) classes can not represent this spatial variation of slopes. Natural breaks classification (Burrough, 1986) has been found suitable in depicting the natural variation of slope in relation to landform. The area does not show much variation in slope except in the escarpments of the basalt hills where it rises to 35° to 45°.

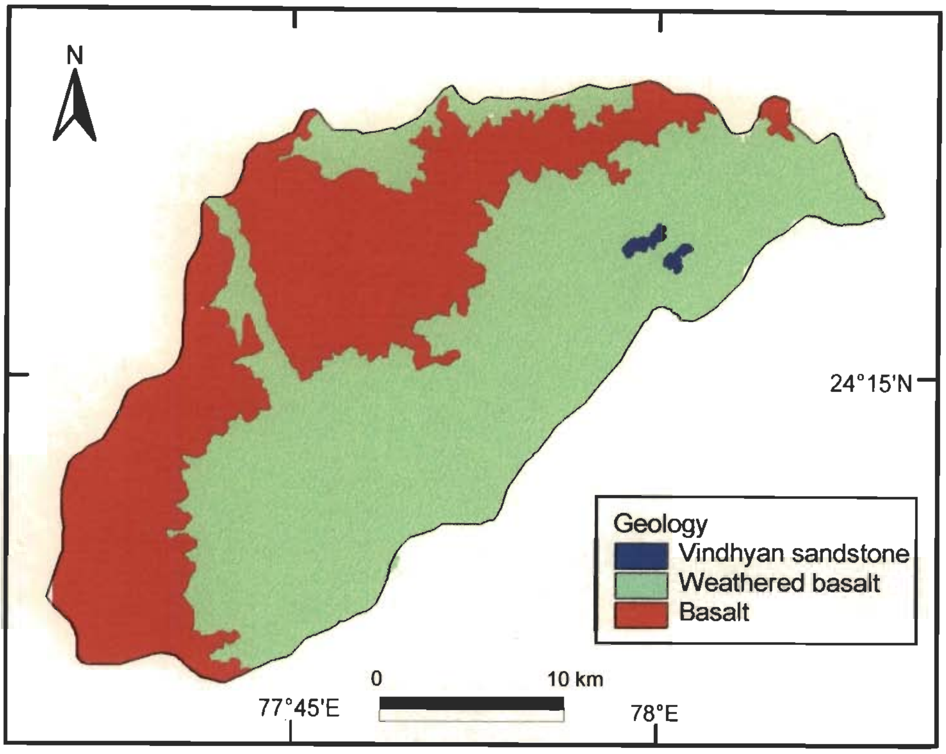
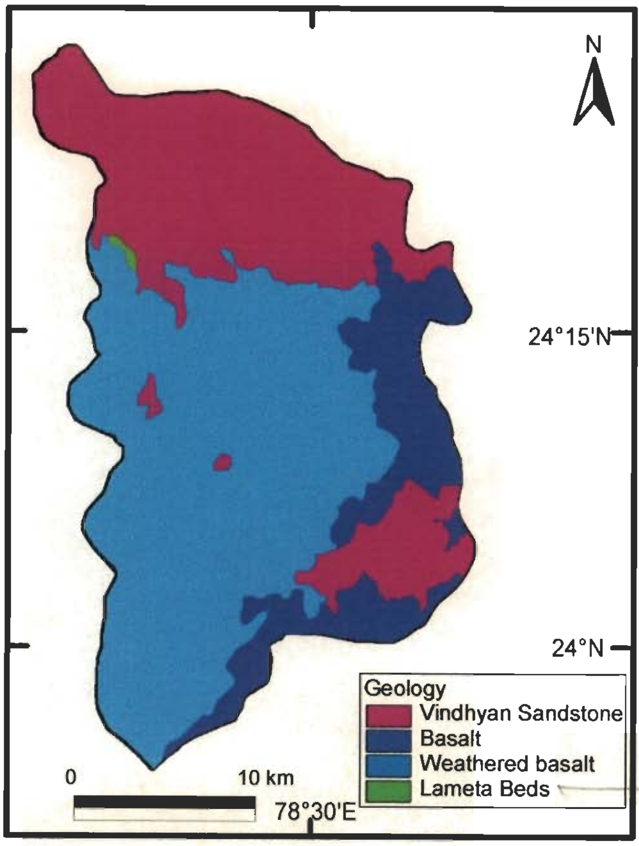


Figure 4.6. Geological map of the Kethan basin.



? give lithology

Figure 4.7. Geological map of the Narayan basin.

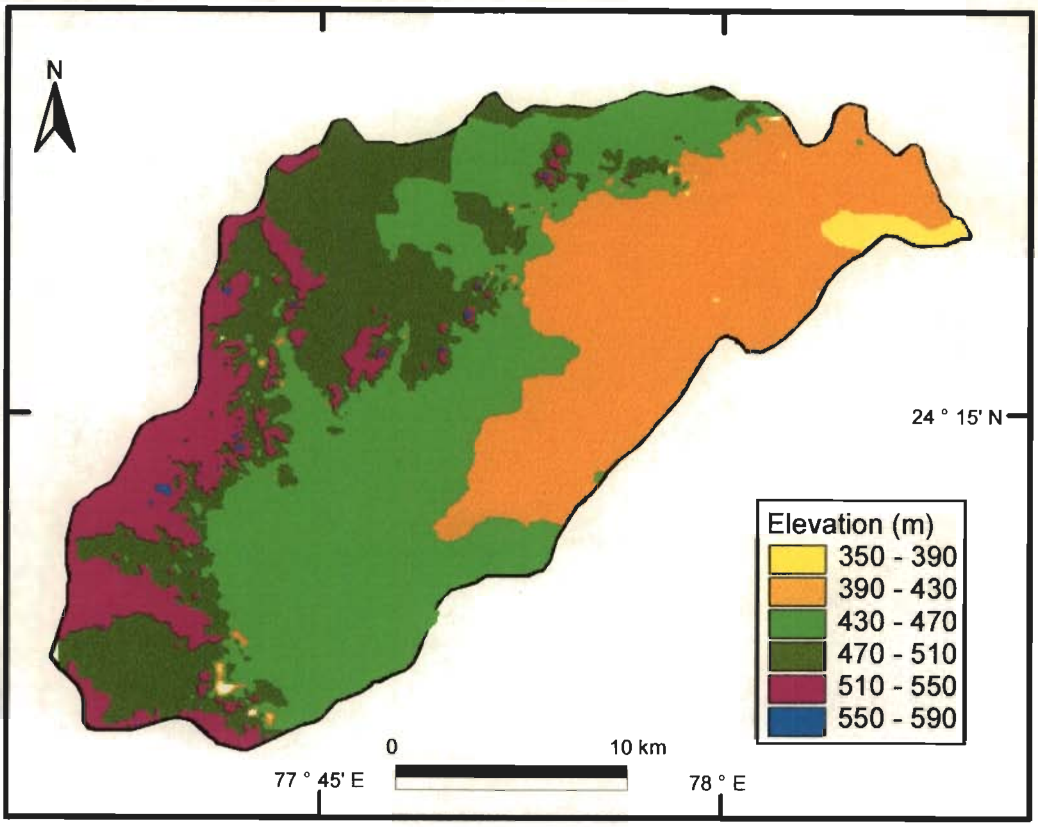


Figure 4.8. Classified relief map of the Kethan basin.

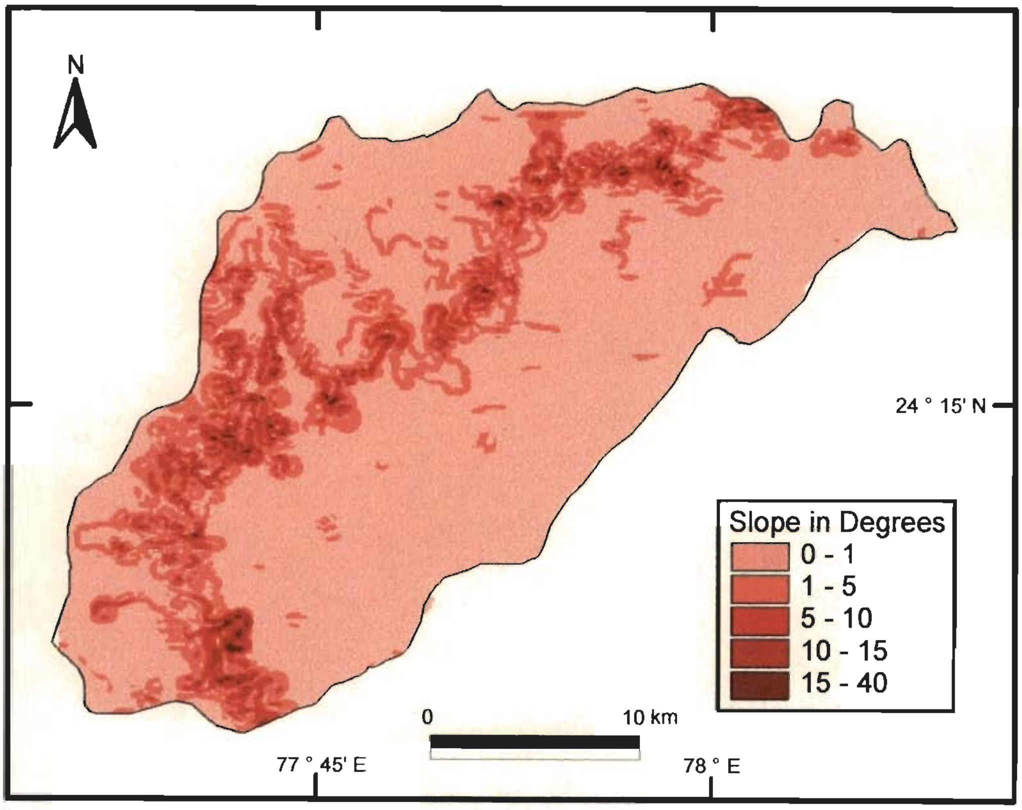


Figure 4.9. Slope map derived from DEM of the Kethan basin.

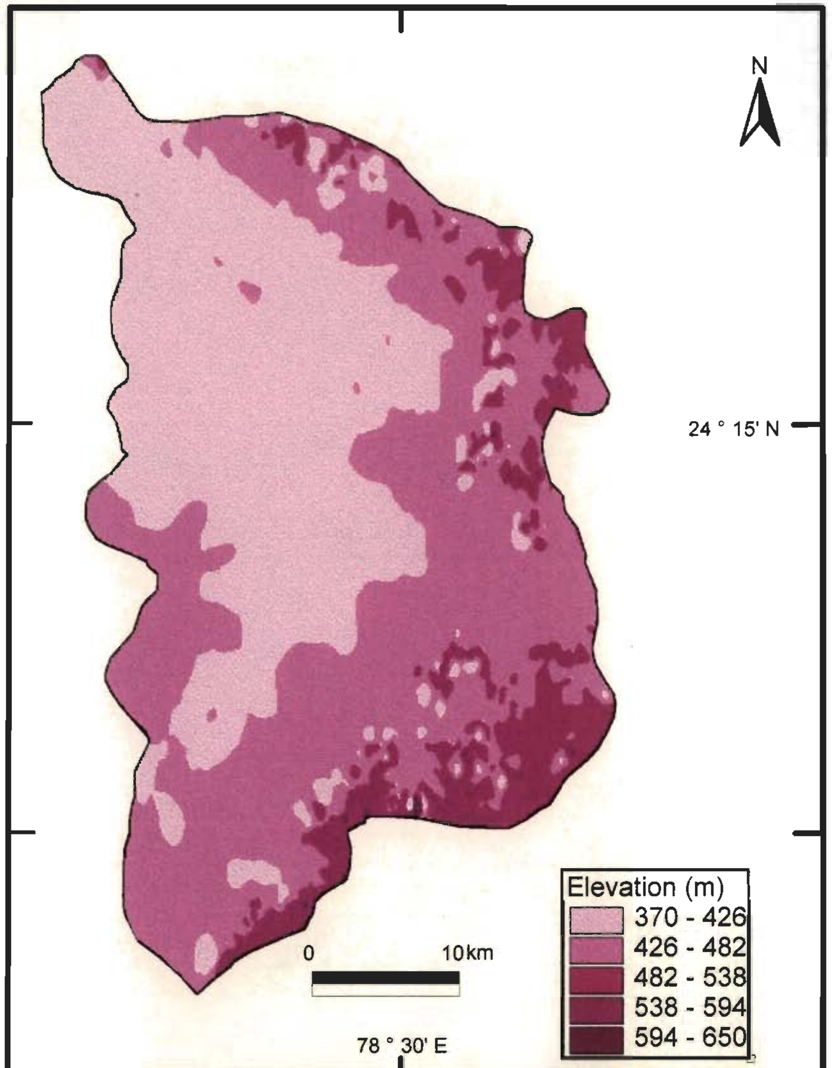


Figure 4.10. Classified relief map of the Narayan basin.

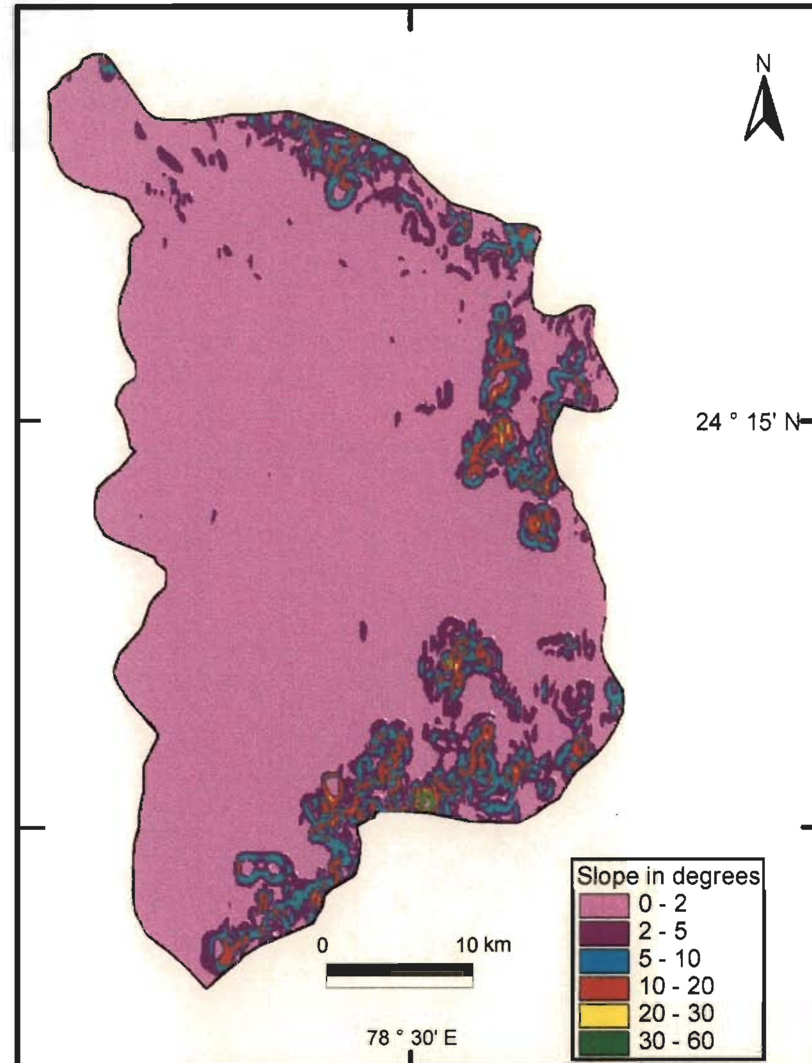


Figure 4.11. Slope map (derived from DEM) of the Narayan basin.

In the Kethan basin, the central part is nearly flat showing a slope of 1° to 2° in some places. The hilly part shows variation in slope from 3° to 10°. Only the bounding cliffs of the hills have a steep slope, up to 40° in some parts (Figure 4.9) Narayan basin is almost flat in the central part. The average slope is 1° to 2° in most of the area. The north-eastern and south-eastern part rises to small hills where slope difference is 5° to 40° (Figure 4.11). Rest of the area is nearly flat.

4.4.2.2 Aspect Map

The aspect map shows the direction of the slope. In the Kethan basin, the boundary of the basalt plateau can be more or less demarcated from this map, by the south to southeastern facing slopes. Further, the plateau shows variable aspect, indicating moderate dissection. Basalt hills, also in the Narayan basin, in the southeastern corner, show variable aspect, whereas the Vindhyan sandstone upland in the northern border shows southerly or southeasterly aspect. Change in aspect is noticed in the lower part of the upland. This coincides with a very strong lineament along the main stream. However, the aspect map has not been used in GIS analysis.

4.4.2.3 Extraction of Catchment Hydrologic Properties

Digital elevation models can provide a wealth of information about the geomorphic and hydrologic properties of an area. Automated extraction of hydrologic properties from DEM has been discussed in Chapter 2 (section 2.3.1). In the present study, drainage network and stream order have been derived from the DEM data (Figure 4.12). Flow direction and flow accumulation have been derived using the method presented by Jenson and Domingue (1988) Flow is routed through the path of the steepest slope of eight neighbouring pixels, assuming the surface to be insulated, i.e. there is no loss of water upward as evapotranspiration or downward as infiltration from the surface. Naturally, there will be some degree of misfit between the surveyed and the simulated drainage from DEM. Depression areas surrounded by neighbouring pixels of higher values are always considered as hindrance for the determination of hydrologic flow

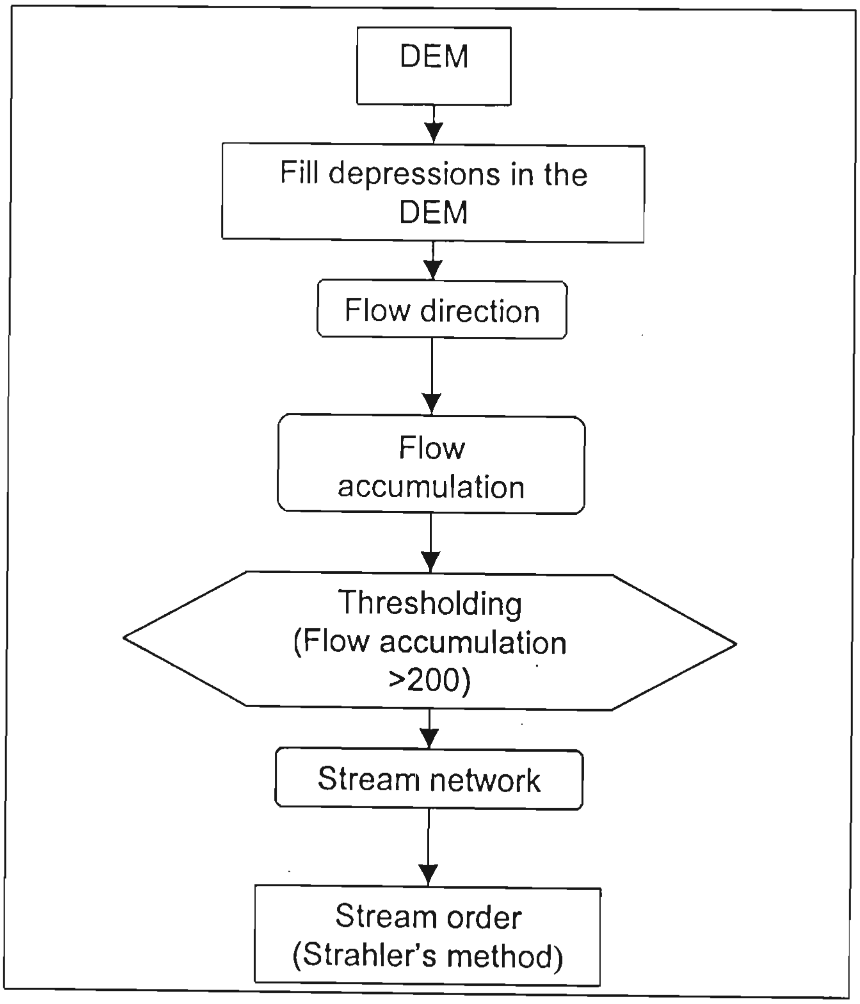


Figure 4.12. Methodology adopted for derivation of stream network from DEM

direction. Some depressions are data errors while some other exist in reality, e.g. queries etc. There are two approaches to remove depression. One is by smoothing the DEM (O'Callaghan and Mark, 1984; Mark, 1984). The second approach is to fill the depression by raising them to the lowest elevation value on the rim of depression (Jenson and Domingue, 1988). The second approach is followed in the present study. The flow direction grid represents the direction of flowout of each cell into one of its eight neighbours. This is in fact synonymous with the aspect grid except for the fact that aspect grid has some `flat' pixels (cells). The output grid has a value of 1 to 128. The values for each direction from the centre cell are:

32	64	128
16	X	1
8	4	2

Flow direction data are used to create flow accumulation grid, where each cell is assigned the value of the number of cells flowing to it. Cells having flow accumulation value of zero generally correspond to local topographic highs, whereas cells with high flow accumulation correspond to stream channels. The flow accumulation has been utilised to produce a drainage network applying a suitable threshold value. Threshold value indicates the minimum number of cells contributing to form a stream. The density of the network increases as the threshold value decreases. The stream ordering has been derived using the drainage network grid and the flow direction grid. Strahler's stream ordering scheme has been followed. Stream order increases when the same order streams intersect. When two first order streams meet, the downslope stream is assigned an order of 2. The intersection of the first and second order streams remains a second order stream.

Figure 4.13 shows a comparison of the surveyed drainage from toposheets with drainage derived from DEM in the Kethan basin. There is considerable degree of match in the western hilly part. In the flat areas, drainage lines are straight due to low gradient. In the Narayan basin, there is a good match between the two in the areas covered by Vindhyan sandstone (Figure 4.14). in the central flat area, straight drainage lines develop.

There are some limitations of this method of automated extraction of drainage. The infiltration loss and evapotranspiration loss are not taken into account while deriving flow accumulation. Secondly, in the process of removal of depressions, actual DEM data are modified. The density of the network depends on the threshold value used for flow accumulation.

However, this misfit can be linked to recharge areas. It has been observed that these areas are covered by weathered basalt which are the permeable areas. In this area, evapotranspiration is more or less uniform. Thus, it can be inferred that in these areas water is infiltrating and these may be recharge areas.

4.4.3 DRAINAGE

Drainage development has direct linkage to the geology of an area, and it indirectly indicates groundwater conditions. The Betwa is the only perennial river in the present area. The sub-basins show different drainage characteristics. The Kethan basin has a dendritic drainage pattern, whereas the Narayan basin shows rectangular or trellis drainage in the lower reaches. Vindhyan sandstones cover this part and rectangular drainage is a typical characteristic of these rocks. Drainage, at places, is structurally controlled. In the Kethan basin, straight drainage course, developed in a narrow valley between two plateaus, indicates structural control. In the Narayan basin, near the junction with the Betwa river, drainage follows a straight course that is related to a strong lineament. The tributaries cut the main stream at right angles. This is also indicative of structural control.

Drainage map has been prepared from SOI toposheet and remote sensing data. In order to understand the role of geology in drainage development, drainage basin characteristics (linear and aerial aspect) have been derived. From the flow direction grid (Figures 4.15 & 4.17) stream order has been derived using Strahler's system. In the Kethan basin, streams up to 5th order have been found (Figure 4.16). Higher order streams indicate greater degree of weathering. The depth of weathering is high in the plain land where it joins the Betwa. In the Narayan basin, streams up to 5th order are developed (Figure 4.18).

Drainage density is the length of a stream in a unit area. In order to compute the drainage density, the area has been subdivided into 1 km X 1 km grid. Then, the length of stream with each grid has been calculated using ILWIS. In each grid, drainage density has been represented in metres. Drainage density surface is generated through density function of centres of the grid cells. In the Kethan basin, drainage density ranges from 0.3-2.8 m /km^2 (Figure 4.19). It has been noticed that high drainage density is associated with higher order of

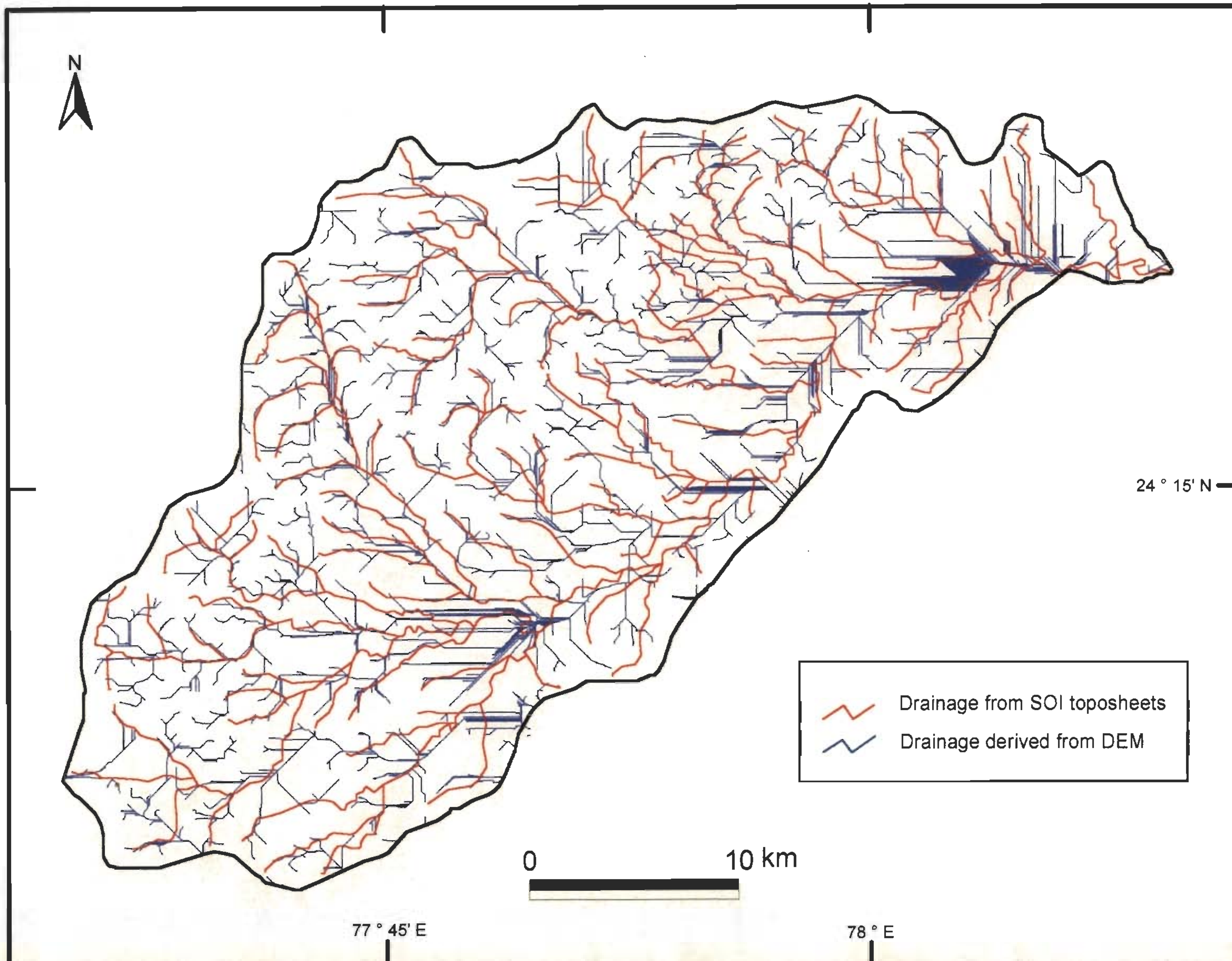


Figure 4.13. Drainage network derived from DEM and the surveyed drainage of the Kethan basin. In the hilly part, there is better match between the two as compared to the valley portion along the main stream.

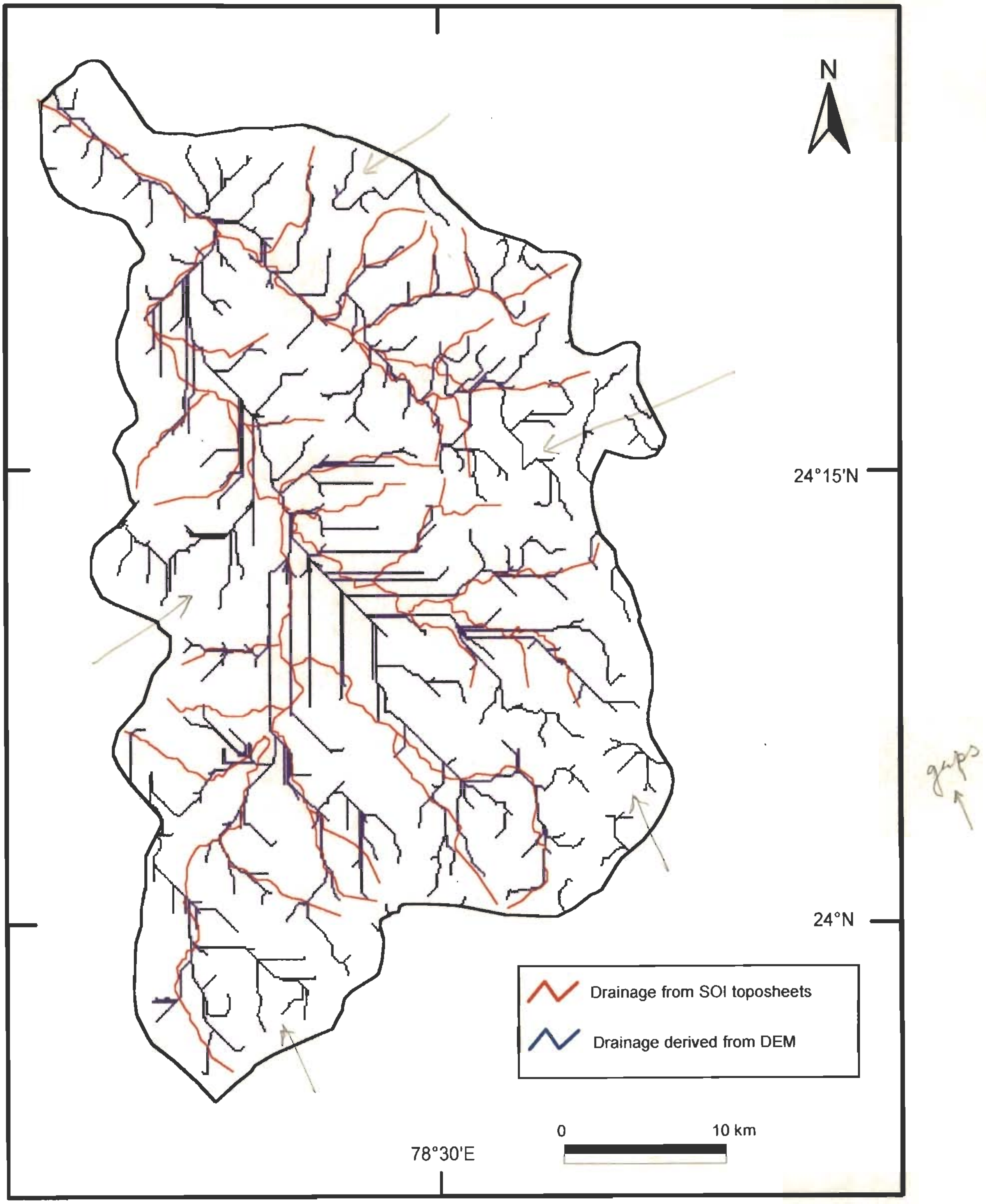


Figure 4.14. Simulated and surveyed drainage of the Narayan basin. There is good match between the two in the northeastern part covered by Vindhyan upland. The valley portion shows much deviation.

stream in the area. Higher drainage density indicates less permeable underlying lithology and higher erodability of the surface material, in general. In this area, the lithology is basalt, spread over 90% of the area. Permeability is practically zero except in the jointed and weathered parts. Vindhyans are also hard and compact rocks with very low permeability. However, even the jointed and weathered basalts and the Vindhyan rocks, having relatively high permeability show high drainage density. Thus, low drainage density does not always indicate more permeable lithology. Rather drainage density is high at the junction of two or more streams. Also the comparison of drainage density and lineament density maps (Figures 4.19 & 4.20) shows that the high drainage density is associated with high lineament density in some parts of the Kethan basin. Detailed discussion is given in section 4.4.5. Lithology being more or less uniform, drainage development is influenced by the structural features like fractures, as in a hard rock terrain drainage development is essentially through planes of weakness. In some areas, there is clear indication of linear control on the drainage, as evident from the rose diagrams of lineament and drainage lines (Figures 4.21 a & b). The misfit between the surveyed and DEM derived drainage network is minimum in the lower order streams and maximum in the higher order streams.

Is this so because of the areas associated with higher order streams are almost flat? (filled channels etc)

4.4.4 GEOMORPHOLOGY

Geomorphic features have been identified from remote sensing data in conjunction with DEM and slope map. FCC (432) of LISS II, 321 of LISS III and principal component composites of LISS II and LISS III (Figures 4.22 & 4.23) have been quite useful in the delineation of different features. The present day configuration of landforms is the expression of various processes of weathering, erosion and deposition operating on the earth's surface during the geologic past. These features result from a complex interplay of physical processes with the prevalent climatic changes. A detailed study on the geomorphic evolution of the area is beyond the scope of this chapter. The features are studied with respect to their influence in the groundwater conditions. Topography has an important link with the geomorphology. In order to have a better understanding of this relation, profiles have been generated along different section lines on the DEM.

The following geomorphic classes are identified in the present area:

(a) Residual hills and plateau of basalt

Basalt lava flows have spread in vast sheets in the geologic past and flooded the area. There is a time gap in between two successive flows, which is evidenced by the development of red bole on the top of the older flow. Basalt being rich in mafic minerals gives way to weathering. However, hard, massive basalt can withstand the effects of weathering to some extent and the residual product remains as hills and plateau. These are the remnants of younger flows. There are no dykes in the area and all the flows have come from a distant source and drowned the area progressively.

A basalt plateau flanks the entire western boundary in the Kethan basin (Figure 4.24). In the Narayan basin, there are a number of small residual hills of basalt along the eastern and southeastern margins. These can be readily identified on the FCC as shades of green (Figures 4.3 and 4.4). Overlaying FCC with the DEM and the slope map shows that these are represented by higher grounds with 0 - 1° slopes. They form mesas, which are quite distinctly discernible in the northwestern corner of the Kethan basin. Along the southeastern margin of the Kethan basin, there is a series of hills or intervenial plateau, nearly at parallel deposition to the mesas in the northwestern margin. This probably indicates a basalt flow, which was weathered in course of time, and the remnants stand out as intervenial plateau. Thus, it forms a drainage divide. These plateaus normally do not hold prospects for groundwater excepting the fractured parts.

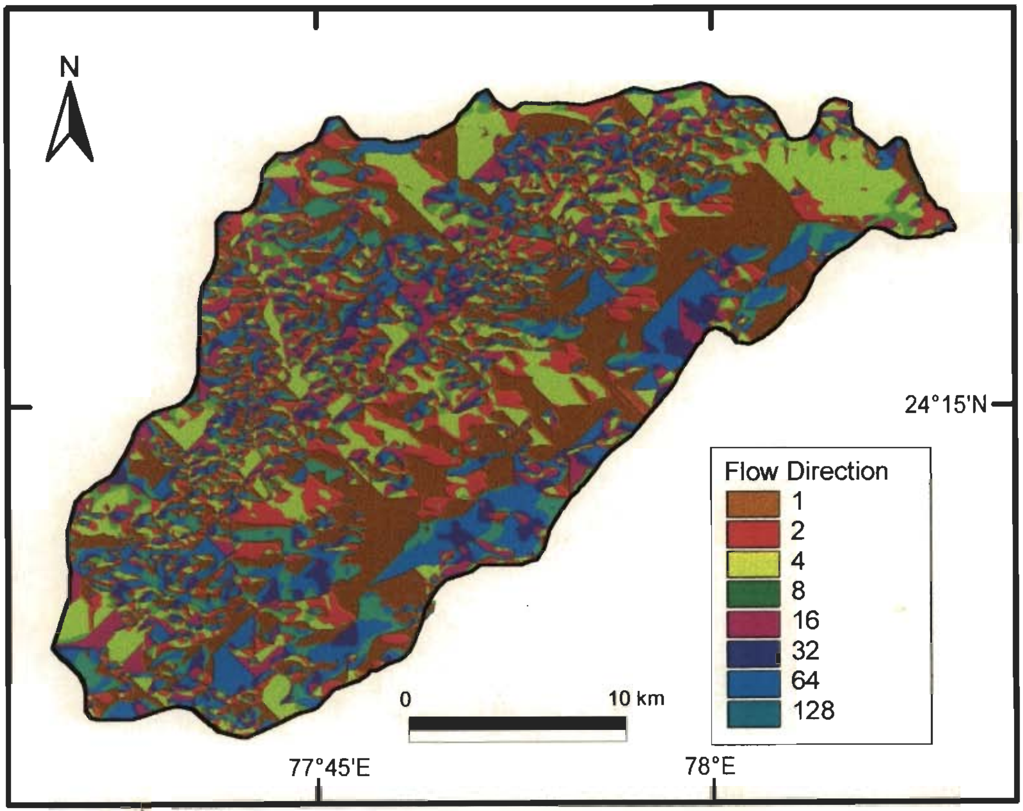


Figure 4.15. Flow direction map derived from DEM of the Kethan basin.

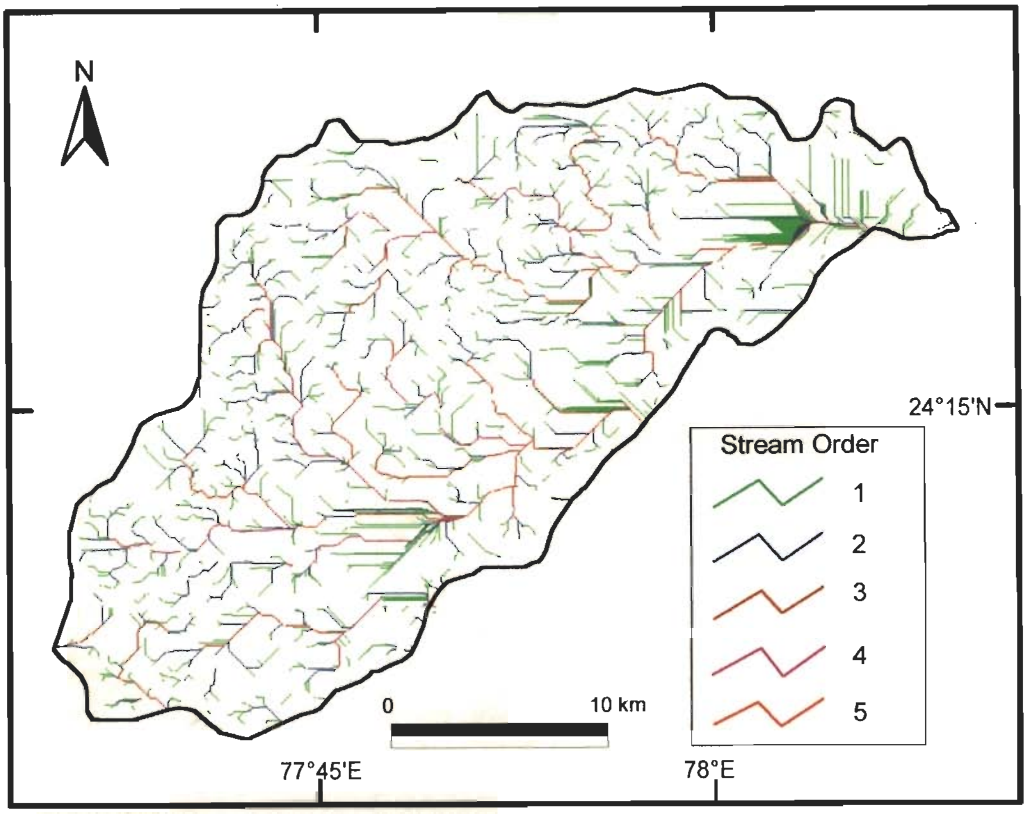


Figure 4.16. Stream order map (Strahler's scheme) of the Kethan basin as derived from drainage and flow direction grid.

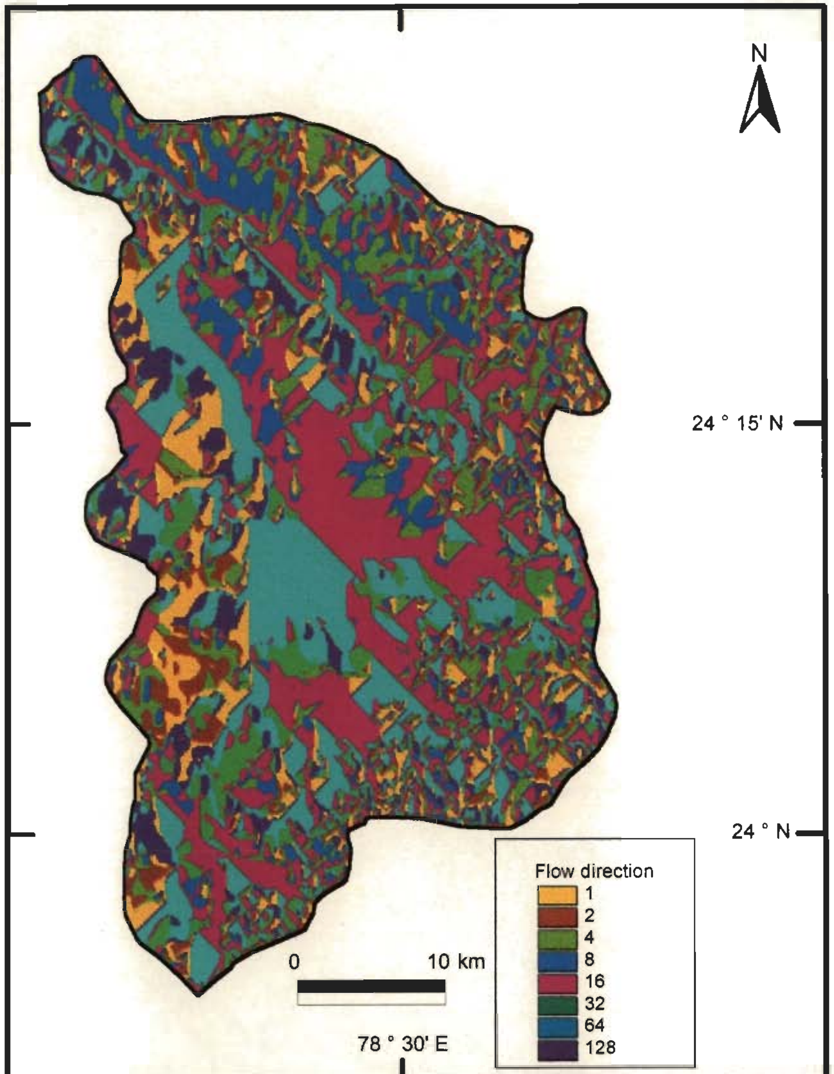


Figure 4.17. Flow direction map derived from DEM of the Narayan basin.

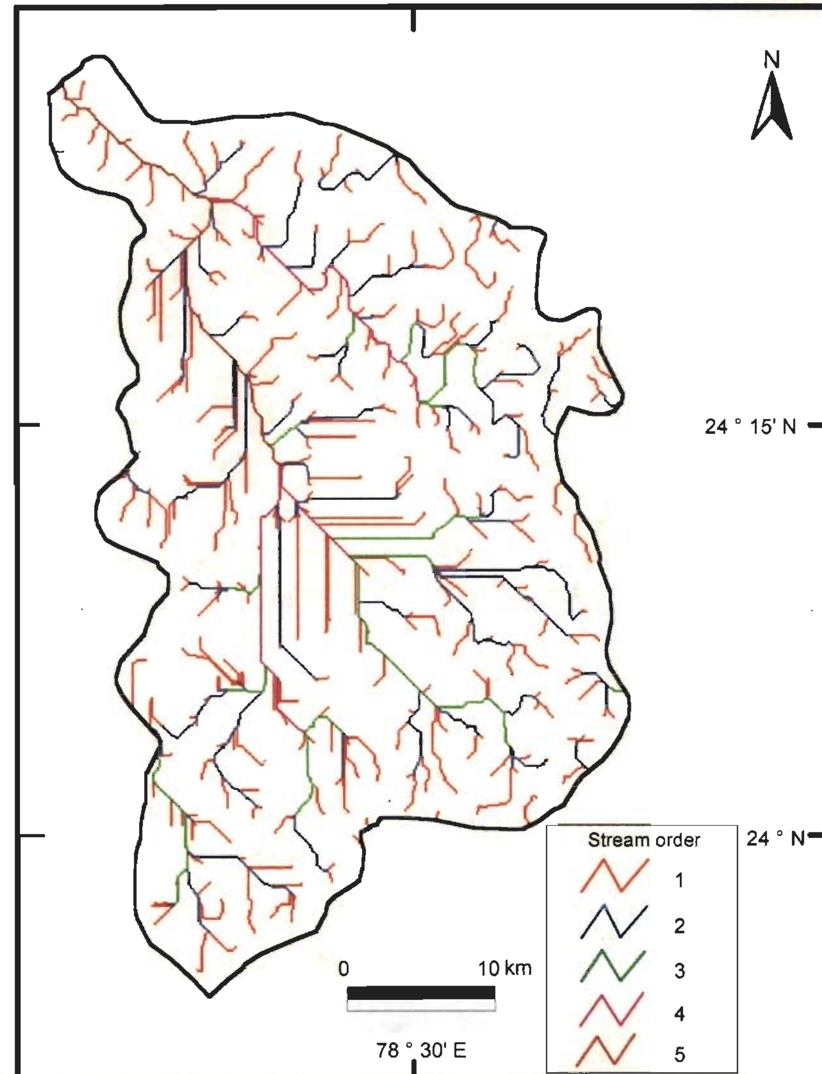


Figure 4.18. Stream order map (Strahler's scheme) of the Narayan basin as derived from drainage and flow direction grid.

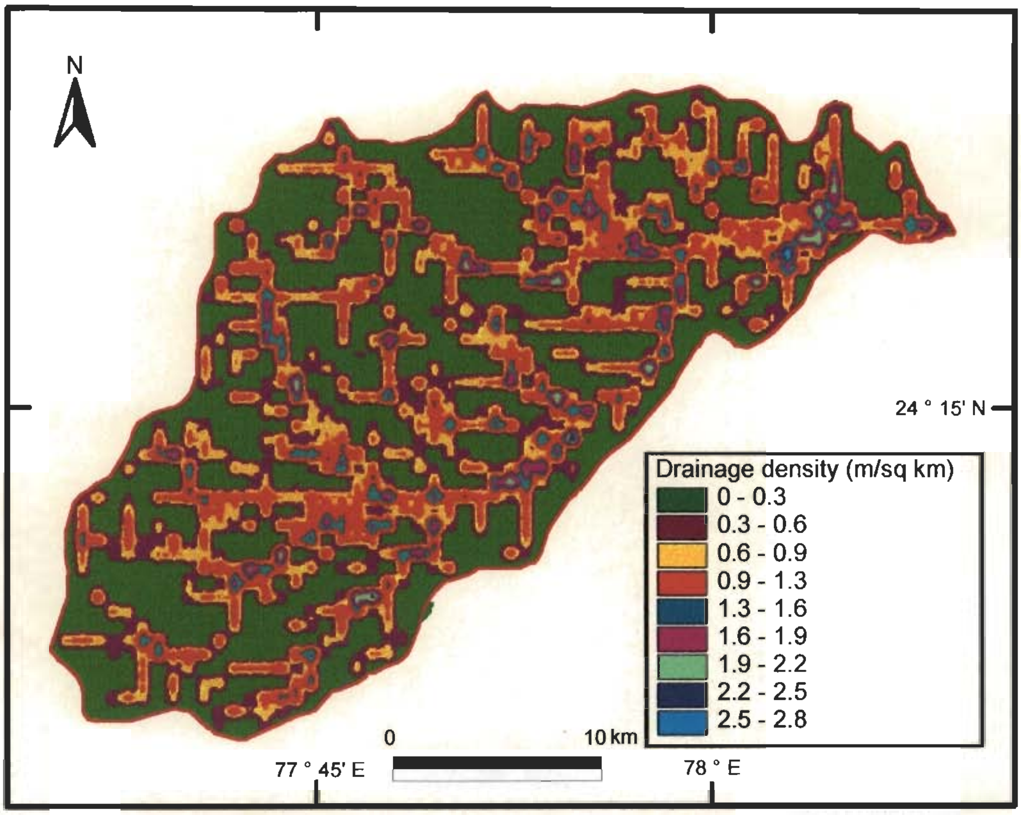


Figure 4.19. Drainage density map of the Kethan basin. Drainage density is highest along the main stream.

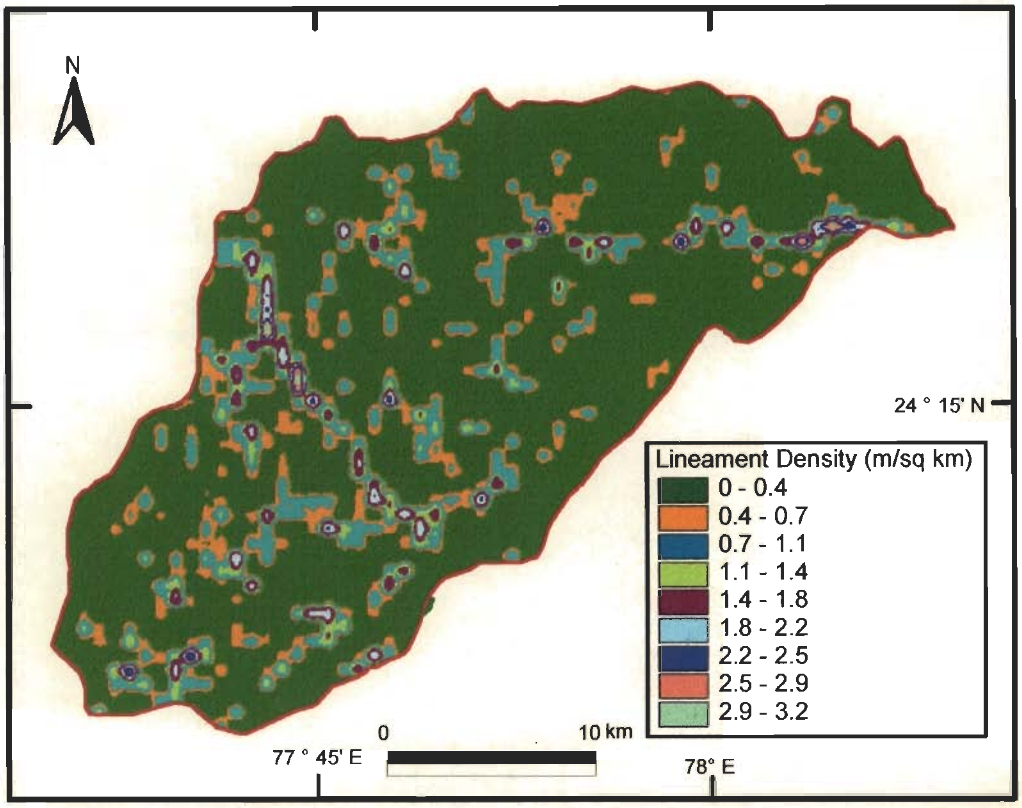


Figure 4.20. Lineament density map of the Kethan basin. High lineament density along the NW-SE line correlates to high drainage density. Probably drainage is related to the lineament as expressed by the straight course followed by the stream.

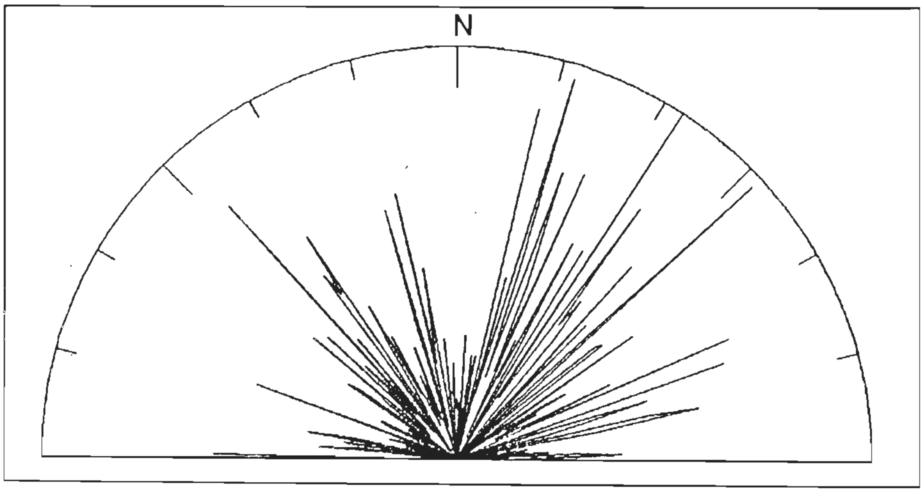


Figure 4.21a: Rose diagram of lineaments of the Kethan Basin

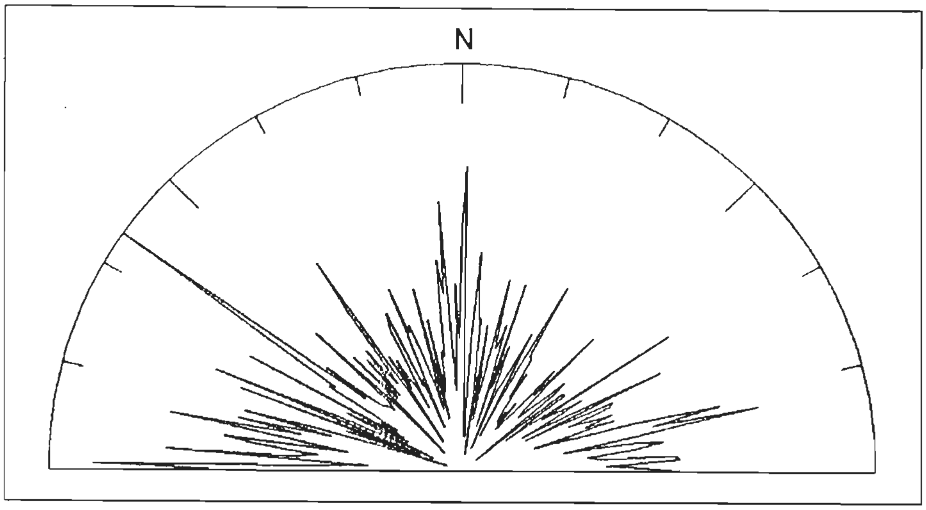


Figure 4.21b: Rose diagram of drainage of the Kethan Basin

(b) Vindhyan upland

An elongated patch of Vindhyan hill flanks the northeastern boundary of the Narayan basin. Along the boundary cuestas have formed (Figure 4.26). These are visible as shades of dark green, and readily identified by their characteristic shape. Vindhyan uplands and the basalt hills have been differentiated on the basis of their different image characteristics. Vindhyan uplands are more or less flat. A small hill has been noticed at the southeastern corner of the study area. Slope map shows that the hills are nearly flat on the northeastern margin.

(c) Dissected plateau / hills

This unit represents undulating topography of small hills and plateau of basalt with a greater degree of weathering. This unit occupies the entire northeastern margin of the Kethan basin. Fractures (especially joints) are common. Principal component-3 of 4 bands of LISS-II (PC3) has been very useful in differentiating this unit from the basalt plateau, which can be seen on the principal component composite of the LISS II bands of the Kethan basin (Figure 4.22). This is visible as green patches on the FCC (432) of LISS II and FCC (321) of LISS III, due to the high reflectance of yellow clay in the band (0.62 - 0.68 μm) as discussed under section 4.4.1. These hills with yellow clay cover on the top are the in situ products of weathering. From groundwater point of view, it holds poor potential.

(d) Pediments

Pediments have formed over gentle slopes varying from 5° to 10° in basalt in this area. They are identified as a gently dipping rocky surface bordering the plateau and occurring as a transition zone between the hills / plateau and the valley plain. On the FCC (432) of LISS II (Figure 4.1), they have been represented in shades of green and blue. On the principal component composite (Figure 4.22), they are visible as shades of blue. In order to improve the interpretation from remote sensing data, vertical profiles along section lines drawn from the plateau downslope through this unit have been generated from DEM (Figure 4.28). These topographic profiles clearly show the transition zone from plateau through steep slopes on the escarpment and finally merging to the valley area. This unit has a thin layer of weathered material. Groundwater potential is moderate. Overlay analysis in GIS of the slope map facilitates understanding of the relationship of topography. Three dimensional perspective viewing has been effective in depicting the landscape (Figure 4.29).

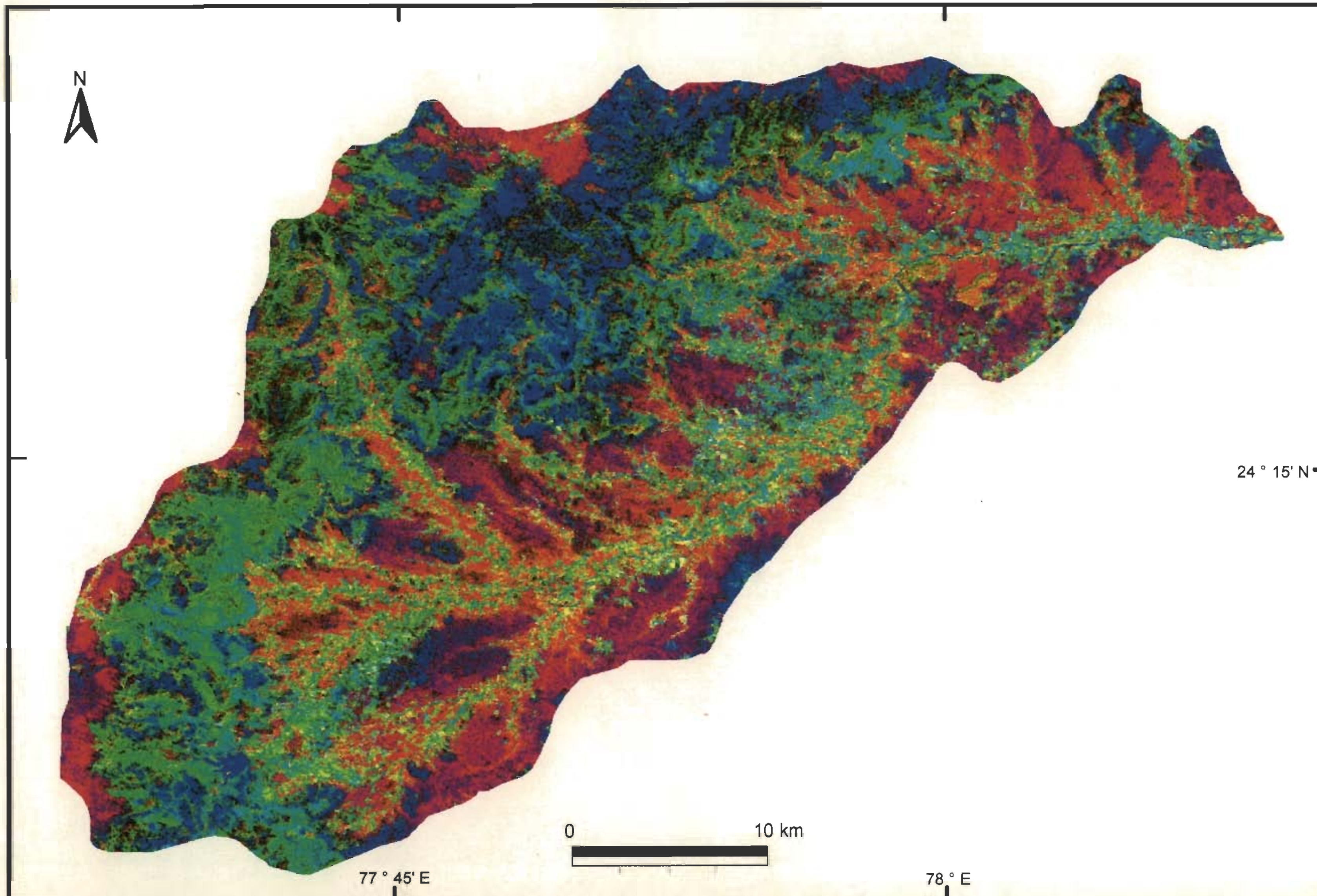


Figure 4.22. Principal Component Composite (PCC) of PC1, PC2, PC3 of LISS-II bands in RGB showing the Kethan basin. The basalt hill/plateau is moderately dissected, especially in the northern part. Residual hills capped by yellow clay soil are seen in blue. The valley part is distinct from the rest in magenta. Channel fills are seen as yellow patches, mixed with light green wherever vegetation is present.

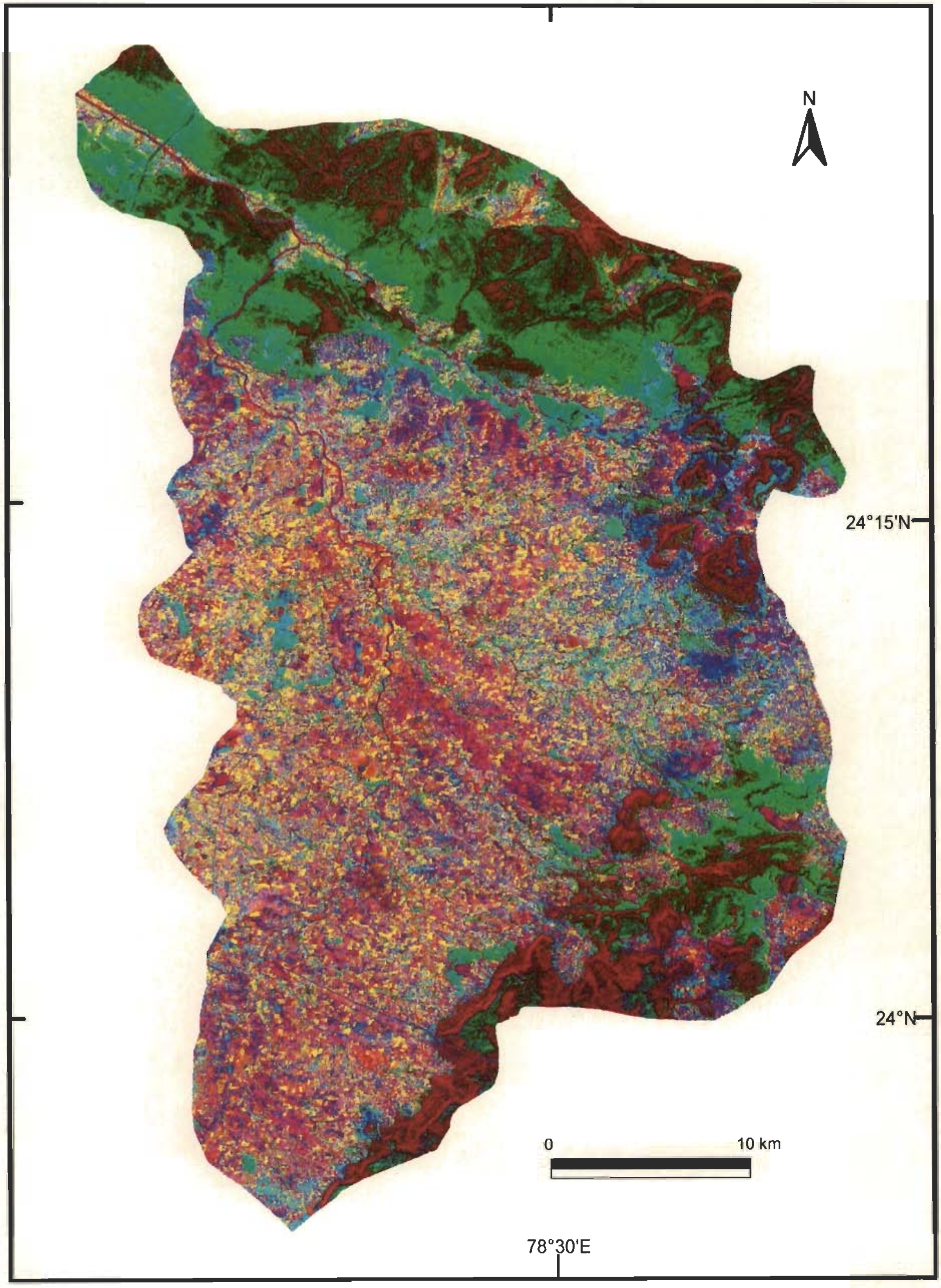


Figure 4.23. Principal Component Composite of the LISS-III bands showing the Narayan basin area (PC1, PC2, PC3 in RGB). Vindhyan upland is seen as green patches.

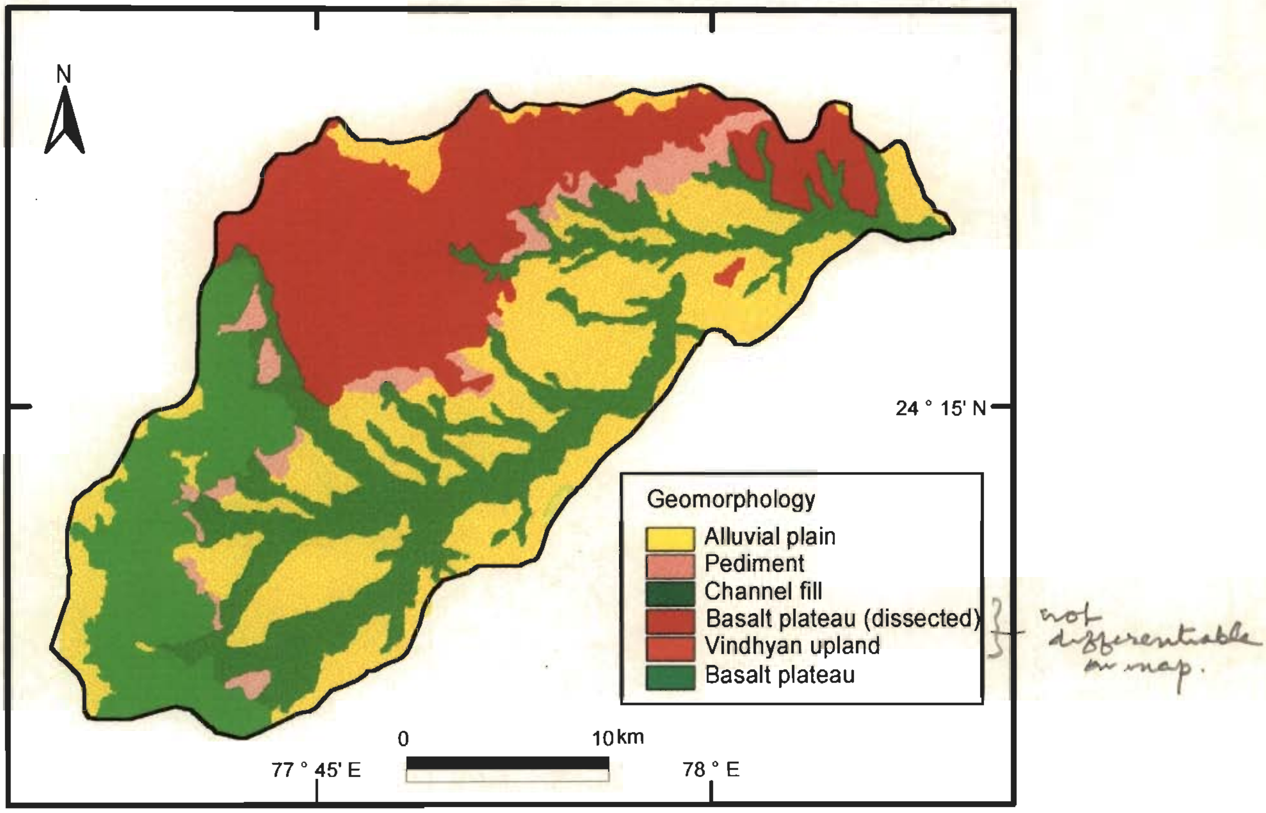


Figure 4.24. Geomorphic features of the Kethan basin as interpreted from IRS-LISS-II & LISS-III data.

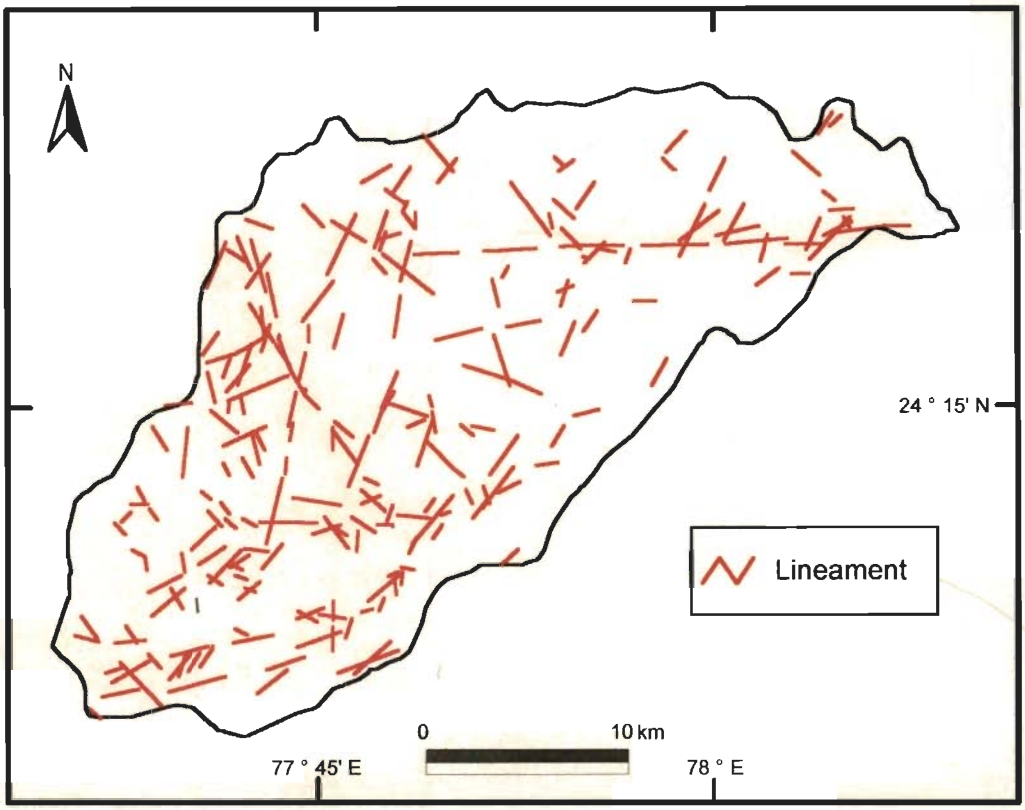


Figure 4.25. Lineament map of the Kethan basin as interpreted from processed IRS-LISS-II & LISS-III data.

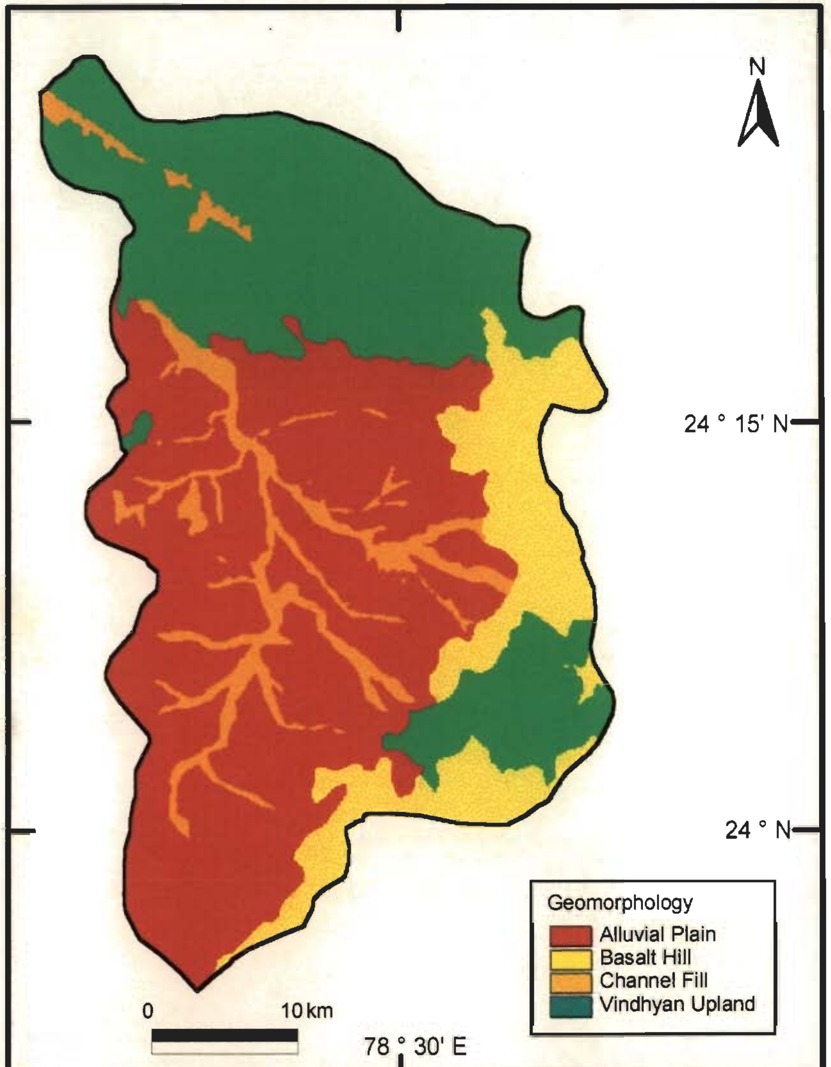


Figure 4.26. Geomorphic features in the Narayan basin as interpreted from IRS-LISS-II and LISS-III images.

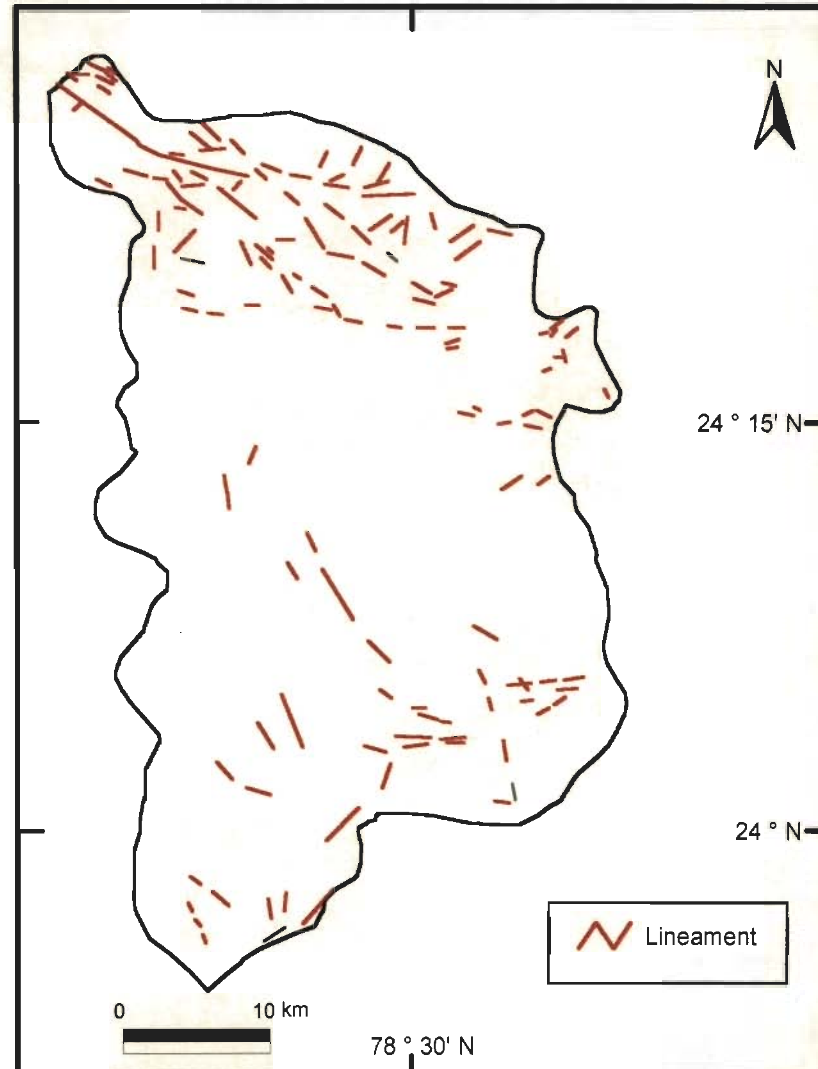


Figure 4.27. Lineament map of the Narayan basin as interpreted from IRS-LISSII and LISS-III images.

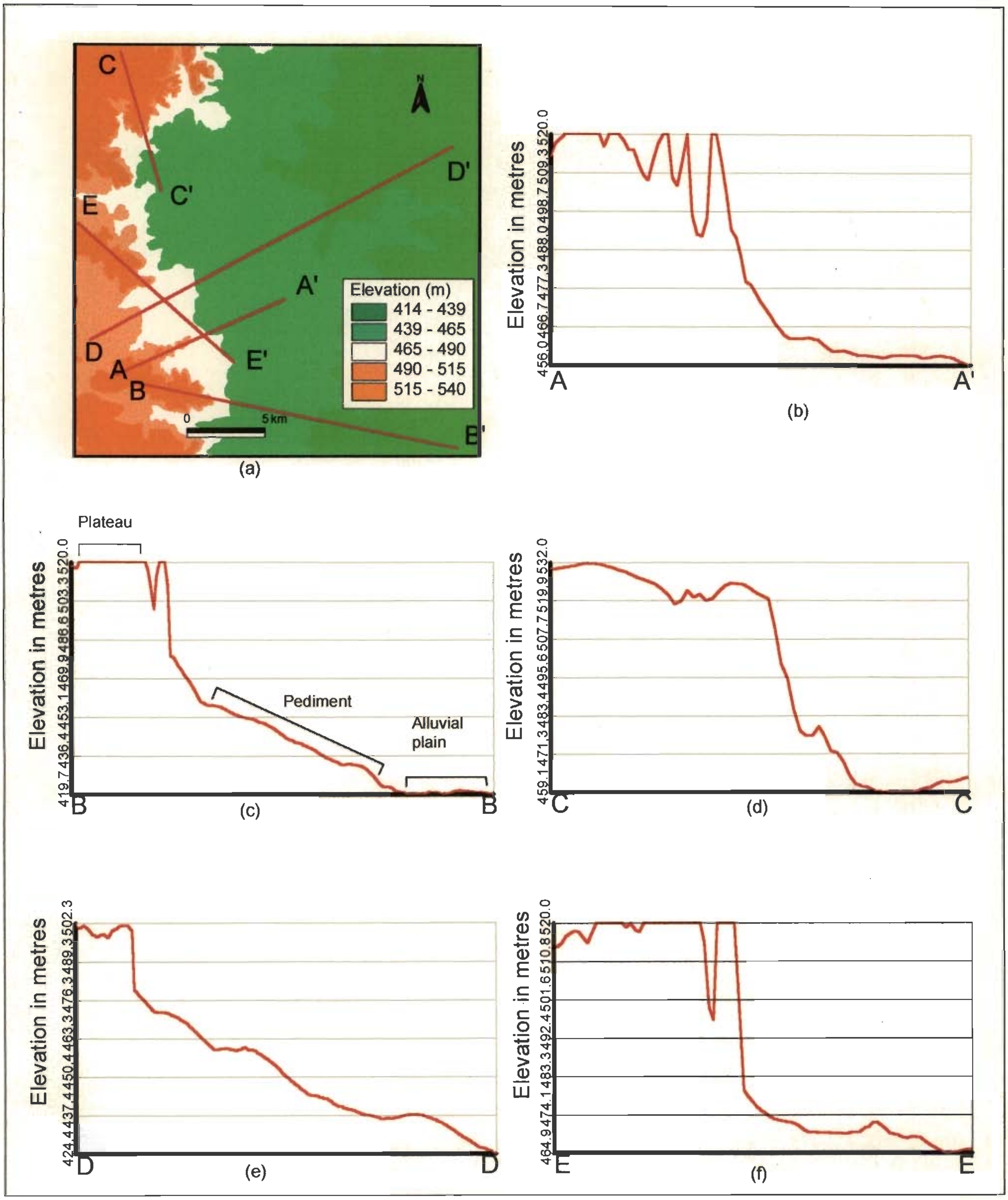


Figure 4.28. (a). DEM of a part of the Kethan basin with section lines AA' to EE'. (b) to (f) Topographic profile of the section lines AA', BB', CC', DD' and EE' respectively, drawn from DEM. The profiles show the variation in elevation from hills to the alluvial plains.

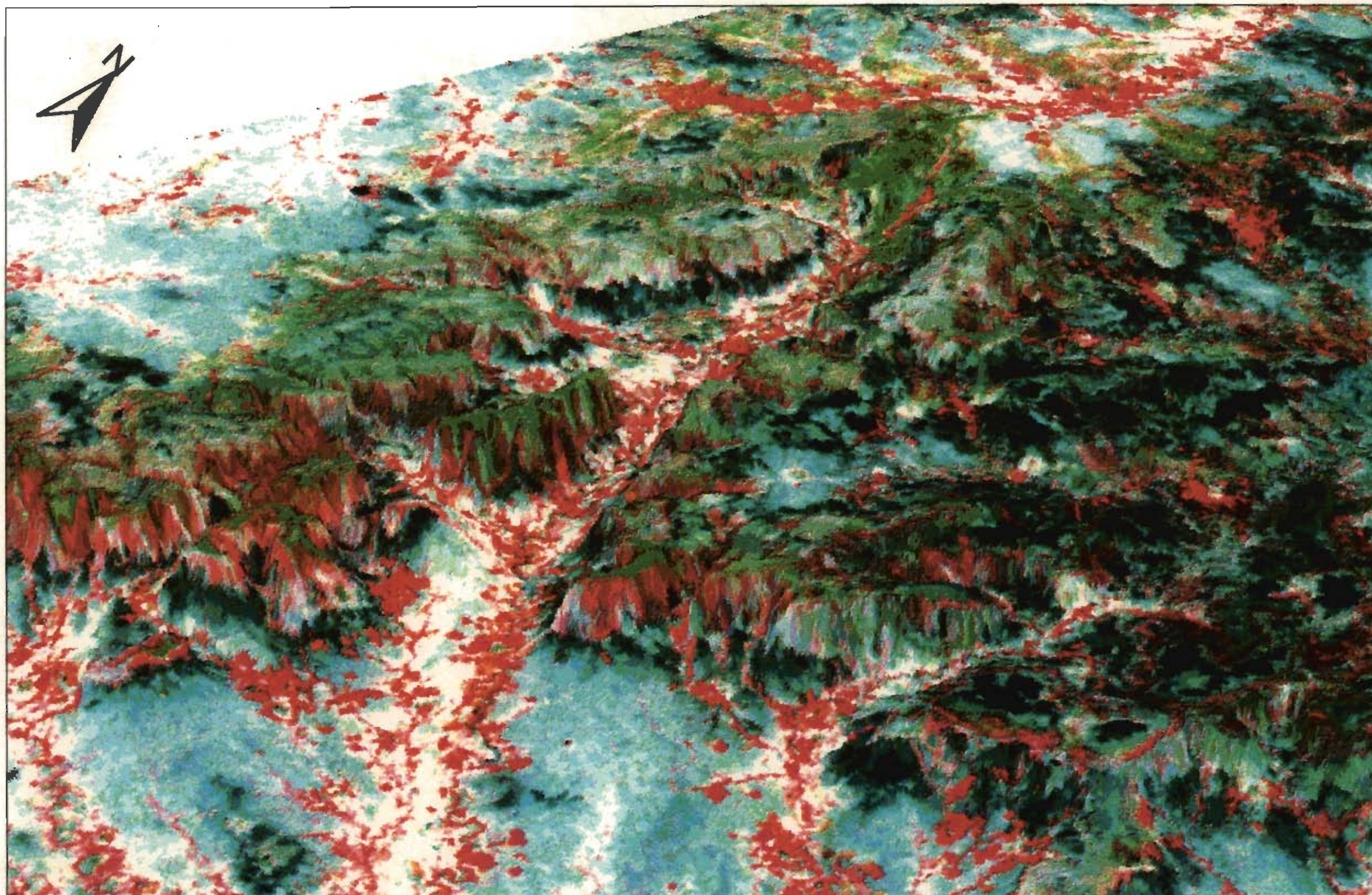


Figure 4.29. 3D - perspective view of a part of the Kethan basin. Basalt plateau and hills are seen in green. Channel fills develop in the valley in between the hills and are seen in shades of red in many places, due to growth of vegetation.

(e) Alluvial plain

Alluvial plains have developed in the low lying area in the Kethan and Narayan basins. These areas are nearly flat or have a slope ~1°. This area has a moderately deep soil cover. These are readily identified as light blue shade on the FCC (432) of LISS II (Figure 4.1.). Wherever agricultural lands have developed, these show red shades. On the PC FCC (Figures 4.22 & 4.23), this unit is seen in magenta and red. These areas hold moderate potential for groundwater.

These alluvial plains may have formed by the transportation of clayey material through the streams or the product of in situ weathering of basalt lava flows having a thick layer of weathered material (CGWB, 1984).

(f) Channel fill

Channel fills have formed along the streams by the deposition of weathered material. Their characteristic bright signature in all the bands of LISS II and III has identified these. On the FCC, they are seen as white patches wherever devoid of vegetation (Figures 4.1 & 4.3). The bright signature is due to the unconsolidated alluvial / colluvial material. Along the main stream of the Kethan basin, wide zones of valley fills develop. These units hold very good prospect for groundwater as expressed by the development of dry season vegetation along this unit in the Kethan and the Narayan basins. This can be seen on the FCC of LISS-II data of late March, which is the harvesting time of most of the winter crops (Figures 4.1 & 4.3).

4.4.5 STRUCTURAL FEATURES

Structural features are mapped from remote sensing data supported by existing geological maps. Remote sensing data can provide very important information about the location and distribution of geological features, potentially relevant for the occurrence and movement of groundwater, through lineament analysis. In the present area, lineaments are reflected in many forms like fractures (especially joints), topographic linear features, straight valleys, and soil tonal lineaments. In this area, the fractures (especially joints) are the most favourable sites for groundwater potential, because they provide porosity and permeability to the bedrock, which is basalt or Vindhyans.

Lineaments have been extracted from LISS-II and LISS-III data. FCC 432 of LISS-II and 321 of LISS-III provide an idea of the prominent lineaments. Further, the lineament enhancement procedure developed by Moore and Waltz (1986) has been utilised to extract lineaments. The procedure has been discussed in Chapter 3. The convolution filters have been applied on PC 1 image as it accounts for the highest spectral variance. By this method of lineament enhancement, linear feature in all directions is enhanced, some of which may have little or no geological significance. Care has been taken to minimise the artifacts or artificial lineaments. Lineaments have been compared with the topographic maps, geological map, and soil map of the area. These maps help to differentiate geological lineaments from cultural lineaments. Finally, the selected lineaments have been digitized from the backdrop of the processed images (Figures 4.25 & 4.27). In order to check the satellite data derived lineaments, comparison has been made with a previous structural map of the area (CGWB, 1984), and a considerable degree of correlation is found. A rose diagram of the length of the lineaments in 15° intervals has been prepared in ILWIS. The prominent azimuth directions are NE-SW and NW-SE, NNE-SSW (Figures 4.21a & 4.30).

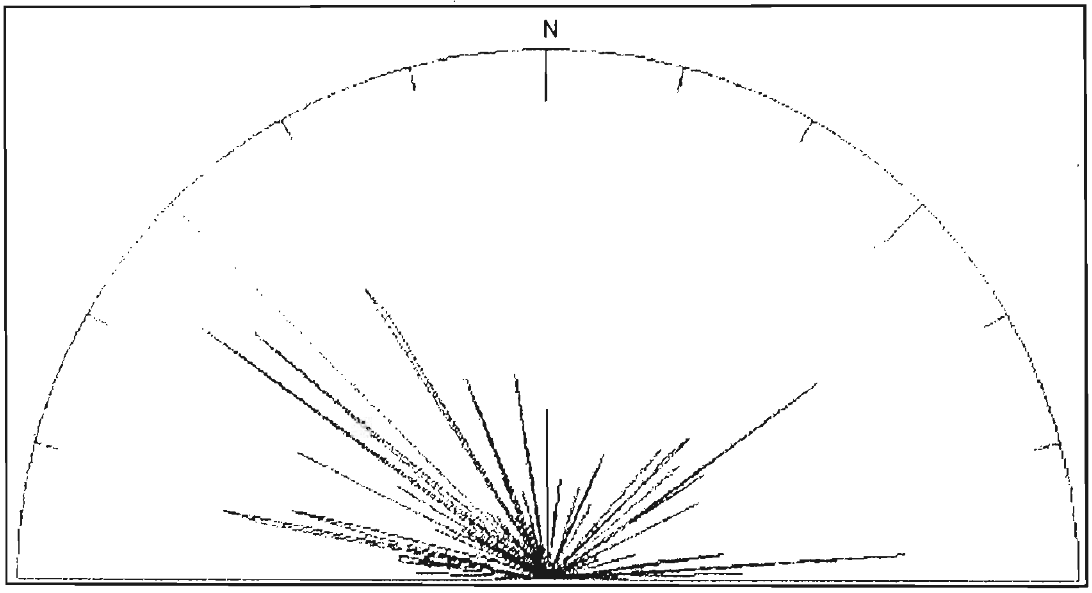


Figure 4.30: Rose diagram of the lineaments in the Narayan basin

In order to understand the spatial variability in distribution of the lineaments, a lineament density map has been prepared (Figure 4.20). The method is same as for the preparation of the drainage density map (section 4.4.3). Length of lineament in m/ sq. km has been computed for each grid of 1 km X 1 km. In the Kethan basin, maxima are in NE - SW and NW - SE directions. From the comparison of the rose diagrams of the lineament and the drainage in the Kethan basin (Figures 4.21a & 4.21b), it is evident that there is a strong correlation between drainage and lineament in the NW - SE direction. This is also seen on the drainage density and lineament density maps (Figures 4 19 & 4.20). It is noticed on the drainage map that a stream course follows a nearly straight course following from NW - SE through a steep valley in between basalt plateaus. This indicates that drainage is structurally controlled in some parts of the area. The Narayan river follows a straight course near the junction with the Betwa river, indicating structural control. A strong correlation between the river course and a prominent lineament is also observed on the remote sensing images. In this basin, the drainage and lineament directions can be correlated in the NW – SE direction (Figure 4.30). Vindhyans are hard and compact sedimentary rocks with poor permeability. Drainage is developed along the fracture planes. Fractures are the pathways for groundwater circulation.

4.4.6 SOIL

The entire area is covered by black cotton soil, which is derived from light brown silty clay, locally known as Muram (yellow clay). Extensive weathering of basalt gives rise to the formation of yellow clay. The hilly areas are covered by shallow to slightly deep loamy soil of a depth of 50 - 70 cm., whereas the plain areas are occupied by moderately deep to deep black soil of a thickness of 75 - 100 cm. In the Kethan basin, the plateau is covered by shallow soil near the northern margin to slightly deep soil (Figure 4.31). The soil in the plain lands has a higher available water capacity (AWC) up to 200mm / m and the higher grounds have medium available water capacity of about 100-150mm / m. Soil map was not available for the whole of the Narayan basin. However, the general soil types are similar to the Kethan basin in the areas covered by weathered basalts.

4.4.7 LANDUSE

Landuse classes are identified from the SOI toposheet (surveyed in 1967-68) (Figure 4.32) and also from the LISS III data of 1998. Supervised classification of the LISS-III data has been attempted. Little success was achieved because of intermixing of individual classes. This is due to high correlation of the spectral bands, which is evident from the scatter plots. Separability of individual classes was very low. Hence, FCC (321) of LISS III (Figures 4.2 & 4.4) has been visually interpreted and digitized on the screen.

A part of the plateau is covered by open forest, the remaining part being covered by scrub. Scrubs are also present in the plain area along the streams. Agricultural lands are developed in the plain area downstream from the reservoirs due to artificial recharge provided by them (discussed in Chapter 5). The major part of the area is cultivated by the Rabi crops, which are the major crops in the winter season. The major crops are wheat, grain, lentils etc. A small area is used for Kharif (monsoon) crops. Thus, a large part of the area lies fallow

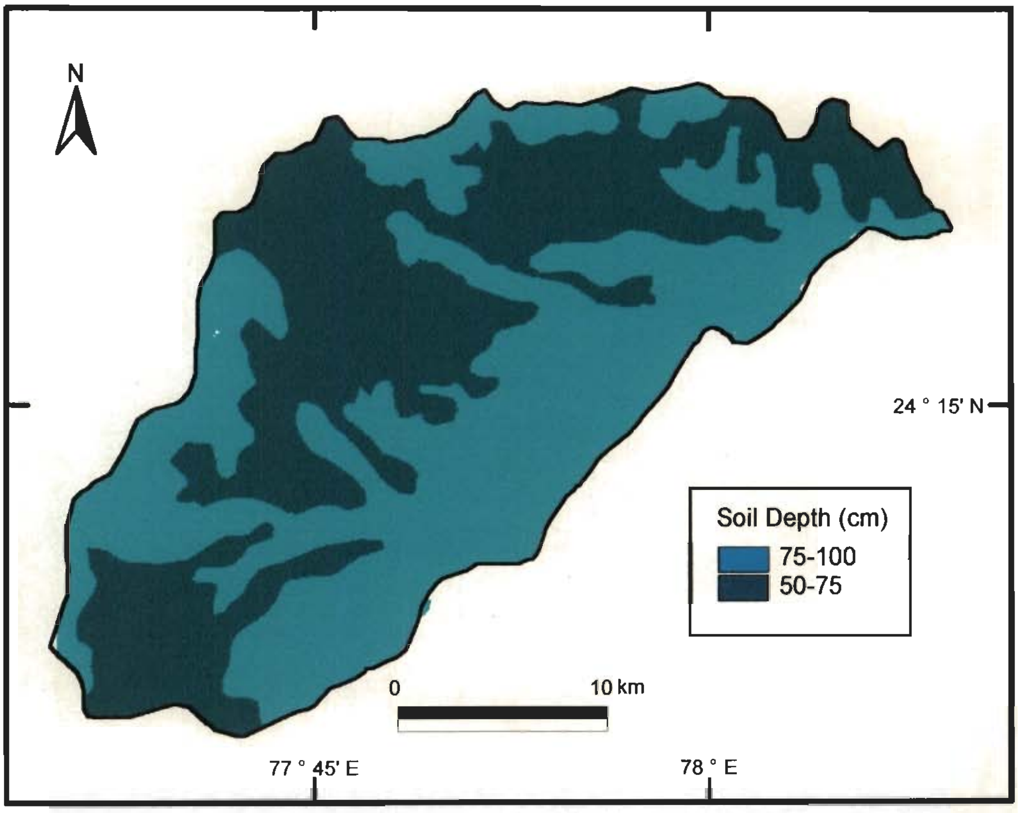


Figure 4.31. Soil map of the Kethan basin showing shallow black soil and slightly deep black soil.

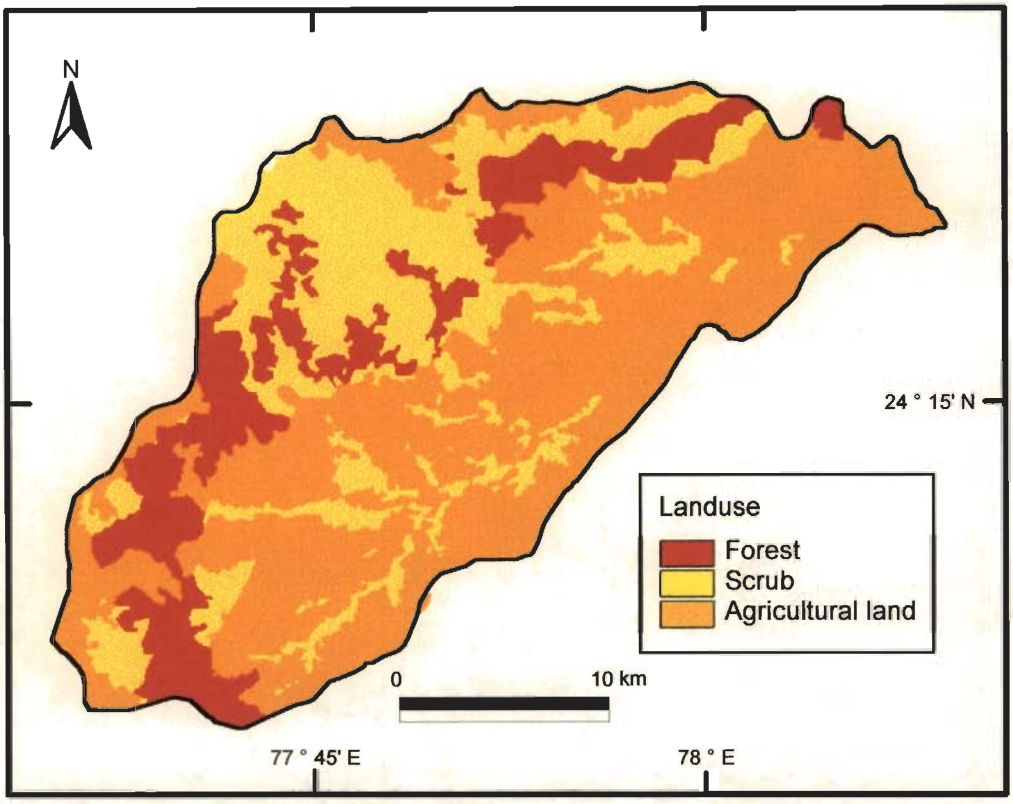


Figure 4.32. Landuse map of the Kethan basin prepared from SOI toposheet.

for most of the months.

4.4.8 VEGETATION

NDVI and ratio vegetation index (RVI) image has been prepared. These indices show the intensity of vegetation. NDVI image prepared from LISS II data of March 1995 clearly shows that the vegetation is restricted mostly to the valley fills and downstream from the reservoir (Figure 4.33 & Figure 5.3). Dry season vegetation is a possible indicator of groundwater. It is interesting to notice that the growth of vegetation in most of the areas is confined to the major lineament direction. It is evident that the lineaments are fractures (especially joints) providing permeability to the basalt facilitating movement of water.

4.4.9 GROUNDWATER LEVEL

Groundwater level data indicate the status of groundwater. Water level data from 60 stations have been collected from the CGWB. Out of these stations, 22 stations are within the study area (Figure 4.34). Depth to water level measurements are taken at the hydrograph network stations and monitored by CGWB four times in a year. These data have been analysed. Average pre-monsoon depth to water level is 8 m b.g.l., ranging from 6 m to 13 m b.g.l. (Figure 4.35 & Figure 4.36). The deepest water level is observed at Bahadurpur at a depth of 16.29 m in May, 1997. In the western hilly part water table is generally shallow whereas in the valley in the central part it is deep. In general, water level fluctuation is high in the weathered basalt as it provides the porosity and permeability to hold water. Water level is very uniform in nature. Figure 4.37 and Figure 4.38 show the average pre-monsoon and post-monsoon water table in the area. The standard deviation image of the water level of 20 years shows that most of the area shows a standard deviation of 1. Water level shows a maximum variation of 1 m from year to year. The general direction of groundwater movement is from NW to SE in the Kethan basin and SE to NW in the Narayan basin.

4.5 WEIGHTED INDEX OVERLAY MODEL FOR GROUNDWATER PROSPECTS

The fundamental aspect of the integrated analysis is the spatial combination of multiple features so as to characterise the area for all the parameters. GIS provide the appropriate tool to combine various spatial information for a single output. Weighted overlay analysis is a simple and straightforward method for a combined analysis of multi-class maps. The efficacy of this method lies in that human judgement can be incorporated in the analysis. Each class of the input maps is assigned different weightage (score or ranking), as well as the maps themselves receive different weightage (discussed in Chapter 3, section 3.8.2). A weight represents the relative importance of a parameter vis-a-vis the objective. In case of binary weights, all the parameters are assumed to have equal importance. Weighted index overlay method takes into consideration the relative importance of the parameters and the classes belonging to each parameter. This is a more flexible weighting method compared to binary weightage. There is no standard scale for a simple weighted overlay method. For this purpose, criteria for the analysis should be defined and each parameter should assigned importance.

Defining the criteria for an analysis is an important aspect of integrated modelling. A criterion is a definition of a relationship amongst the different parameters in commensurate terms i. e. expressing the different parameters in the same units or scale. A criterion could be categorised as statement criterion and table criterion (Rao et al. 1994). This method is class dependent i. e. the relationship of a parameter within a class is defined. Several statement criteria are to be made in order to encompass all the classes of different parameters. Table criterion is more organized as the relationship among the parameters and their categories are defined.

Determination of weightage of each parameter is the most crucial in

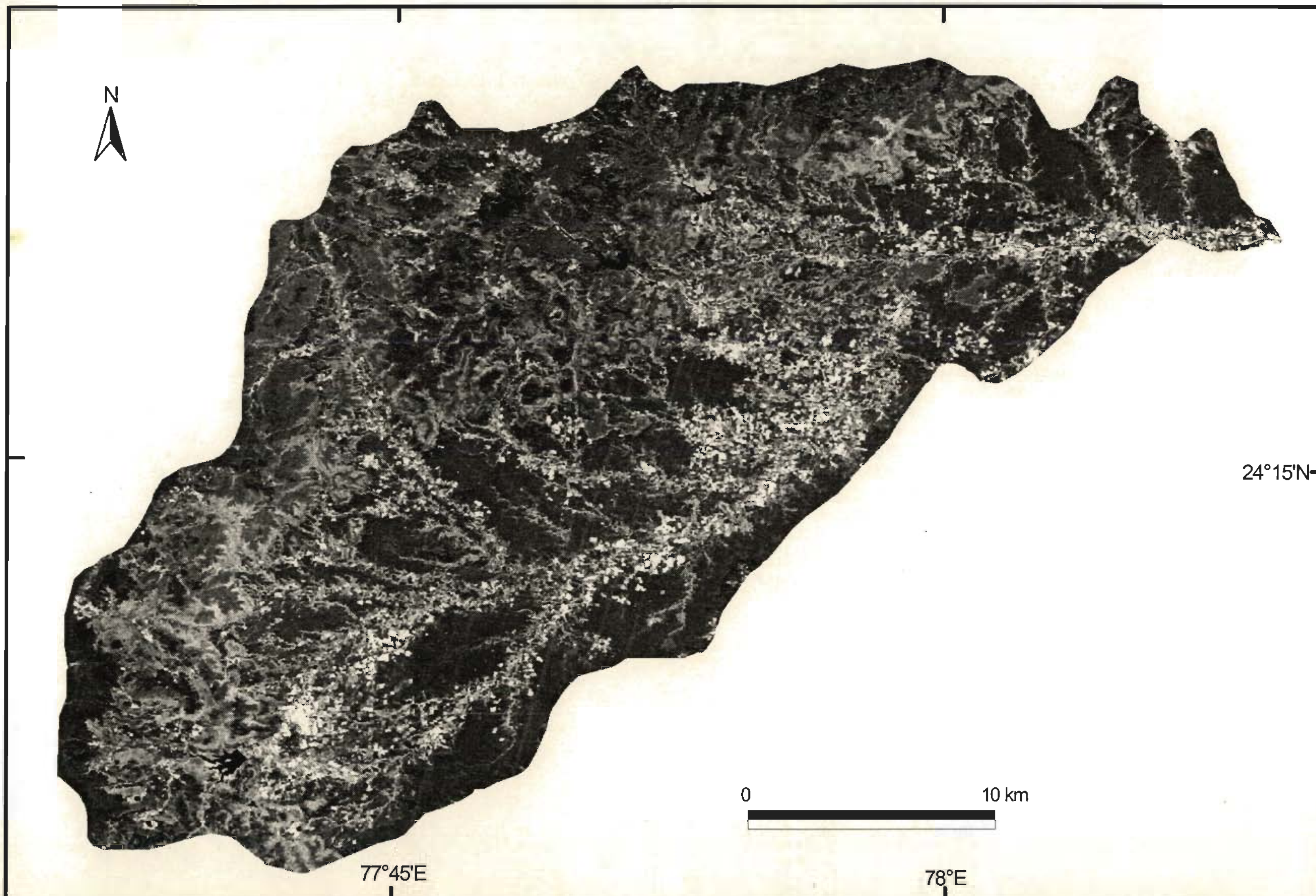


Figure 4.33. Normalized difference vegetation index (NDVI) image of the Kethan basin. The lighter shades indicate dense vegetation, and the darker shades indicate sparse vegetation. Black indicates no vegetation.

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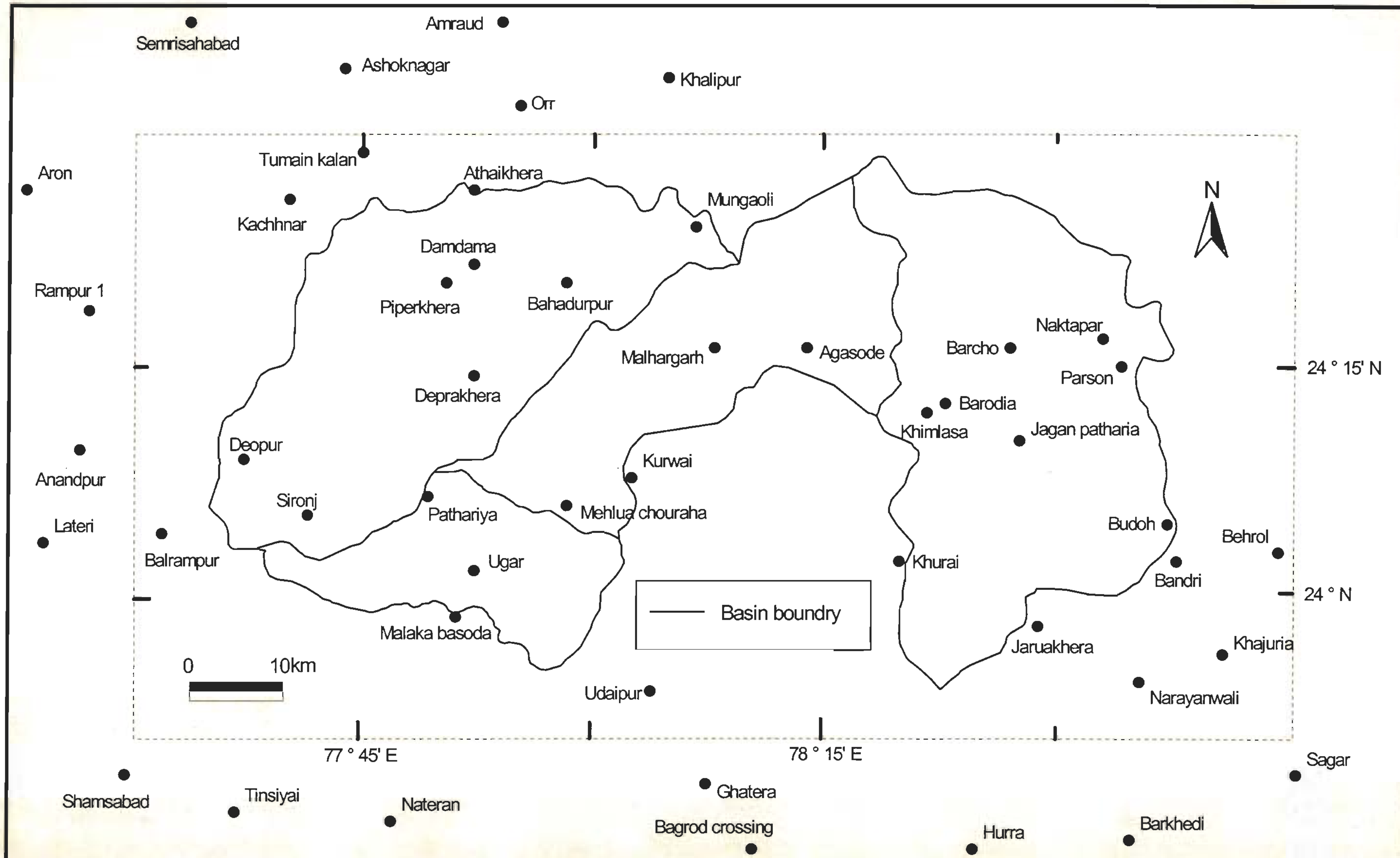

Figure 4.34. Location map of hydrograph network station around the study area.

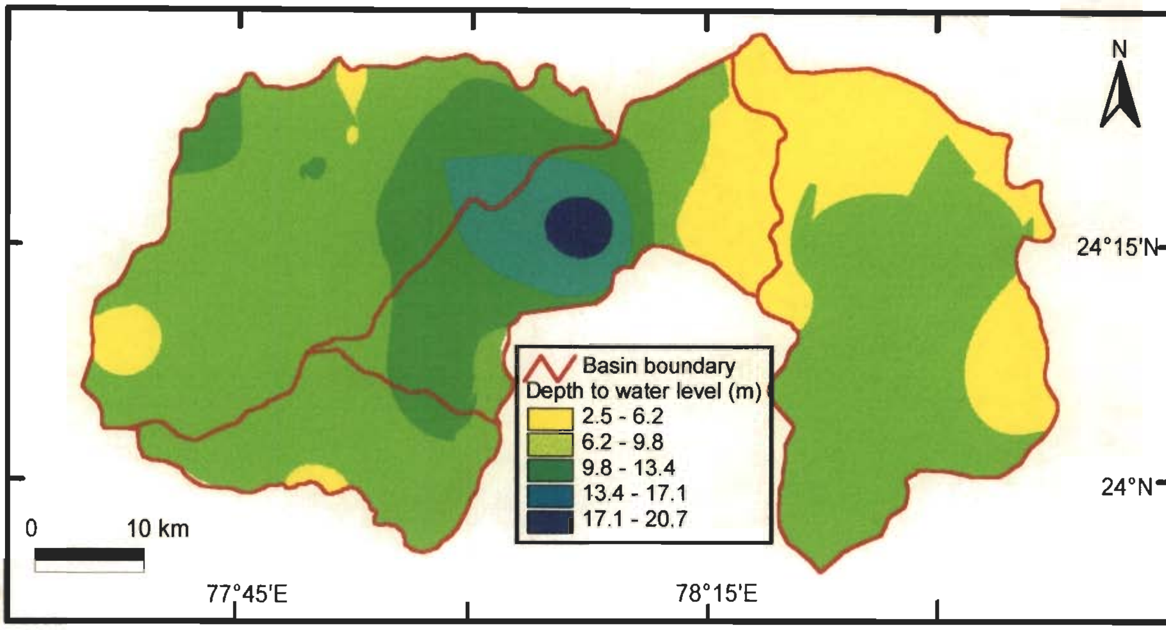

Figure 4.35. Average pre-monsoon depth to water level (m b.g.l.) in the study area. ↑

Can you correlate with reflectance variations on Infrared image/FCC/ NDVI images for correlating the gr.water areas ↓

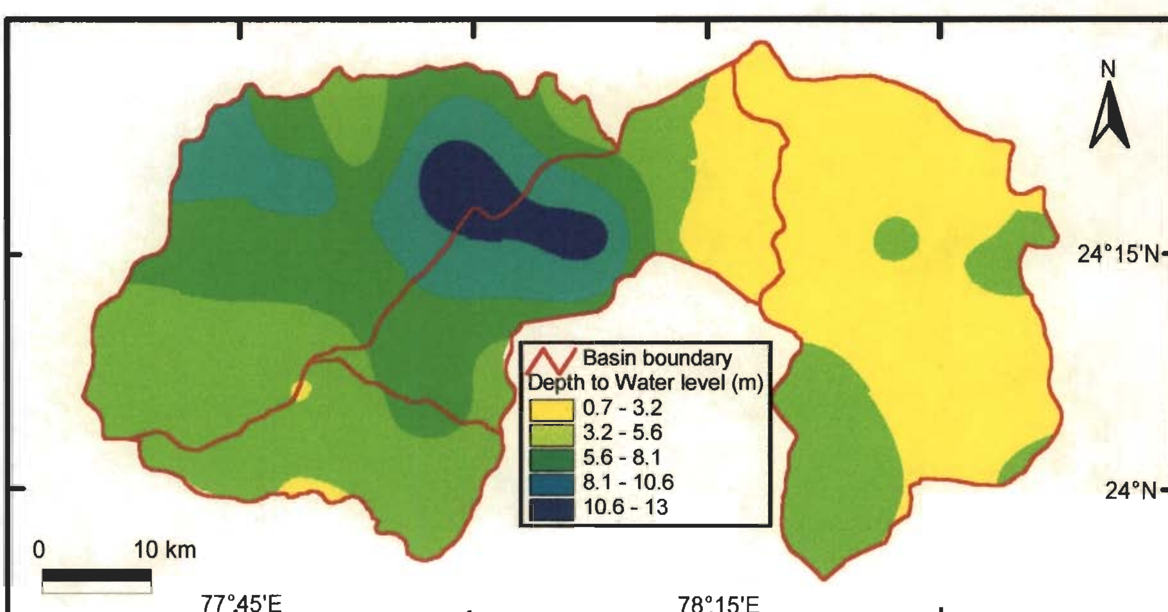

Figure 4.36. Average post-monson depth to water level (m b.g.l.) in the study area.

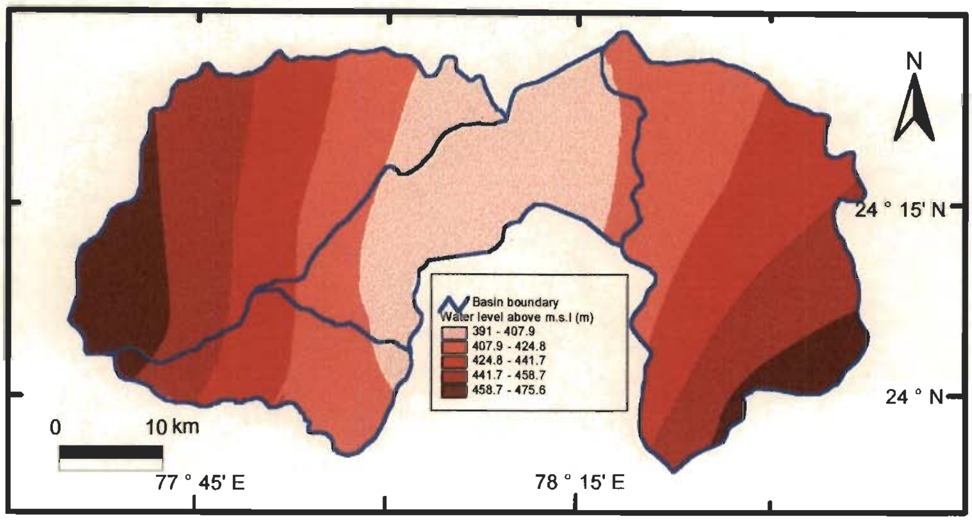

Figure 4.37. Average pre-monsoon water level map of the study area. The hilly parts show shallow water level.

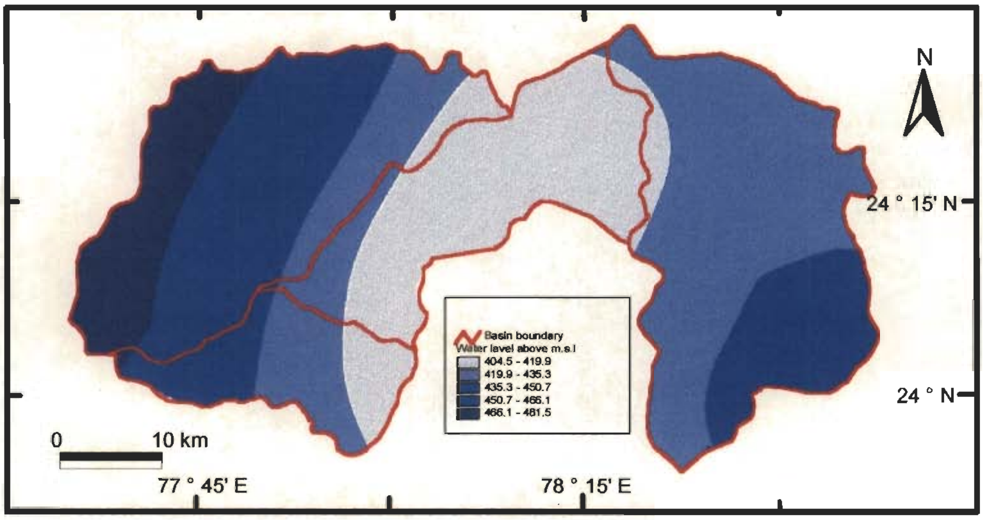

Figure 4.38. Average post-monsoon water level map of the study area.

integrated analysis, as the output is largely dependent on the assignment of appropriate weightages. Consideration of relative importance leads to a better representation of the actual ground situation. There are various methods of determining weightages (United Nations, 1996).

(a) Weightage based on cross-parameter relationship, which is defined for n parameters as per a standard scale of importance - Saaty's scale of importance (Saaty, 1980).

(b) Weightage based on data orthogonalization, where the relationship among the parameters is determined on the basis of statistical analysis of data set by factorial analysis, canonical analysis etc.

(c) Weightage based on census where the weightages are defined subjectively on the basis of consensus of expert views.

(d) Weightage based on instances of parameter where the importance of parameters is defined by the instances of the parameters in a given data set.

Groundwater prospective zones have been demarcated in the Kethan and the Narayan basin. The method used has been sumarised in Figure 4.39. For this, the relative importance of each parameter for groundwater prospective zone mapping has been derived by overlay analysis in GIS.

First of all, the parameter influencing the groundwater occurrence in this area has been identified from overlay analysis in GIS. For the Kethan basin, the following parameters have been considered for weighted overlay analysis for groundwater prospective zone mapping:

a) Geology
b) Geomorphology
c) Lineament density
d) Slope
e) Soil depth

These parameters are assigned with appropriate weightage (Table 4.1) and then the individual classes within each parameter have been given

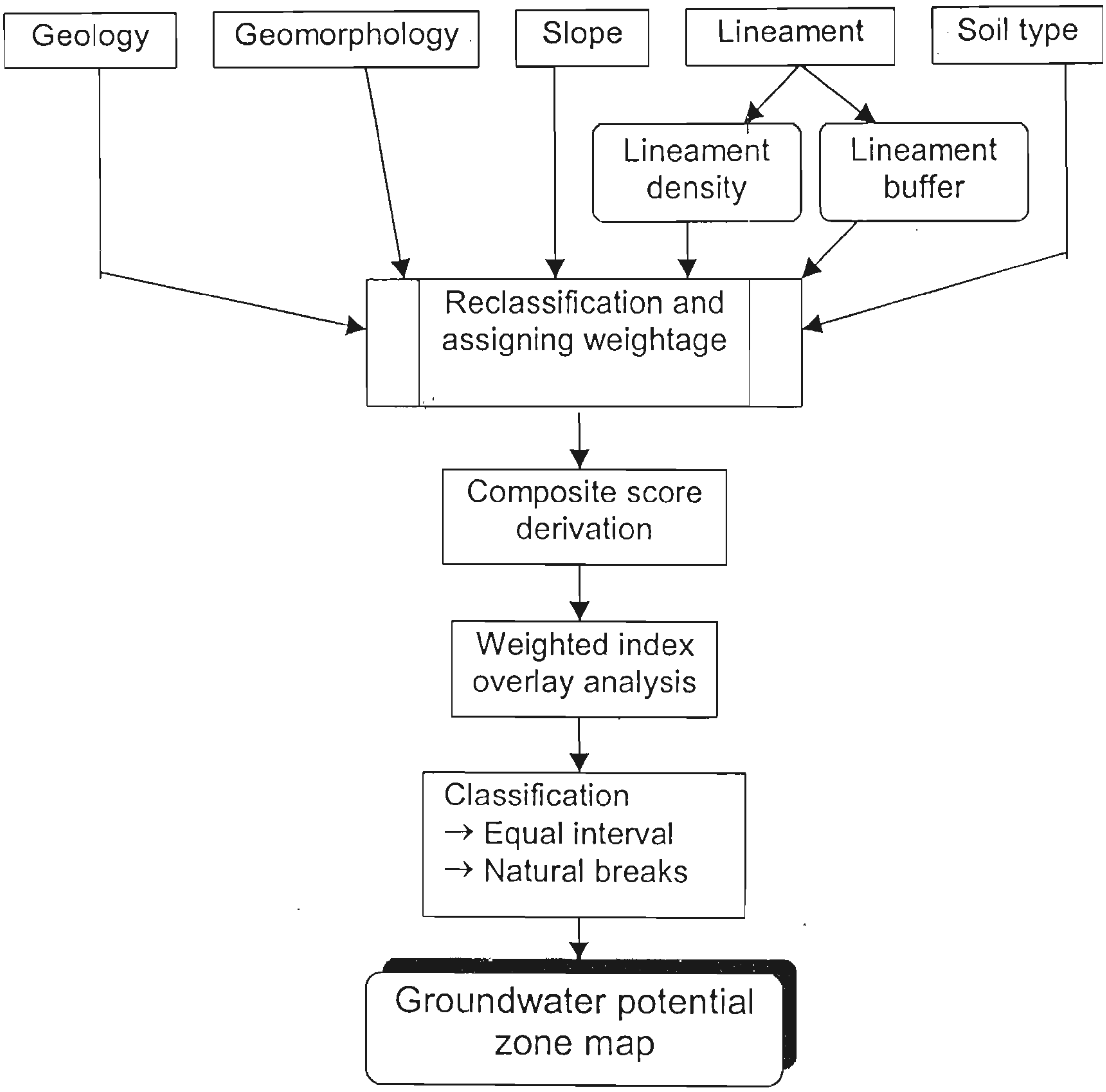

Figure 4.39. Schematic representation of the weighted index overlay analysis to delineate groundwater prospective zones.

weightage. Composite score or index for each pixel has been derived using equation 3.1 (Chapter 3, Section 3.8.2). For generalisation of weightages 0-10 scale has been followed in this study. 0 denotes not suitable and 10 denotes most suitable. These parameter weights are divided by the sum of parameter weights for normalisation. Finally, the composite scores for each map are added and the higher values indicate better groundwater prospect. Soil data were not available for the whole of the Narayan basin. Hence, soil information could not be used. The other parameters (geology, geomorphology, slope and lineament) have been used and assigned with proper weightage (Table 4.2).

Now, for better interpretability, the groundwater prospective zone map has been classified into 5 classes, Different schemes of classification have been tried. Equal interval classes divide the range of values in equal sized sub-range. However, in this case equal interval classes may not represent the actual scenario. There may be more than one class within a short interval of values. Natural breaks method has been found to give a better representation of the grouping and inherent pattern of the data set. This methods identifies the breakpoints between classes using a statistical formula (Jenk's optimization). Basically, this method minimises the sum of variances within each of the classes. The number of natural breaks and the multi-modal appearance of a data set can depend greatly on the number of classes used (Burrough, 1986).

Sl. No.	Parameter	Weightage	Classes	Class weightage
1	Geology	10	Weathered basalt	10
			Unweathered basalt	3
			Vindhyan sandstone	1
2	Geomorphology	9	Channel fill	10
			Alluvial plain	9
			Basalt plateau/hill (Dissected)	2
			Pediment	1
			Basalt plateau/hill	1
			Vindhyan upland	1
3	Lineament density (m / sq. km)	8	2.6-3.2	10
			1.9-2.6	8
			1.3-1.9	6
			0.6-1.3	4
			0.3-0.6	2
			0	0
4	Slope (in degrees)	7	0-2	10
			2-5	8
			5-10	3
			10-15	2
			15-25	1
			>25	0
5	Soil depth (cm)	6	75-100	10
			50-75	5

Table 4.1 Criterion table for groundwater prospects in the Kethan basin.

Sl. No.	Parameter	Weightage	Classes	Class weightage
1	Geology	10	Weathered basalt	10
			Unweathered basalt	3
			Vindhyan sandstone and shale	1
			Lameta bed	2
2	Geomorphology	9	Channel fill	10
			Alluvial plain	7
			Basalt hill	2
			Vindhyan upland	1
3	Slope (in degrees)	8	0-2	10
			2-5	7
			5-10	3
			10-15	2
			15-30	1
			>30	0
4	Distance to lineament (m)	5	20	5
			>20	1

Table 4.2 Criterion table for Groundwater prospects of the Narayan basin.

The groundwater prospective zone map of the Kethan basin shows that the channel fills have the highest priority in groundwater occurrence (Figure 4.40). The alluvial plains rank next, followed by the pediments. The basalt hills have very poor prospect. In the Narayan basin, the hills of basalt and Vindhyan upland in the northeastern part and in the southeastern corner have very poor prospect (Figure 4.41). The basalt hill in the eastern part has moderate prospect. The channel fills along with lineament have good prospect.

4.6 ESTIMATION OF GROUNDWATER RESOURCES

Quantitative assessment of groundwater resources is an important issue in groundwater development. Estimation of groundwater resources requires proper understanding of the recharge and discharge process and their interrelationship with geological, geomorphological, soil, landuse and climatic factors. In 1972 the ministry of Agriculture, Government of India, circulated guidelines for approximate evaluation of groundwater potential. In 1979 the first attempt to estimate groundwater resources on a scientific basis was made by Ground Water Over Exploitation Committee by the Agricultural Refinance and Development Corporation (ARDC). Later, in 1984, the Government of India

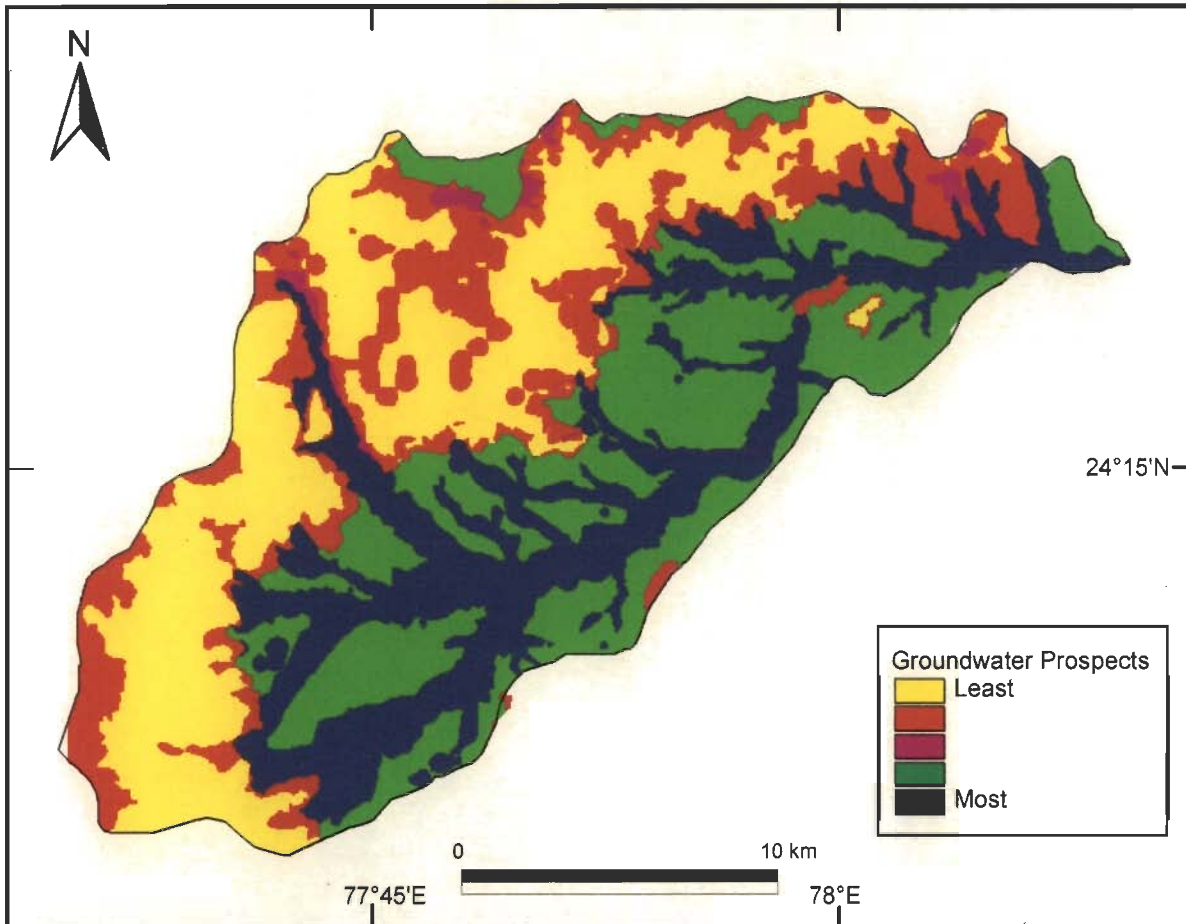

Figure 4.40. Groundwater potential zone map of the Kethan basin, prepared by weighted indexing method applied to the following thematic information layers : (a) geology, (b) geomorphology, (c) slope, (d) soil depth, (e) lineament density. The channel fills represent the most favourable class for groundwater occurrence. The alluvial plains rank next. The basalt hills have poor groundwater potential.

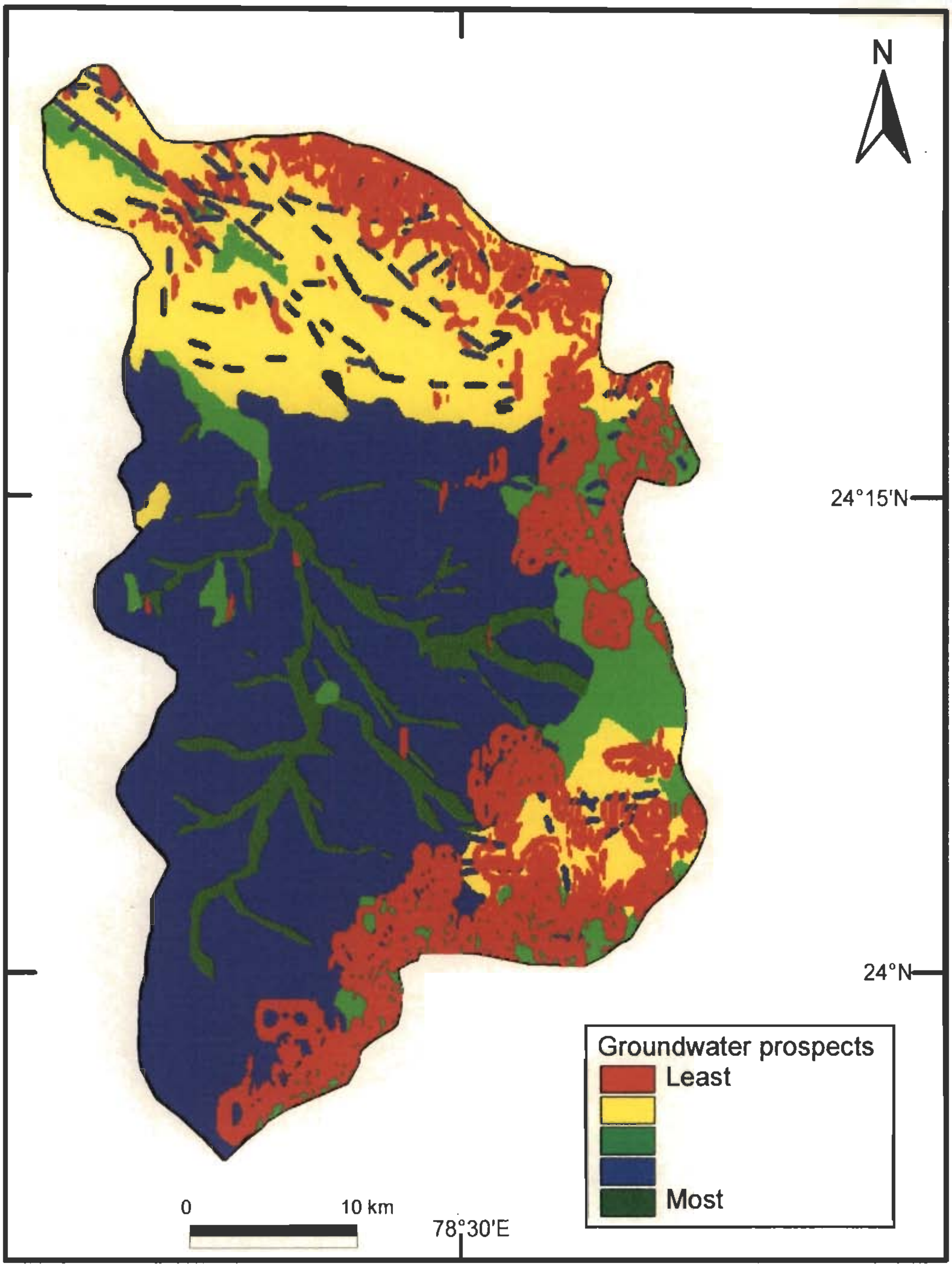

Figure 4.41. Groundwater prospective zone map of the Narayan basin, prepared by weighted indexing method applied to the following themes : (a) geology, (b) geomorphology, (c) slope and (d) lineament. The channel fills hold the highest groundwater potential. The Vindhyan upland and basalt hills have poor potential, except around the lineaments.

formed the Groundwater Estimation Committee (GEC). After reviewing the existing methods. GEC recommended two approaches for groundwater recharge estimation: a) Groundwater level fluctuation and specific yield method and b) Rainfall infiltration method. There are various other methods in use, like the soil moisture balance method.

In the present study, an attempt has been made to estimate recharge in the Kethan basin through soil moisture balance method developed by Thornthwaite and Mather (1957), and by groundwater level fluctuation and specific yield method (Saraf and Jain, 1996). Comparison of the results of the two methods has also been presented.

4.6.1 CONVENTIONAL VIS-A-VIS REMOTE SENSING AND GIS BASED APPROACH

The conventional approach for groundwater resource assessment has some limitations in spite of its simplicity and wide applicability in varied hydrogeological setup. Groundwater resource estimation is traditionally done for an administrative unit like district, block, or taluka that does not necessarily coincide with natural boundary. Groundwater movement is controlled by natural boundaries like valley and ridge. Hence, watershed is the most appropriate unit for groundwater resources evaluation.

In case of rainfall infiltration method or water level fluctuation method average values of rainfall or water level fluctuation is taken for a part of the land. The spatial variability in the components of recharge is not considered. In case of remote sensing and GIS based method spatial distribution of the variables are taken into account, thus preparing an information layer for the whole of a watershed. Further remote sensing data provides most accurate information of the ground, thus minimising fieldwork. Seasonal information is required for estimation of recharge. Remote sensing data of different dates e.g. pre- and post-monsoon can provide information about the cropping pattern and landuse, which influence groundwater recharge.

4.6.2 WATER LEVEL FLUCTUATION METHOD

This is a very simple method for seasonal groundwater recharge estimation. Water level fluctuation due to the monsoon rainfall is considered as the index for groundwater recharge. Difference between post- and pre-monsoon water level gives the water level fluctuation image. In the present area monsoon rain starts by the end of June and continues up to September. Hence, water level data of May and November have been taken and the fluctuation has been computed. Average water level fluctuation of 22 years has been taken and interpolated to give rise to a water level fluctuation image. Values of specific yield for basalt and weathered basalt have been taken as 0.02 and 1 respectively (CGWB, 1984) and for the Vindhyan rocks as 2 (Karanth, 1987). Groundwater recharge image generated in this way gives a rough estimation of dynamic groundwater recharge. Figures 4.42 and 4.43 show groundwater recharge for the year 1976 and 1996 respectively. In 1976, weathered basalt received recharge up to 7.3m whereas in 1996, it was up to 5.3m. The general trend of recharge variation on both the images is similar except for some localised pockets. This may be due to minor variation in rainfall.

However, this method has a serious drawback. Groundwater recharge is dependent not only on the specific yield of the aquifer material but on many other factors like soil properties, geomorphic features, and landuse. This method can not account for the other variables for recharge computation.

4.6.3 THORNTHWAITE AND MATHER MODEL FOR GROUND WATER RECHARGE ESTIMATION

Groundwater recharge is a continuous process and is dependent on many factors e.g. precipitation, topography, runoff, actual evapotranspiration, landuse, depth, and permeability, aquifer material and nature of the stream i.e.

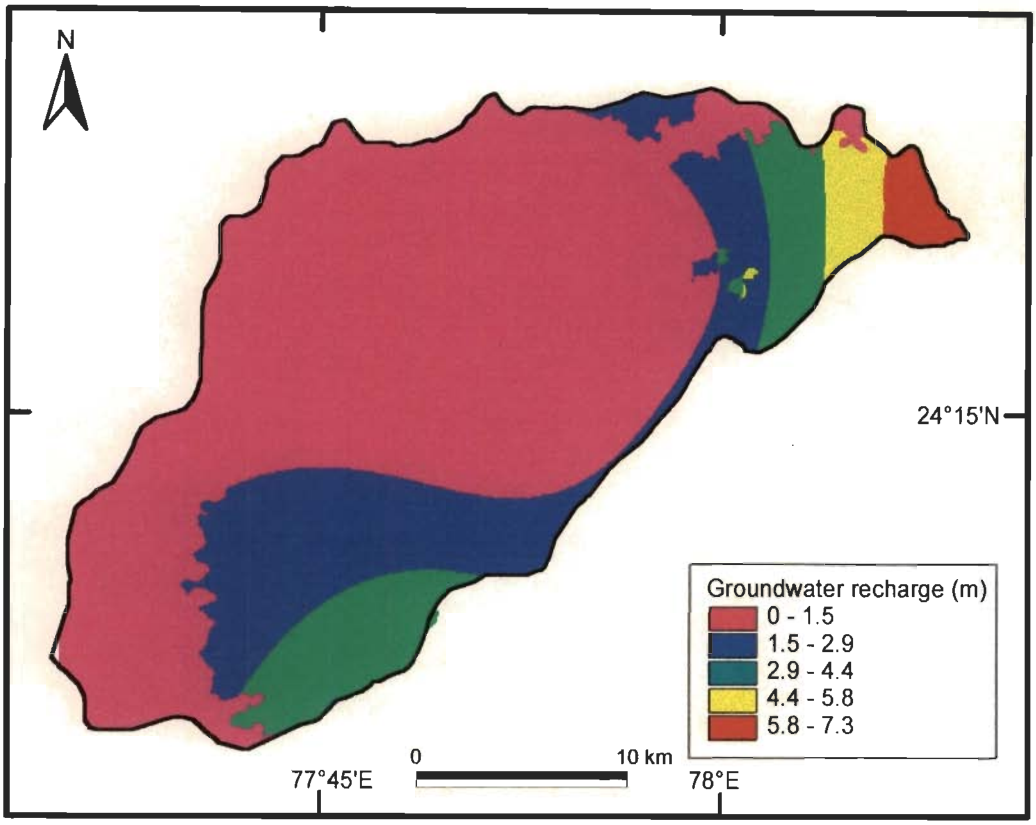

Figure 4.42. Groundwater recharge of the Kethan basin in 1976, computed by water level fluctuation and specific yield method.

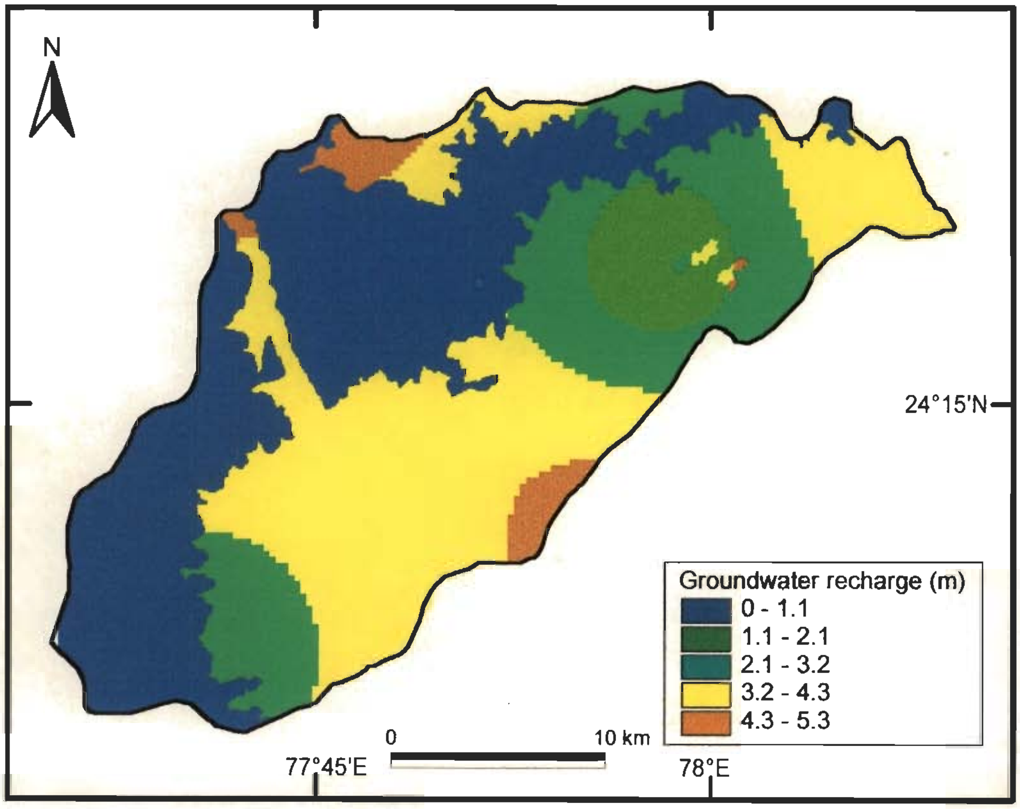

Figure 4.43. Groundwater recharge of the Kethan basin in 1996, computed by water level fluctuation and specific yield method.

influent and effluent. As it is the result of a complex interplay of so many factors, it is very difficult to estimate ground recharge. Many models have been developed in order to address this problem. Models can simulate the natural processes but cannot portray the exact natural ground conditions because models are always simpler representations of nature. Consequently, representation of the natural phenomenon requires some assumptions.

With the advancement of remote sensing and GIS technology, it has become more convenient to compute the lumped parameter models in a semi-distributed method. Remote sensing data provide continuous spatial information of the ground surface. The input parameters for the models can be estimated from remote sensing data supported by ancillary information.

4.6.3.1 The concept

Thornthwaite and Mather (1957) developed this model for groundwater recharge computation. This method is based on simple lumping representation of a continuous natural process. It works on the principle of soil moisture balance, which can be represented as

$$\text{Recharge} = P - AE - SR_{off} \pm \Delta S_m \quad (1)$$

Where, P = Precipitation (rainfall)

AE = Actual evapotranspiration

SR_{off} = Surface runoff

ΔS_m = Change in soil moisture

This model works on the following assumptions: (Joseph, 1993)

a) When rainfall (P) exceeds potential evapotranspiration (PET), then evapotranspiration (AE) equals PET.

b) All the rainfall is assumed to infiltrate till the soil moisture is saturated.

c) During dry periods when PET exceeds P, there is a logarithmic decrease in the water retained in the soil.

d) The soil moisture surplus can not be stored in the soil. Either it flows on the surface as surface water runoff or it seeps down to groundwater.

This lumped parameter model has been used in a GIS environment. This is a compromise between lumped and distributed parameters. Van Deursen and Kwadijk (1993), to estimate soil storage in river Rhine on a monthly basis, used this model. Meijerink et al (1994) have estimated groundwater recharge using this model in a GIS environment in a catchment in Bandung basin (Indonesia). The following data sets are required for the model calculation:

(a) Rainfall

(b) Actual Evapotranspiration

(c) Field capacity of the soil

4.6.3.2 Generation of the input data layers

Rainfall map

Monthly rainfall data were available for 20 years (1976-1996) from 5 meteorological stations in the vicinity of the present area. Rainfall maps for each month in a year have been generated by inverse distance weighting interpolation method. Kriging method could not be used as the density of the data points is low and kriging gives abnormal results in this case.

Evapotranspiration

Actual evapotranspiration data were available for only one station (Bhopal) which is outside the study area. Using this value in the model calculation has led to overestimation. This is probably due to the fact that the average temperature in Bhopal is higher than the present area. Potential evapotranspiration (PET) data from seven stations were available in the neighbouring area. These data have been interpolated using inverse distance weighting method to prepare potential evapotranspiration map. As mentioned in section 4 6.3.1. Actual evapotranspiration is assumed to be the entire potential rate when rainfall is greater than PET.

Direct surface runoff coefficient

In this area rainfall distribution over 20 years shows a uniform pattern.

The rainfall generally increases from the northern to the southern parts. A fixed value of runoff coefficient as 0.23, calculated on the basis of long term rainfall and runoff relationship (CGWB, 1984) has been used for the entire basin to compute runoff. It is assumed that a fixed percentage of rainfall flows down as runoff.

Water holding capacity

Soil moisture storage depends on soil texture, type of plant and moisture availability. Certain species of plants have deeper root systems and can store more water in the soil zone. In the soil map available, water capacity (AWC) values have been added to each polygon and AWC map has been prepared (Figure 4.44a). Rooting depth has been assigned to each class of the landuse map (Figure 4.44b). Finally, field capacity or water holding capacity (WHC) map has been obtained through the following relation (Figure 4.44c):

WHC (mm) = AWC/(mm/m) * Rooting depth (m) (2)

In the present area, wheat is the most common crop. Hence, rooting depth value of wheat has been generalised for the agriculture area and taken as 0.90 m (Karanth, 1987). The values for forest and scrub have been taken from Schultz (1993b) (Table 4.3).

Type	Rooting depth (m)
Forest	1.25
Scrub	0.45
Crop land	0.90

Table 4.3. Rooting depth for different landuse classes.

4.6.3.3 Model Calculations

As soil moisture storage data were not available, a convenient month, when soil is at water holding capacity (WHC), has been chosen to start the calculation. WHC is the maximum amount of water a soil can hold against the force of gravity. In the present area, at the onset of monsoon in June, water quickly resaturates the soil through the tension cracks that develop in black cotton soil as it loses water during the dry season. Due to these cracks the soil becomes a highly permeable stratum (Herbert et al. 1981). It has been assumed that, in July, soil is at its water holding capacity and hence July has been taken as the starting month.

There are two different situations in this calculation:

(a) When P-PET is positive.

In this case it has been assumed that a fixed percentage (c) of the rainfall will flow as surface runoff (SR_{off}). Surface runoff has been computed as:

$$SR_{off}=P*C \qquad (3)$$

Now, separating the outflow component (AE and SR_{off}) from the rainfall, the water available for percolation into the soil zone is given by:

$$SRech=P - AET - SR_{off} \qquad (4)$$

where AE is assumed to be equal to PET.

Now, a part of this will be added to the soil moisture storage (SM) and the rest will contribute to groundwater. In July, soil is at its water holding capacity. Hence, in July,

SM=WHC.

For the successive months,

$$SM_i = SM_{(i-1)} + SRech_{(i)} \qquad (5)$$

After the soil moisture reaches WHC, the remaining part of SRech will seep to groundwater.

$$GRech=SRech - (WHC-SM) \qquad (6)$$

When GRech>0, water is added to the groundwater store (GWS). A fixed part of the GRech joins the ground water runoff (GR_{off}) in the same month. The remaining part is detained in the groundwater storage and acts as groundwater recharge (GWR) for separation of rapid and delayed groundwater runoff from GRech, fixed value of 0.2 has been used (Van Deursen and Kwadijk, 1993;

Meijerink et al. 1994). Thus,

$$GWS = GRech + GWS_{(i-1)} \quad (7)$$

Then $GRO = GWS_i * C1$ where $C1 = 0.2$ (8)

$$GWR + GWS_i - GRO \quad (9)$$

(b) When P-PET is negative, SRech is negative.

Rainfall, then, can not meet the demands for AE and water is withdrawn from soil moisture, resulting into exponential soil moisture depletion. The soil moisture is given as:

$$SM = WHC * Exp(APWL/WHC),$$

where APWL is the accumulated potential water loss which describes the accumulated water shortage for a month.

APWL is zero for the month having surplus water (SRech>0). If the month (i-1) with surplus water is followed by month (i) with a deficit, a starting APWL value is calculated as (Meijerink et al. 1994):

$$APWL_{(i-1)} - -WHC * Ln(SM_{(i-1)}/WHC) \quad (10)$$

For the subsequent months, APWL is calculated as:

$$APWL = APWL_{(i-1)} + SRech_{(i)} \quad (11)$$

In the present area, from October up to May, P-PET is negative. Accordingly, APWL has been calculated for these months.

4.6.3.4 Results

Groundwater recharge estimated through this model shows that recharge takes place only in the monsoon months in this area. The highest recharge takes place in September. It has been observed that the recharge is highest in the channel fills (Figure 4.45). Some parts of the basalt hills covered by scrubs also receive good recharge. The maximum recharge is 350 mm. In this area, base flow measurement data were not available, hence, the model result could not be verified with the field data. However, the total runoff has been compared with the average annual runoff calculated from long term records (CGWB, 1984), which is 168 mm. The model calculation shows a total runoff value of 190 mm.

Comparison of recharge map generated by this model with the water level fluctuation method shows that in the weathered basalt the latter gives a very high recharge value compared to the former. This can be explained by the fact that the specific yield of the weathered basalt, as well as the water level fluctuations, are quite high in this area.

This method for recharge estimation has some limitations. The use of potential evapotranspiration data in place of actual evapotranspiration data may lead to incorrect results. The variability of runoff with respect to landuse has not been considered. However, the model recharge areas match with the areas showing misfit in the surveyed drainage and the drainage simulated from the DEM.

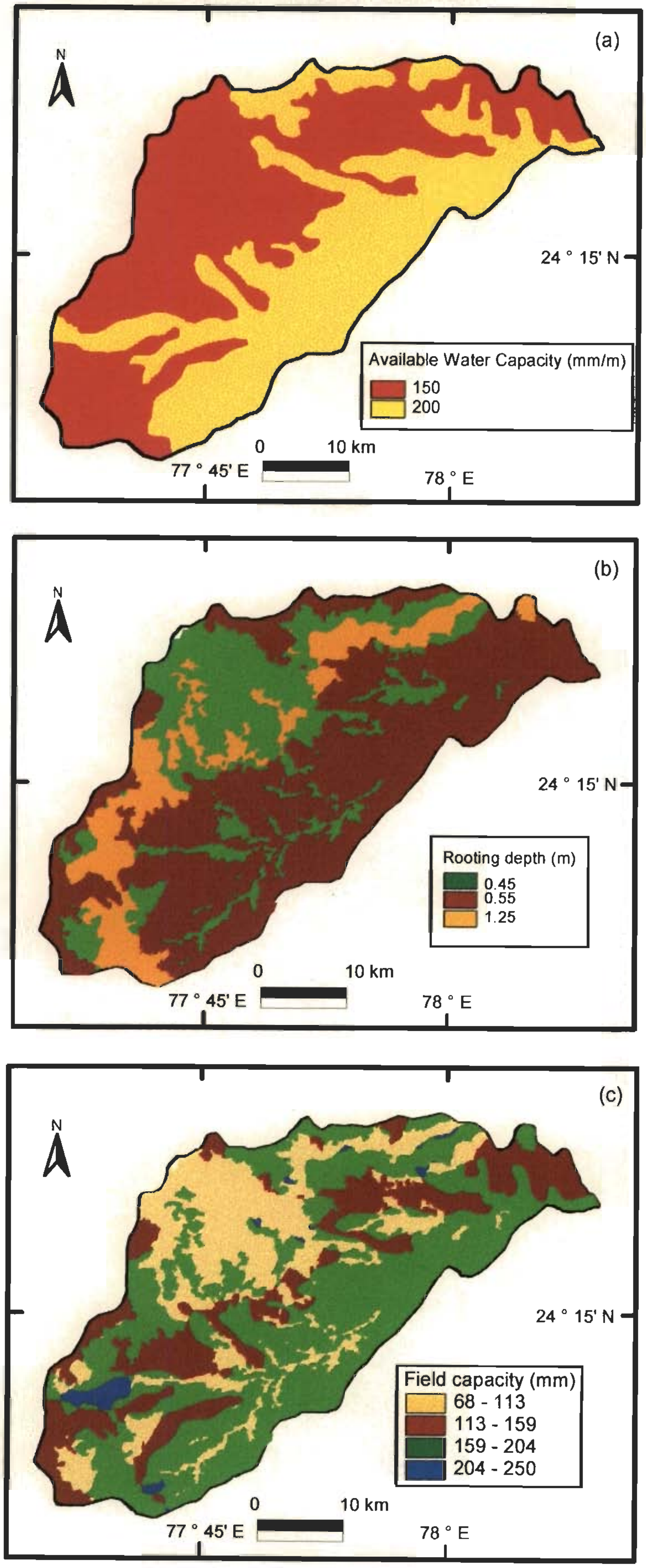

Figure 4.44. (a) Available water capacity of the soil, (b) rooting depth of different vegetation types and (c) field capacity (water holding capacity) of the soil in the Kethan basin.

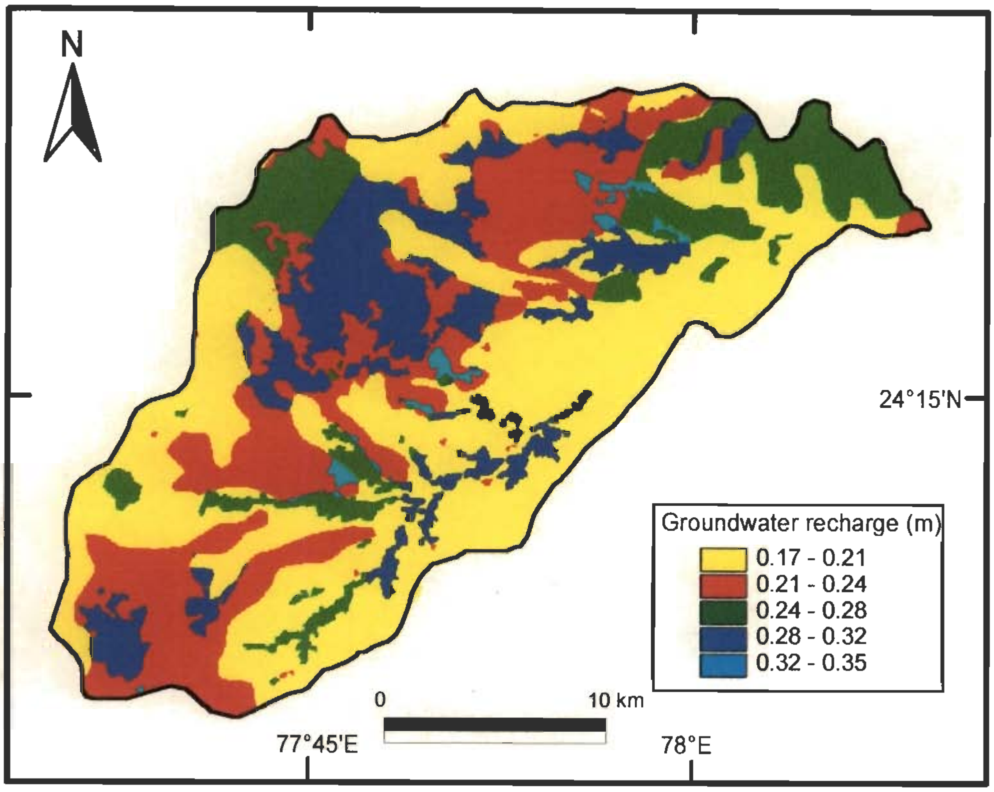

Figure 4.45. Groundwater recharge of the Kethan basin in 1976 as computed by Thornthwaite Mather model. The zones showing higher values of recharge are covered by channel fills. The agricultural lands show poor recharge whereas the scrubs show good recharge.

↓

Do the recharge zones correlate with reflectance zones on images?

CHAPTER 5

ARTIFICIAL RECHARGE

5.0 INTRODUCTION

Artificial recharge is the process by which infiltration of surface water into the groundwater storage is enhanced by artificial means. This is accomplished by constructing infiltration facilities or by inducing recharge from surface water bodies. In hard rock areas, the underlying lithounits do not have sufficient porosity and permeability. In these areas, groundwater recharge exceeds groundwater draft and, hence, groundwater can not suffice the requirement for agriculture or drinking water. Thus, additional recharge by artificial methods becomes necessary to meet the water deficit.

Water is a precious resource and, especially in a hard rock terrain, each drop of rain water is to be conserved for future use. At the present rate of consumption and the present status of groundwater development, the country would be in the grip of acute water crisis in 25 years (Pachauri and Sridharan, 1998). In many areas, groundwater exploitation exceeds recharge, leading to depletion of the water table. This situation calls for a serious consideration for artificial recharge to meet the ever-increasing demand of water. In India, artificial recharge measures are taken in the vast hard rock terrains, mostly in Maharashtra and south India. Many farmers carry out rainwater harvesting by percolation tanks and contour bunding on the streams known as *'bandhara'*. Efforts are being generated at the individual level to store water; a carpenter in Jaisalmer, Rajasthan digs *'bedis'* (narrow deep wells in stone) lined with Gypsum to draw sweet water in the Thar desert; farmers from Kerala dig *'surangam'* (underground tunnel) in the hard rock regions of Kerala, which collects water and retains throughout the year (Kanungo, 1999). The performance of these efforts can be immensely increased if they are performed through proper scientific planning. Integrated remote sensing and GIS can be a very powerful tool for planning of suitability for artificial recharge structures. However, this powerful tool has not attained wide applications for this purpose till now in India. This chapter demonstrates remote sensing and GIS techniques to suggest suitable locations for future artificial recharge structures in the Kethan and the Narayan basins by studying the existing artificial recharge systems.

5.1 SCOPE OF THE WORK

In the present area, average annual rainfall is about 1040 mm. Most of the rainfall is contributed in the monsoon months starting from end of June up to September. Groundwater recharge takes place only during this period through fractured parts of basalt and the channel fills (discussed in Chapter 4). The monsoon recharge cannot meet the demands of agriculture and drinking water till the end of the dry season. Most of the dug wells/ tube wells go dry in the month of May. Depth to water level goes down to 13m b.g.l. in some wells e.g. Bahadurpur. Generally, the pre-monsoon depth to water level ranges from 8 m to 12 m. Artificial recharge measures can appreciably improve the groundwater condition within a short time.

There are 4 medium sized reservoirs in the area along with a number of small reservoirs (Figure 5.1). Remote sensing data reveal that all reservoirs are augmenting groundwater recharge of varying quantity in the area, which is visualized by the growth of dry season vegetation downstream the reservoirs. Based on this observation, a study has been undertaken to suggest suitable location of artificial recharge structures for the augmentation of groundwater recharge. This combined tool of remote sensing and GIS is found to be very useful in this study. The site selection is purely based on hydrogeological point of view, the engineering aspects are not considered here.

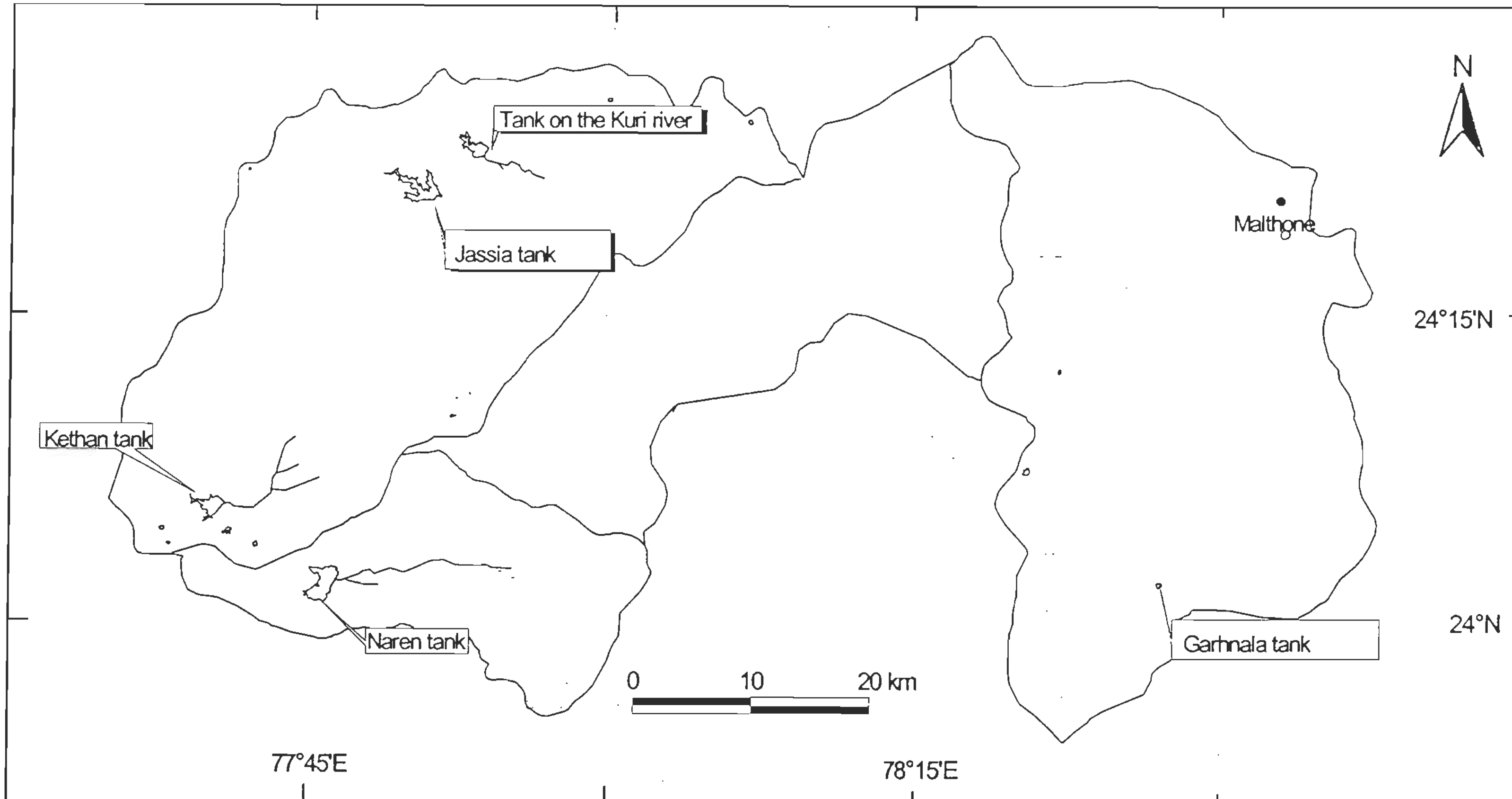

Figure 5.1. The location of the irrigation tanks and canal in the study area. The canals of the Jassia tank and the tank on the Kuri river are mostly dry as seen on the remote sensing images.

In this chapter, an attempt has been made to develop an integrated remote sensing and GIS based methodology for suitable site selection for artificial recharge structures. The main objectives are:

(a) to have an understanding of performance of the existing reservoirs in relation to their hydrogeologic conditions.

(b) to demarcate the suitable zones for artificial recharge structures

(c) to suggest suitable sites with specific methods with GIS analysis functions.

5.2 METHODOLOGY

In this chapter suitable sites for artificial recharge have been suggested using a combination of weighted index overlay analysis and Boolean logic analysis. With the spatial database already built up, some other information layers are generated through GIS operations.

The following steps, as shown in Figure 5.2, have been followed:

(a) IRS-LISS-II and LISS-III data supported by DEM, geology, geomorphology, lineament etc. have been studied to identify the areas of artificial recharge from the existing structures.

(b) The criterion for the suitability of recharge has been identified and the information layers have been assigned with weightage on the basis of their relative contribution in influencing artificial recharge. Each class of individual information layers has been assigned weightage as well as the class itself.

(c) Weighted index overlay analysis has been performed in order to demarcate the zones of suitability for artificial recharge.

(d) Boolean logic analysis has been performed to suggest the artificial recharge sites.

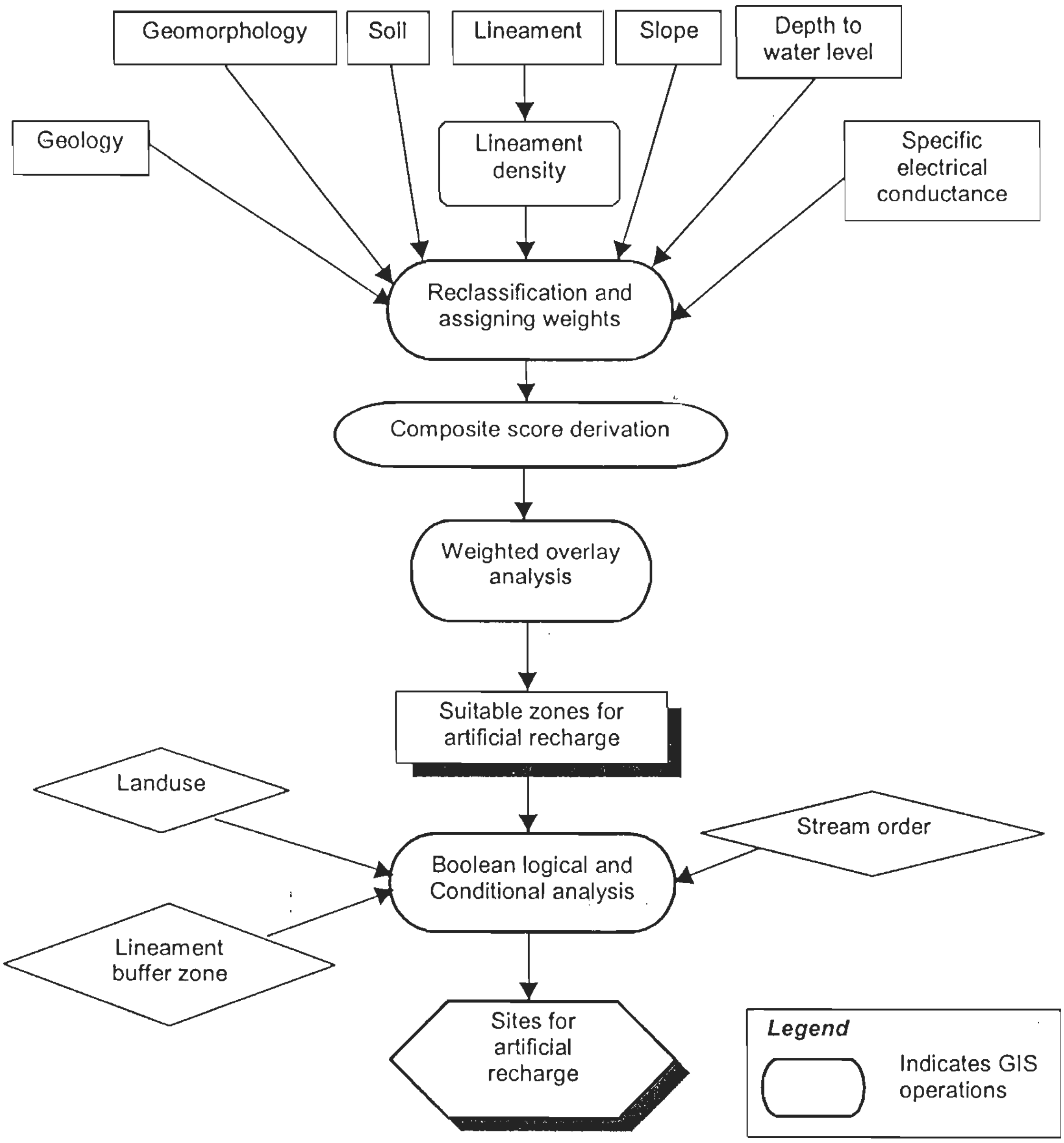

Figure 5.2 Flowchart of steps for weighted indexing method and Boolean logic model for identification of artificial recharge sites.

5.3 ARTIFICIAL RECHARGE METHODS

Various methods are in use for artificial recharge (Table 5.1). Detailed discussion can be found in Karanth (1987). A brief description of the surface methods is given below:

1 Direct methods Surface spread techniques (1) Flooding; (2) Ditch and furrows; (3) Recharge basin (4) Run-off conservation structures (i) Gully plugs; (ii) Bench terracing; (iii) Contour bund; (iv) Nala bund; (v) Percolation tank; (vi) Individual well recharge (5) Stream modification; (6) Surface irrigation Sub-surface techniques (1) Injection wells; (2) Gravity head recharge wells; (3) Aquifer Storage and Retrieval (ASR); (4) Soil Aquifer Treatment (SAT) **2. Indirect methods** Induced Recharge (1) Pumping wells; (2) Collector wells; (3) Infiltration gallery Aquifer Modification (1) Bore blasting; (2) Hydrofracturing **3. Combination methods** Groundwater conservation structures (1) Groundwater dams, underground bandharas (percolation tanks); (2) Fracture Sealing Cementation techniques (FSC).

Table 5.1 Different categories of artificial recharge methods (after Raju, 1998)

Phadtare (1989), Sinha and Sharma (1990) have discussed the criteria for site selection of these structures in the Indian context.

5.3.1 DIRECT METHOD

Among the direct methods, spreading method is the most widely used method in India. It comprises increasing the surface area of infiltration, thereby increasing the detention time of storage water. Water is either collected in a basin or allowed to flow through natural or artificial channels or the ground surface. It facilitates recharge to the phreatic aquifers and semi-confined aquifers that are in hydraulic connection with phreatic aquifers.

Recharge Basin/Ponds/Percolation Tank

Recharge basins collect surface runoff from rainfall. The size of the basin depends on the slope of the land surface. Small reservoirs (percolation tank) are very common in hard rock areas in India. An influent stream, where the water table contour slopes towards the downstream direction, is the ideal site for a percolation tank, as the recharged water keeps moving away from the recharge site, thus constantly providing space for additional recharge.

Ditch and furrow method

Water is allowed to move through shallow flat bottomed, closely spaced ditches provided with sufficient gradient to prevent silt deposition. The ditches take water at an upstream point and return the surplus water to the stream at a downstream point. Commonly used ditch systems are lateral and dendritic. The lateral type consists of a series of subparallel furrows and the dendritic type comprises benching of the main flow into a dendritic pattern through ditches.

Channel method

This method involves widening, leveling and lengthening of stream channels, and increasing the time and area of contact with water. Constructing check dams or *bund* of small height, so that water spills from one to the other, increases width of the flow. Lengthening of flow channel is done by erecting dykes from either bank, extending to about three-fourth of the distance across the stream channel, thus forcing the flow to take a sinuous course.

Sub-surface dykes are constructed in hard areas in narrow, gently sloping valleys where bed-rock occurs at shallow depth and valley consists of 4-8 m of pervious material.

Recharge well

Water is directly fed into the aquifer through recharge well. It is suitable in an area where there is an impervious layer hindering the flow in the zone of aeration or the aquifer is confined.

5.4 EXISTING RESERVOIRS IN THE AREA

In order to understand the artificial recharge phenomena in the study area, it is critical to study the existing reservoirs and their contribution in enhancement of the groundwater recharge process. There are four medium sized reservoirs in the area (Figure 5.1) of which three are in the Kethan basin. The Kethan tank is situated on the Kethan river near Sironj. The Jassia dam is constructed on the Koncha river near Jassia. Another tank is situated on the Kuri river near Damdama. The Naren tank is constructed on the Naren river near the Azamnagar village. There are few small tanks spread over the area. In the Narayan basin, there are four small tanks, one is near the Malthone, one near Balabahat town, and one near Khimlasa and the Garhnala tank is in the upper reaches of the Narayan river near Garhnala. The details of the medium size tank are furnished below (Table 5.2).

	Name	Scheme started	Scheme completed	Culturable command area (km^2)
1.	Kethan tank	1973	1986	31.67
2.	Jassia tank	1963	Ongoing	48.83
3.	Naren tank	1979	1992	41.16
4.	Tank on Kuri River (Maula tank)	1955	1962	Data not available

Table 5.2 Details of medium size reservoirs in the study area.

IRS-LISS-II and LISS-III data (Figures 5.3, 5.4 & 5.5) have been used to study the hydrogeomorphic conditions around the reservoirs. The most interesting feature noticed on the FCC generated from LISS-II data of 27th February, 1995 (bands 4,3,2 in RGB) is the good vegetation growth downstream the reservoir (Figure 5.3). The channel fills support prolific vegetation where there is a reservoir/tank across the stream. In the remaining parts, vegetation is

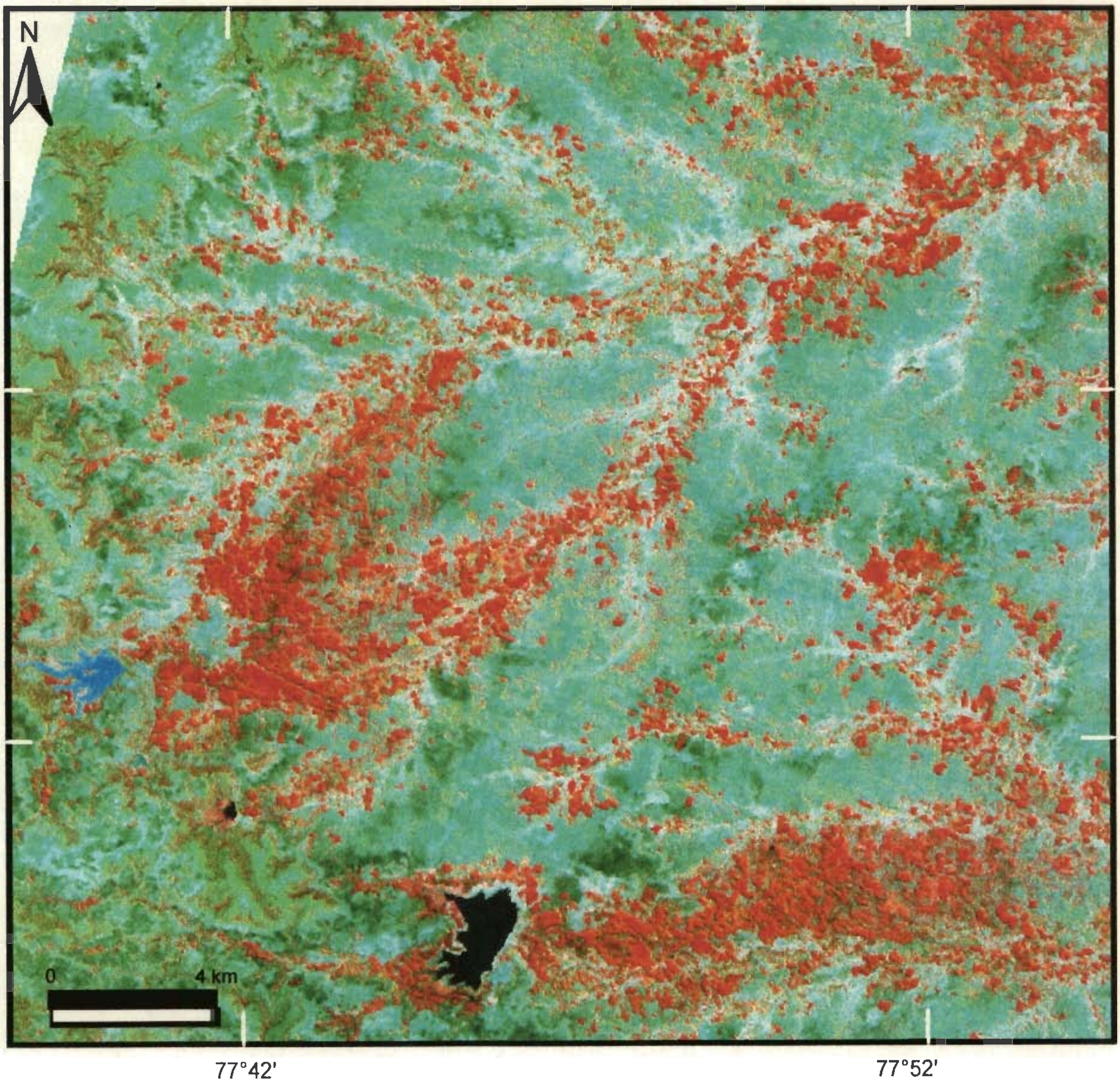

Figure 5.3. IRS - LISS - II FCC (bands 4,3,2 in RGB) of 27th February 1995. This image shows the anamolous vegetation growth downstream the Kethan and the Naren tank. This clearly indicates that these tanks are augmenting groundwater recharge in the area.

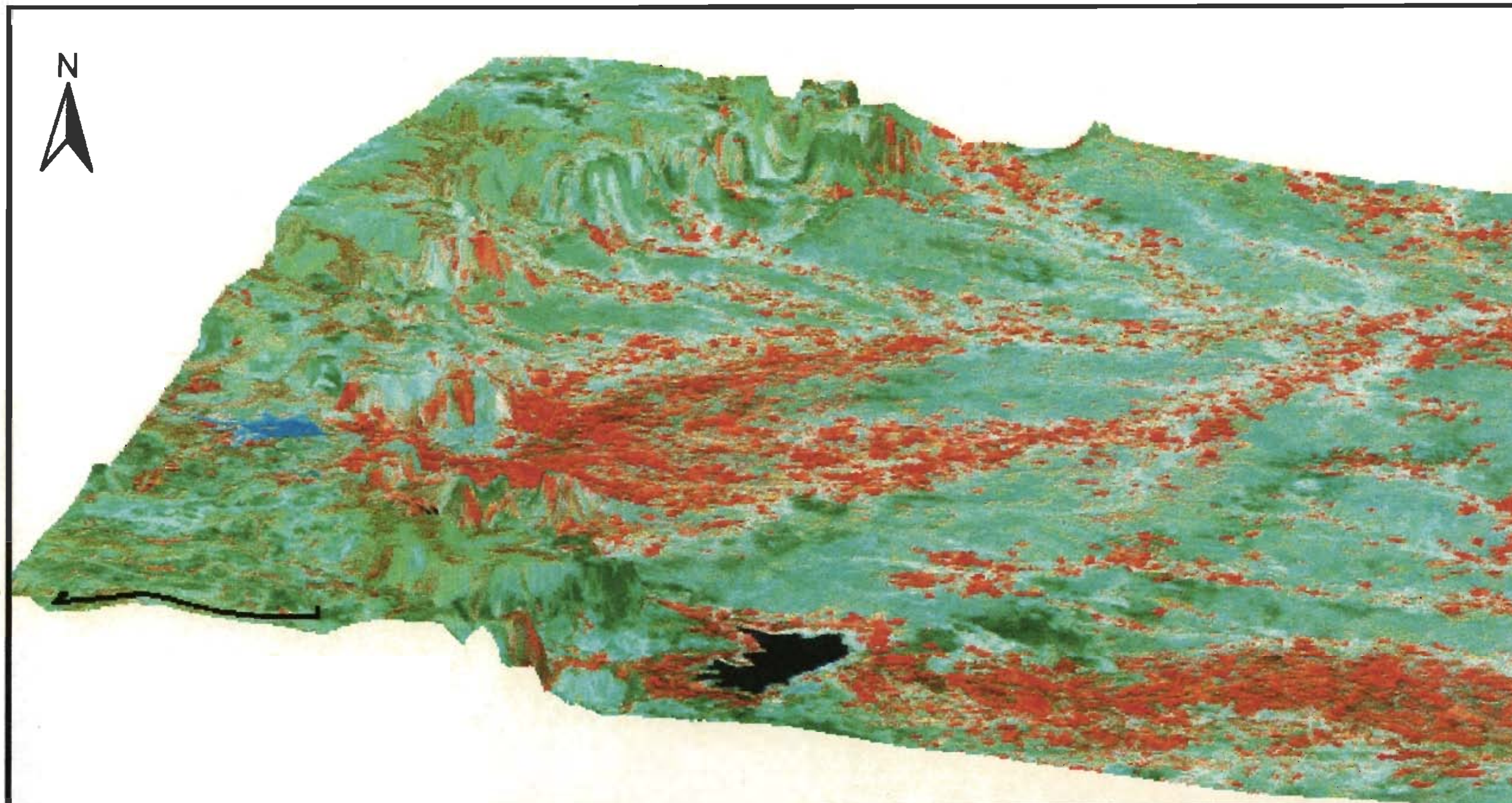

Figure 5.4. 3D - perspective view of the area covering the Kethan and Naren tank. The higher topographic location of the Kethan tank followed by a gentle slope downstream provide a better groundwater recharge. Though the size and extent of the Kethan tank is smaller than the Naren tank, it provides recharge to a larger area. The Naren tank, inspite of being larger in size provides recharge to smaller area because it is situated in an almost flat area where the hydraulic gradient is very low.

only slope/gradient can decide your inference?

Permeability? (Directional)

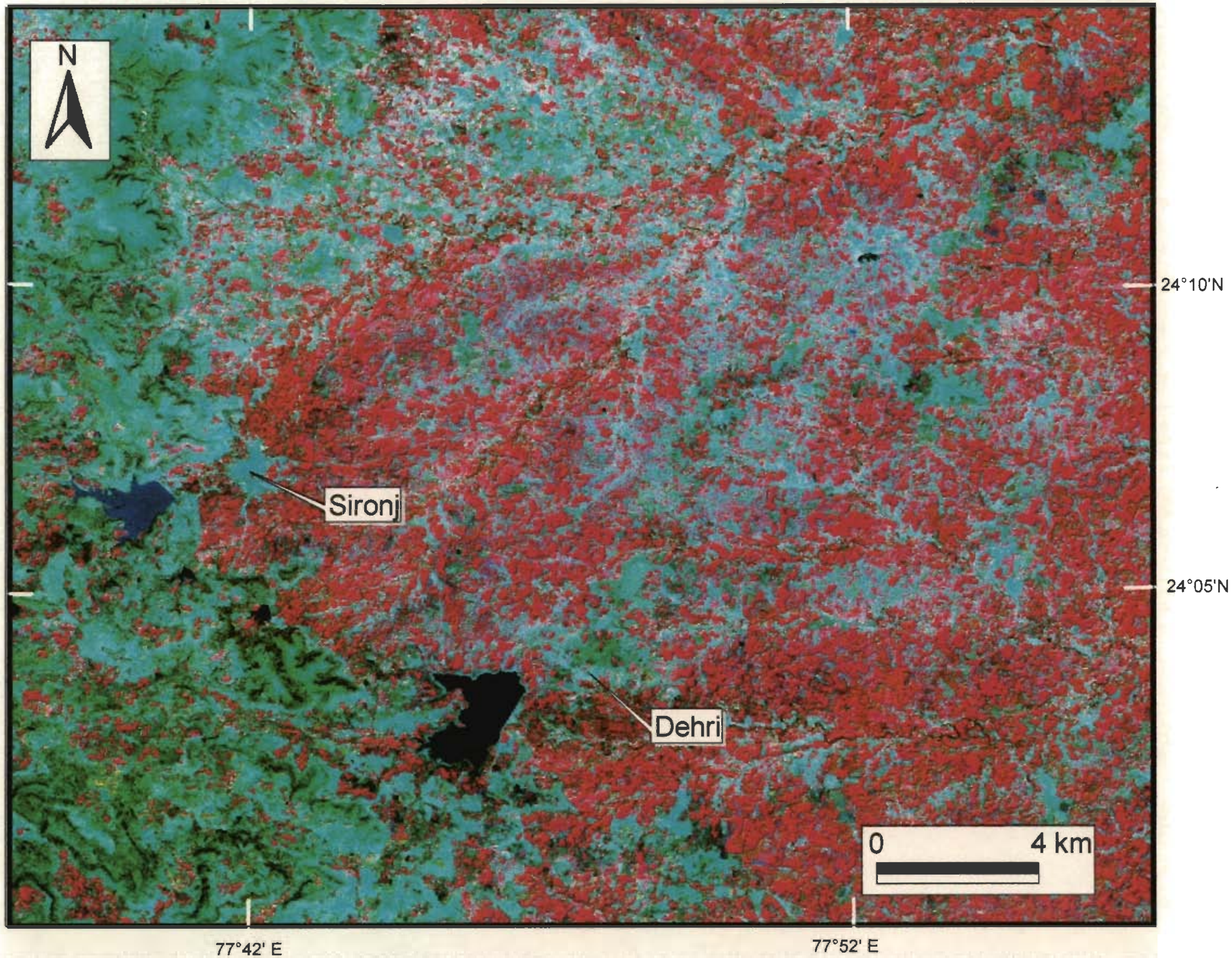

Figure 5.5. IRS - LISS - III FCC of 20th February, 1998, showing the area near the Kethan and the Naren tank. The dark green patches indicate yellow clay layers. One such layer is noticed in the Dehri village near the Naren tank. This is probably obstracting seepage into the zone of aeration.

only sporadic or even totally absent. The dry season vegetation is a possible indicator of groundwater.

By the end of February, harvesting of crops starts in this area. Thus, it can be inferred that these tanks are augmenting groundwater recharge to the shallow aquifer (Saraf and Choudhury, 1997; 1998). All the tanks are contributing to the recharge. The areal extent of recharge is different due to the difference in size, capacity of the tanks and the hydrogeological conditions of the area. The effective area receiving recharge from the larger reservoirs is 8-10 km^2, depending on the catchment area of the stream, whereas smaller tanks affect an area of about 1-2 km^2.

The recharging capability of these tanks depends on many factors, namely, porosity and permeability of rocks, topography, soil properties, structural features and landuse of the surrounding areas. GIS overlay analysis helps to understand the inter-relationship of all these factors in controlling the performance of the tanks. These factors are investigated and inferred from integrated modeling through remote sensing images and GIS database.

Although the Kethan tank is smaller in area (2.8 km^2) as compared to the Naren tank (5.3 km^2), the areal extent of the recharge provided by the former is larger than the latter (Figure 5.3). This is due to the favourable topographic location of the Kethan tank. Overlay of the reservoir with the DEM reveals that this tank is situated in between a narrow valley bounded by two hills or plateau over a gentle slope. 3D-perspective view prepared by draping the FCC on the DEM makes the situation more clear (Figure 5.4). The gentle slope provides sufficient hydraulic gradient to maintain the rate of groundwater movement as well as to check runoff. The Naren reservoir is situated in an almost flat area, thus providing less hydraulic gradient.

The Jassia tank has a larger catchment area of 133 km^2 and the culturable command area is 48.83 km^2. It was designed to irrigate an area of 37.64 km^2. The tank on the Kuri River provides less recharge in comparison to the Jassia tank. Sparse vegetation is visible in the valley fills (Figure 5.6). On the FCC of 21st March 1995, the tanks are seen to be partly filled with shallow water. Although, on the FCC of February 1998, the water column is quite deep (Figure 5.7) in both the tanks, there is not much difference in the vegetal growth. There are patches of yellow clay in the immediate vicinity downstream the tank. An elongated patch of yellow clay is present in between the Koncha river and the Kuri river (Figure 5.6). These inhibit the flow of water into the soil zone. Vegetation is developed in a narrow band just around the channel fills and some parts in the alluvial plain near the Kethan river (Figure 5.6). These yellow clay patches are also visible on the LISS-III FCC of 20th February (bands 321 in RGB) (Figure 5.7). This image shows better growth of vegetation, probably due to the higher monsoon rainfall in 1997. This is also reflected in the higher water level during November '97 and January '98 compared to 1995. The Jassia tank is situated over a slope of about 1° whereas the tank on the Kuri river is situated on a slope varying from 1°-6° in the basalt hill. 3D-perspective view (Figure 5.8) gives a clear picture of the location of the tanks. Overlay analysis in GIS reveals that these two tanks are constructed across streams of 4th and 5th orders, whereas the Kethan and the Naren tank are across streams of 2nd order (Strahler's system of ordering). 2nd order streams provide a small catchment area. On the other hand, higher order streams make a larger catchment area. In this case, the runoff velocity is quite high by the time water reaches the higher order streams. The lithology being impermeable there is little chance of recharge and most of the water flows as runoff. In case of the Kethan tank, the area immediately following the tank is covered by weathered basalt. The lineament density is also quite high, indicating presence of fractures. Thus, the possibility of seepage of water is enhanced. In case of the Jassia tank, lineament density is very poor or zero.

There are many small tanks in the Kethan and Narayan basins that are recharging to smaller extents. There are four tanks in the Narayan basin, but the extent of recharge provided by them is not appreciable. The reasons may be due

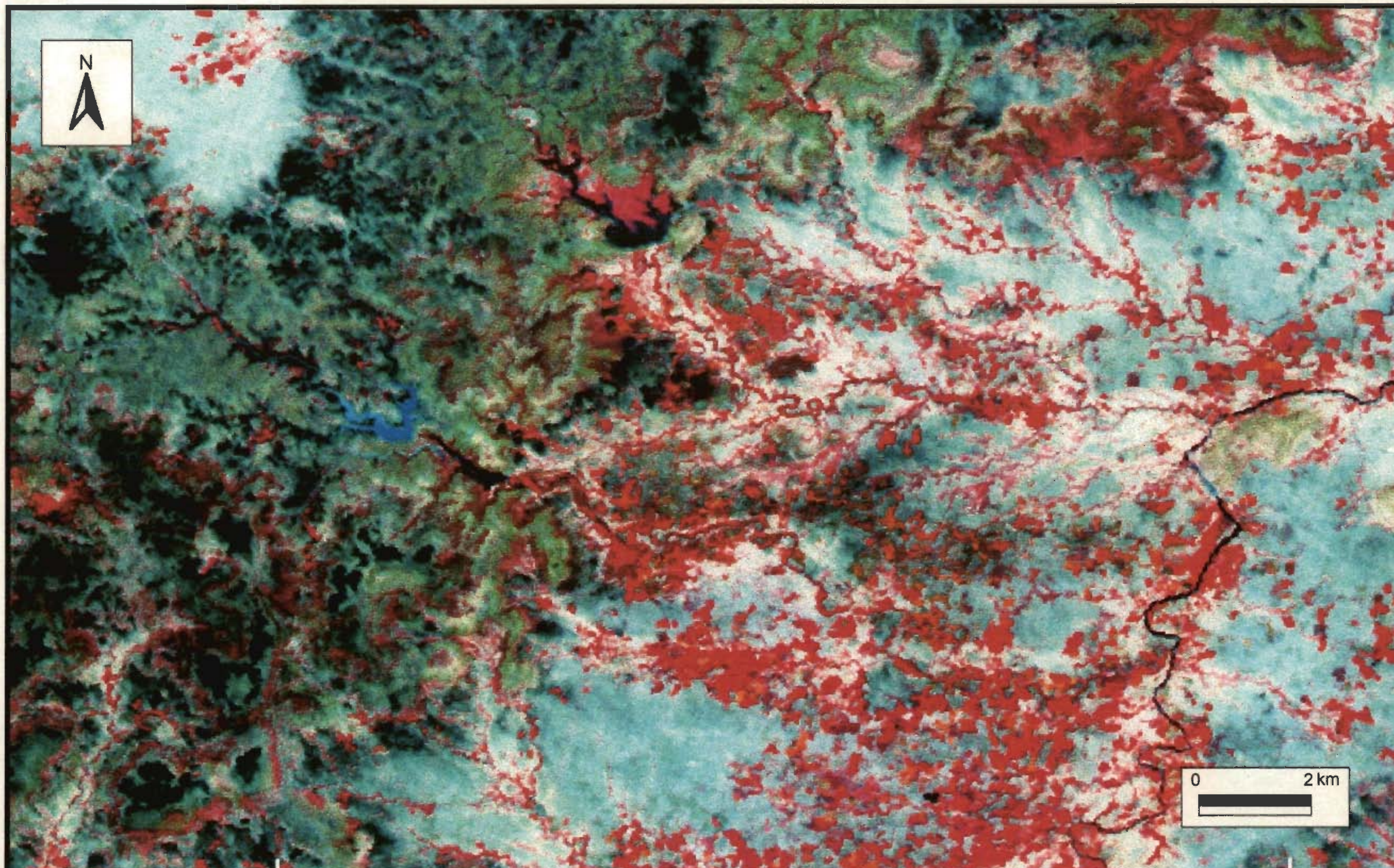

Figure 5.6. IRS-LISS-II FCC of bands 4,3,2 in RGB, of 21st March, 1995. The Jassia tank and the neighbouring area is shown. There is sparse vegetation growth downstream the tanks. The tanks are partially filled with water. There is an elongated patch of yellow clay, seen as dark green patches downstream the tanks.

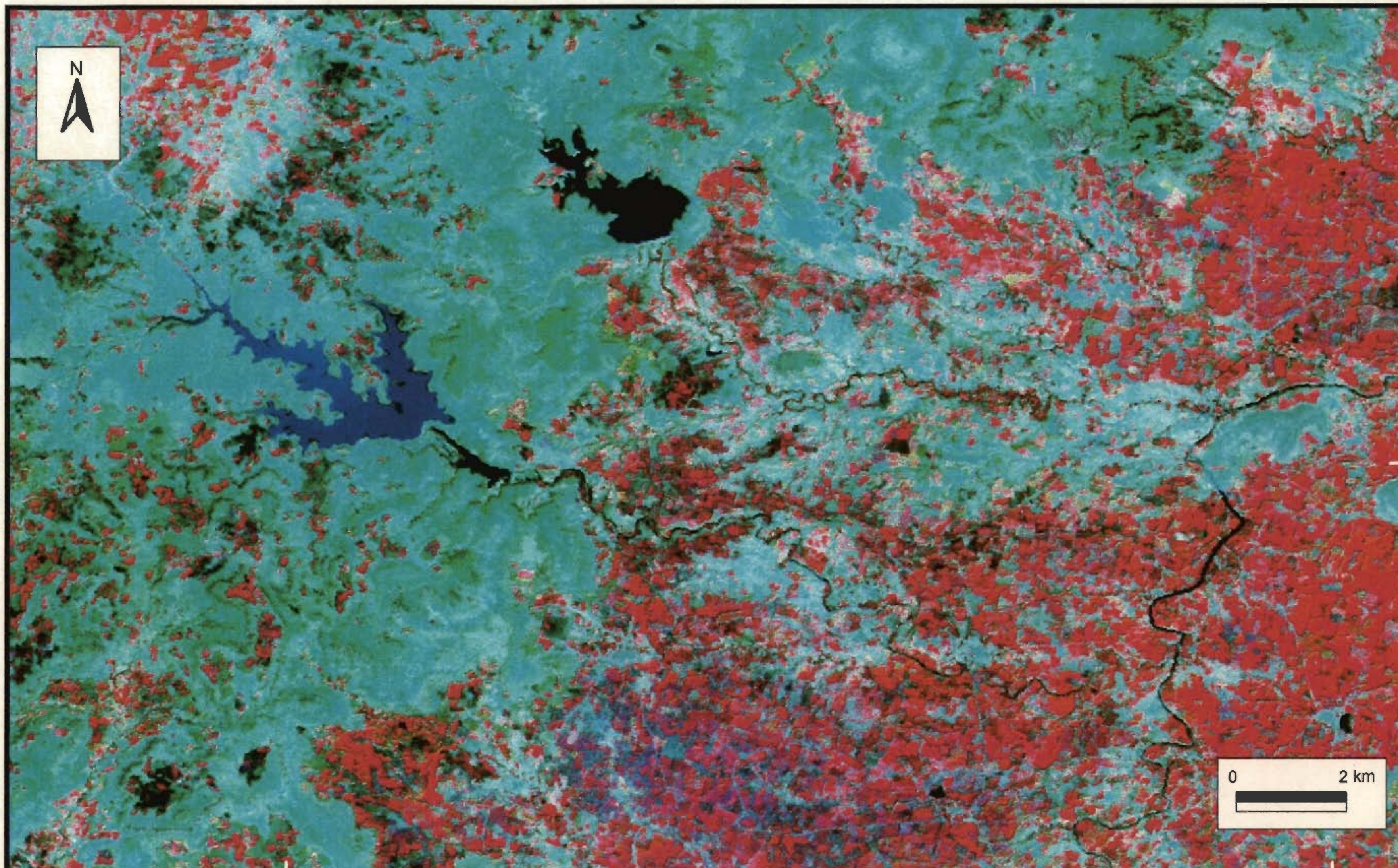

Figure 5.7. IRS-LISS-III FCC (bands 3,2,1) of 20th February, 1998. The tanks are filled with water. The Jassia tank has shallow depth whereas the tank on the Kuri river has clear deep water. The channel fills downstream support sparse vegetation growth.

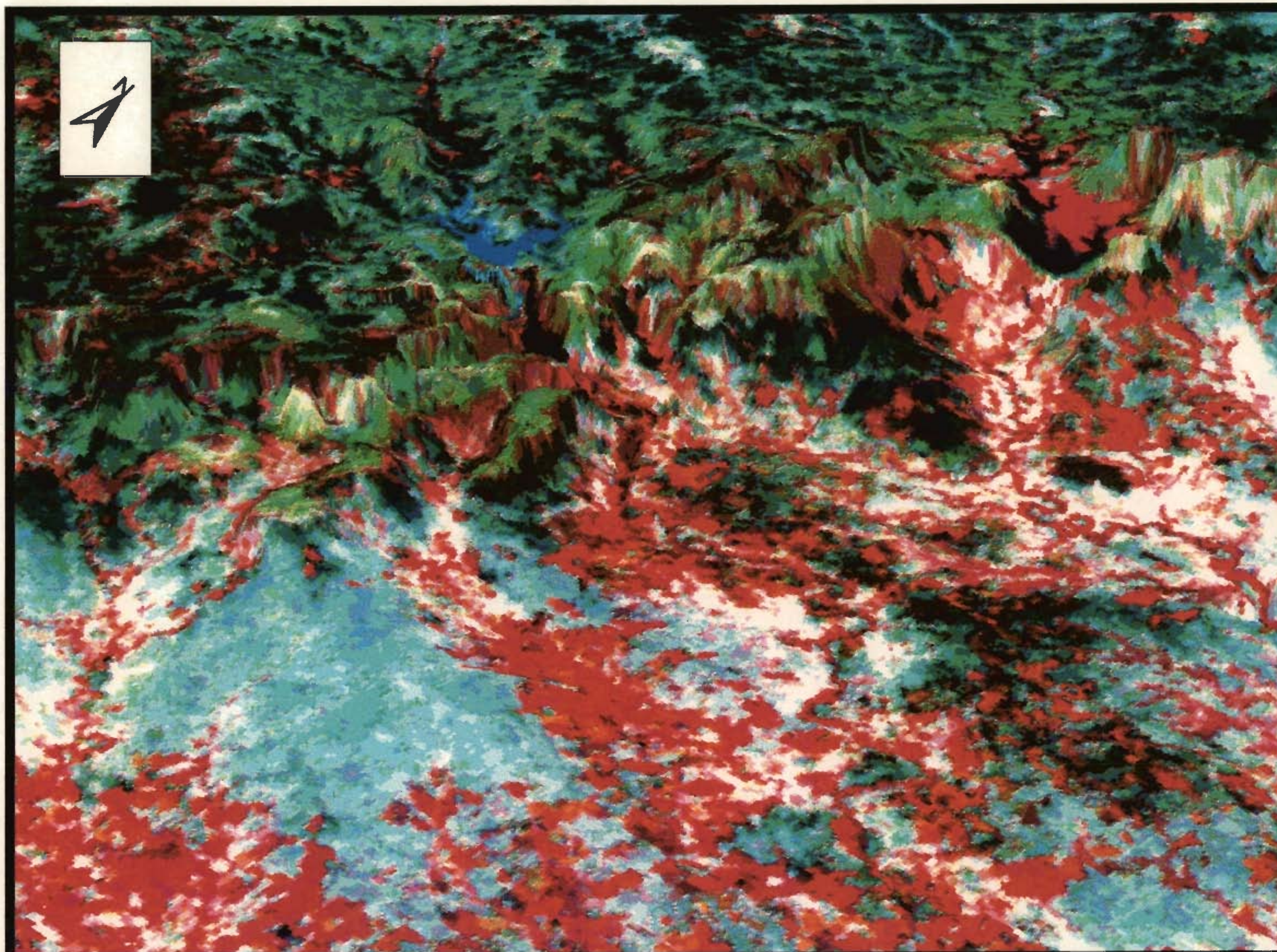

Figure 5.8. 3D-perspective view of the area around the Jassia tank.

to their smaller size, null slope or the presence of yellow clay layers in the neighbourhood, as seen on the FCC as dark green patches (Figures 4.3 and 4.4).

In order to validate the findings through integrated remote sensing and GIS based investigations of the artificial recharge in the area, the Kethan tank and the Naren tank, along with the surrounding areas have been visited in the month of December, 1998. The tanks, in respect to their topographic location, geomorphology and landuse, were studied. The Kethan tank is situated 3 km NW of the Sironj town (Figures 5 9a & 5.9b). It is surrounded by gently sloping basalt hills (Figure 5.11a). It has a canal network connected to it. Exposures of basalt are present by the side of the canal of the Kethan tank (Figure 5.9c). The canal runs for less than three months in a year. It has been known from the local people, that the functioning of the Kethan tank has considerably changed the groundwater situation. The entire Sironj town and its adjoining areas get water supply from this tank. Due to artificial recharge, agricultural conditions have also improved. Immediately behind the dam there are only scrubs or fallow land (Figure 5.10a). Extensive agricultural fields have been developed downstream from the tank (Figure 5.10b), at some distance from the tank.

The general physiography of the area is either plateau or hills of basalt (Figures 5.10c & 5.10d) or low lying plains with an intermediate zone of moderate slope. The major crop of this area is wheat. It is sown in the month of October and harvested in March. As discussed in Chapter 4, recharge from rainfall in this area is not adequate to supply water for agricultural purpose till end of the dry season. Agricultural and drinking water requirements are met with by the spreading method of recharge through tanks. Irrigation from groundwater is practiced in this area. Water is pumped out through bore wells at suitable locations and supplied to long distances (like 1-2 km) through pipes.

The Naren tank is situated on the Naren river, 10 km southeast of Sironj. It is constructed over a more or less flat area (Figures 5.12a, b & c). As interpreted from GIS analysis, the hydraulic gradient is low in the case of Naren tank. However, this tank is augmenting groundwater recharge. Agricultural fields are developed in the alluvial plains downstream from the tank (Figures 5.11b & c). The major crops are wheat and lentils. These areas are irrigated by groundwater through pipes from borehole for long distances. Figure 5.12d shows agricultural land downstream the tank where groundwater irrigation is practised, as indicated by the pipes. The Naren river, in the upper reaches, is almost dry in the pre-monsoon period. In the vicinity of the tanks groundwater condition is good within an area of about 7-8 km^2. Most of the wells in this area sustain water throughout the year. But the presence of yellow clay changes the groundwater condition. It is difficult to recognize yellow clay in the field. The groundwater characteristics, however, is different in the case of yellow clay soil. Dehri village (Figure 5.5) is situated in the alluvial plains along the Naren river on the road from Basoda to Sironj. Two parts of the village, on the two sides of the road, have contrasting groundwater situation. The part of the village on the side of the Naren tank has better groundwater conditions, but on the other side of the road, the tube and dug wells go dry from March. Remote sensing data show that there is an exposure of basalt along with yellow soils. This acts as an impermeable layer, thus restricting the seepage of water inside.

Thus, the field visit has provided a clear picture of the ground conditions. It has been realised that properly planned artificial recharge can appreciably improve the availability of groundwater in this area. Site selection analysis for artificial recharge has been performed on the basis of the results of integrated analysis supported by the ground truth.

5.5 SELECTION OF FUTURE ARTIFICIAL RECHARGE SITES

A remote sensing and GIS based method is found to be very useful in suitability analysis for artificial recharge structures in this area. The first task is

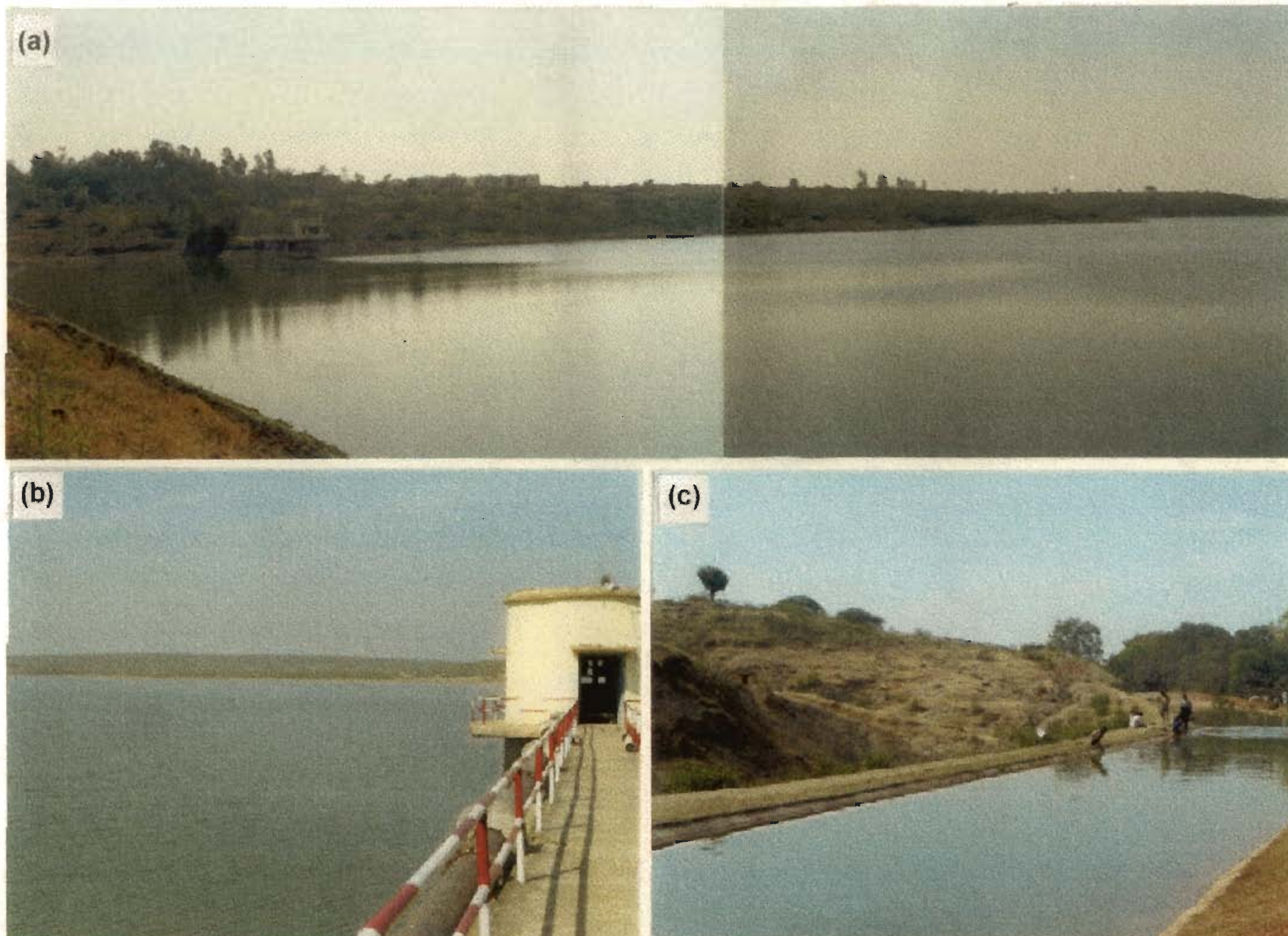

Figure 5.9 (a) A view of the Kethan tank situated 3km west of Sironj town. Photograph taken from the Kethan Dam. (b) The Kethan tank bordered by basalt hills. (c) Exposure of basalt on the left of the main canal of the Kethan tank partially covered by a thin layer of soil. The canal runs only for less than three months in a year, around two and half months in the monsoon period and a half month in the dry period. Photograph taken in the month of December.

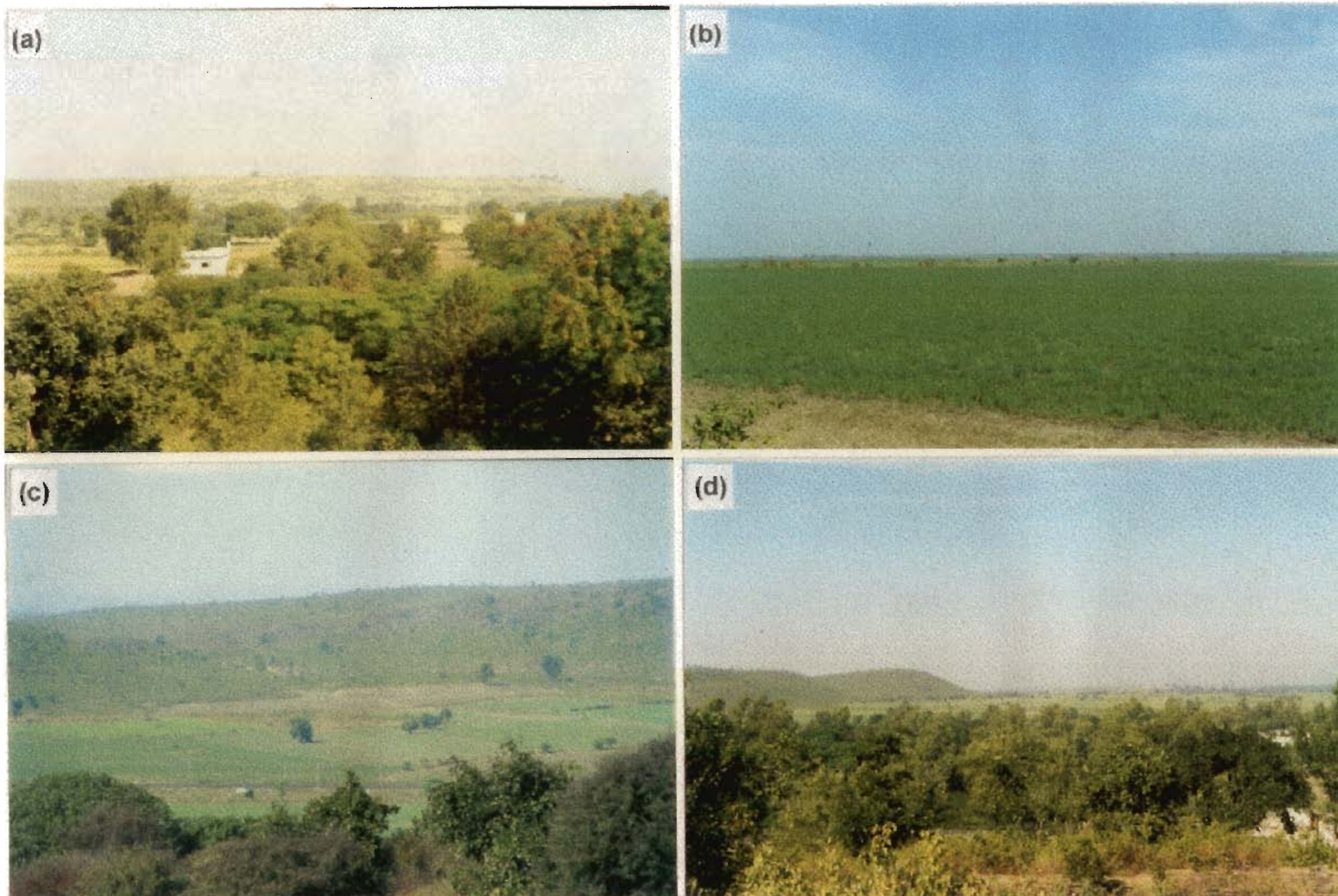

Figure 5.10 (a) Scrub land behind the Kethan dam. (b) Agricultural field down stream the Kethan tank. This area is getting recharged by the Kethan tank. (c) & (d) General view of the topography in the area showing the basalt plateau and the plain land.

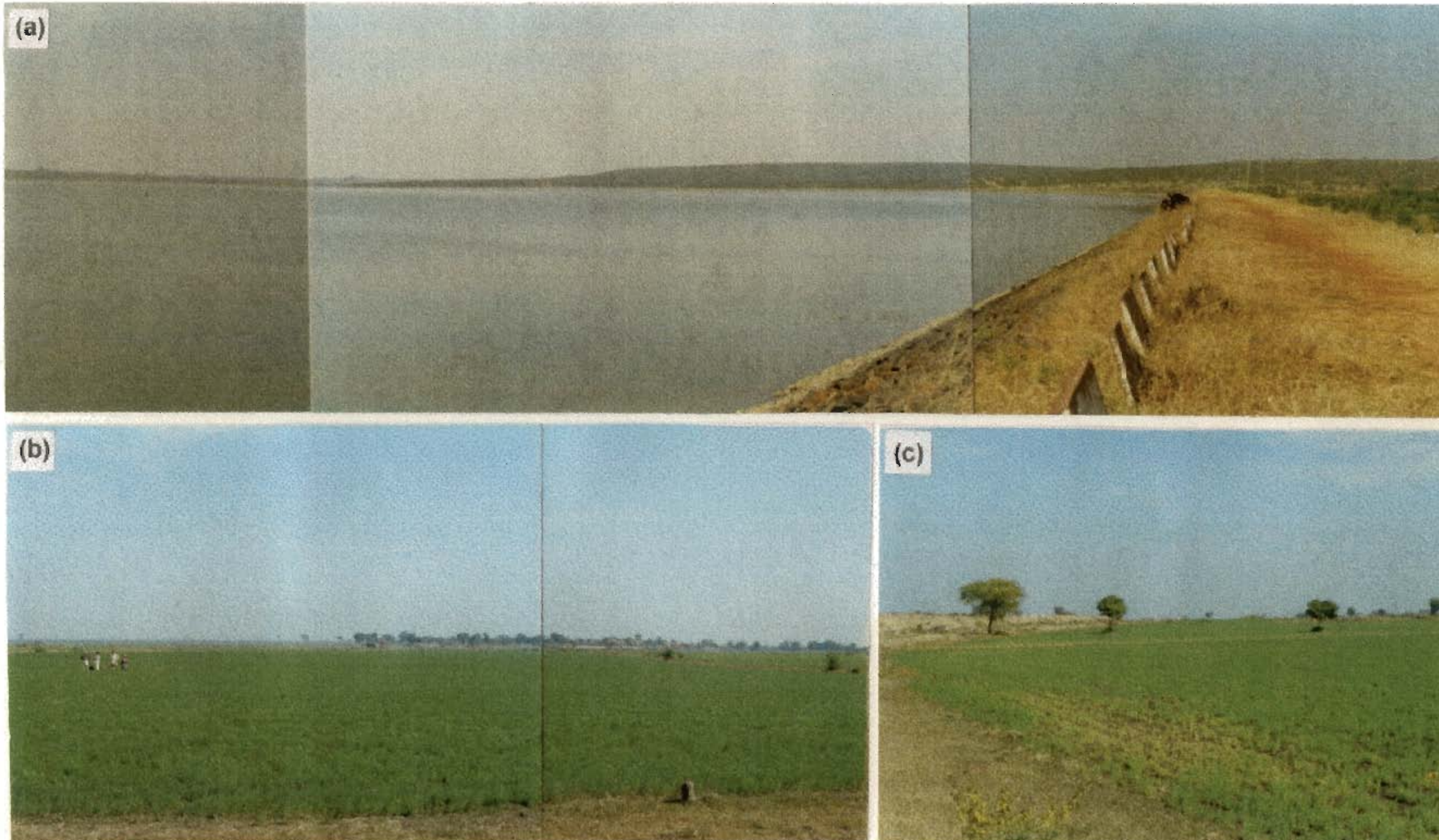

Figure 5.11 (a) Gently sloping basalt hill bordering the Kethan tank. Photograph taken from the Kethan dam. (b) Agricultural land downstream the Naren tank, on the way to the Naren tank from Sironj. These areas are receiving recharge from the tank. (c) Agricultural field behind the Naren dam.

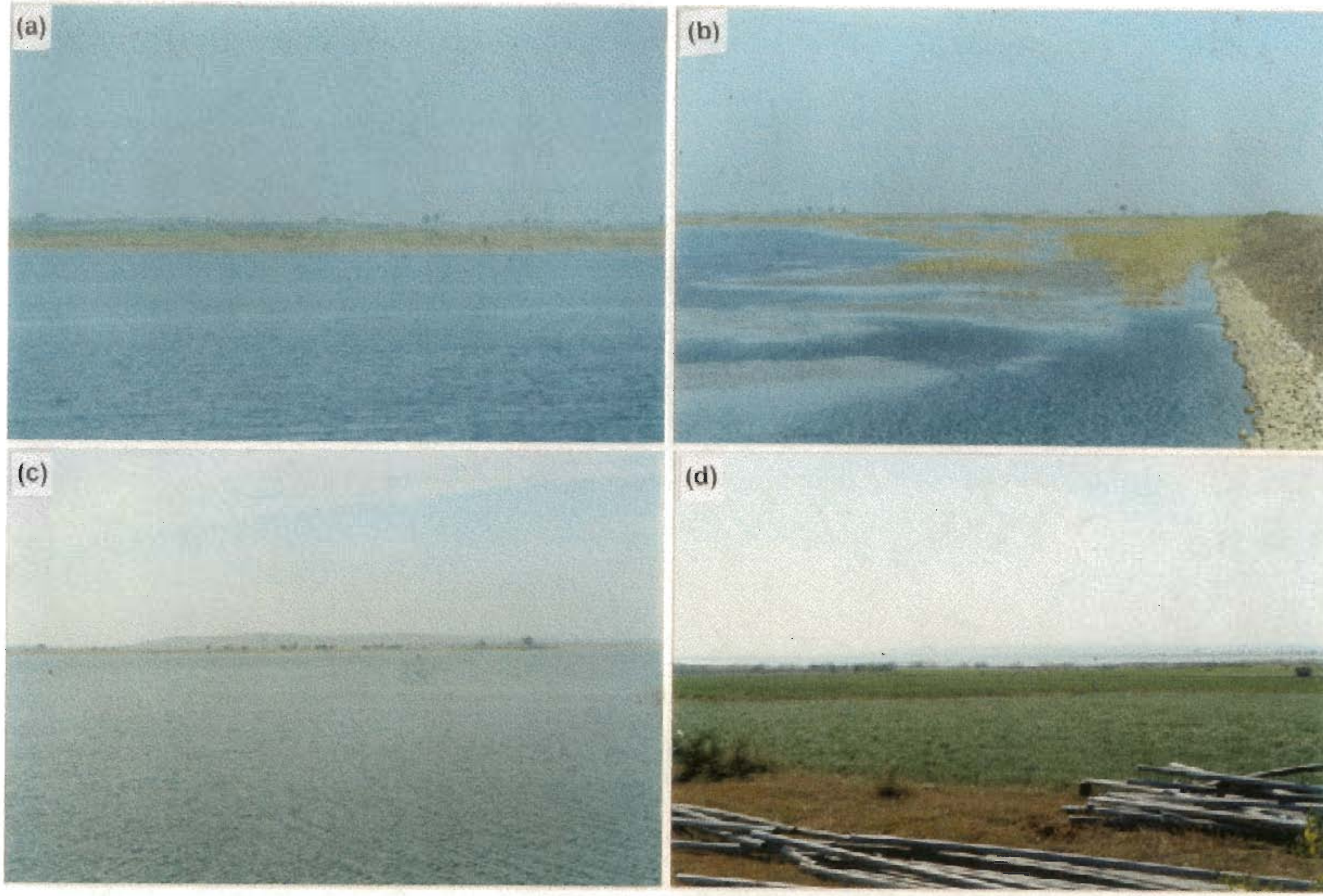

Figure 5.12 (a), (b) and (c) The Naren tank is situated 10 km SE of Sironj town. Photograph shows that it is in a more or less flat area. (d) Groundwater from bore well is taken to long distances to irrigate agricultural field through pipes.

to identify the factors facilitating recharge to take place. These factors are identified in Chapter 4. The existing artificial recharge system in the area has been studied with respect to its hydrogeology, topography and response in the water level of the wells. Based on these observations, a set of rules has been designed to demarcate the most suitable zones and also to find out the exact sites for artificial recharge structures. The following thematic information layers are used in this suitability analysis:

(a) Geology
(b) Geomorphology
(c) Slope
(d) Lineament density
(e) Distance to lineament
(f) Soil types
(g) Stream order
(h) Land use
(i) Specific electrical conductance
(j) Depth to water level

Boolean logic model and weighted overlay model have been applied. In Boolean logic model, the areas, where a certain set of conditions are satisfied, are delineated through the logical operations AND, OR, XOR, NOT. In weighted index overlay, the individual thematic layers and also their classes are assigned weightage on the basis of their relative contribution towards the output. In the present study, weighted indexing method has been used to demarcate the suitability zones. For artificial recharge structures Boolean logic model is used to suggest the sites in the suitable zones for these structures. Specific methods based on the hydrogeomorphological conditions of the site have been suggested. At the initial stage, all parameters were considered to be of equal importance and the most favorable class of each parameter had been given rank 1; increasing ranks indicating decreasing importance. Then, weighted overlay was performed to give the zones of suitability for artificial recharge, where minimum value indicated highest suitability. In reality, however, all the parameters do not have equal importance. In this type of ranking there was no option for the unsuitable class. One or more classes of a parameter may be unsuitable for a particular analysis. Therefore, a 0-10 scale has been used (discussed in Chapter 3 in detail). In this scale of ranking, each parameter is assigned an appropriate weightage and each class within a parameter is also assigned a weightage. In this scheme, the unsuitable classes are assigned a zero value, with rank 10 indicating highest suitability.

5.5.1 CRITERION FOR ARTIFICIAL RECHARGE IN THE AREA

The hydrogeomorphic condition of the existing artificial recharge facilities in the area forms the basis for suitability analysis. Naturally, these sites should be the areas where the recharge conditions are favourable. At the initial stage of the work, suitability analysis had been performed using four themes, namely, geology, geomorphology, topography, and lineament (Saraf and Choudhury, 1997; 1998). As more information layers were added to the database, more parameters were considered for analysis. Finally weights have been assigned to each parameter (Table 5.3). In the following section the parameters used in this analysis are discussed. These themes are described in descending order of their importance. Although, hydrogeologic characteristics of the rock control the rate of recharge, geology has not been given the highest weightage. Instead, slope has been give a weightage of 10. Two reasons best explain this. Topography plays a very important role in maintaining a steady rate of recharge. Secondly, geology alone does not decide the recharge capabilities. Although both alluvial plains and channel fills develop on the weathered basalts, the channel fills provide better recharge conditions compared to alluvial plains. Geomorphic classes within the same geologic unit have different characteristics. Thus, geomorphology shows absolute importance over geology and it has been assigned a weightage of 9. In the area, presence of lineament is considered favourable for the movement of groundwater since these are surface expressions of joints and other. Lineament density receives a weightage of 8. It shows higher importance over geology (which has been assigned a weightage of 7) because the fractures impart permeability to the basalt. Soil properties have equal importance as geology.

Sl. No.	Parameter	Weightage	Classes	Class weightage
1.	Slope (in degrees)	10	2-5	10
			0-2	8
			5-10	3
			10-15	1
			>15	0
2.	Geomorphology	9	Channel fill	10
			Alluvial plain	8
			Pediment	6
			Basalt hill/plateau (dissected)	2
			Basalt hill/plateau	1
			Vindhyan upland	1
3.	Lineament density (m/km^2)	8	>2.6	10
			1.9-2.6	8
			1.3-1.9	6
			0.6-1.3	4
			<0.6	2
			0	0
4.	Geology	7	Weathered basalt	10
			Unweathered basalt	5
5.	Soil depth	7	Slightly deep	10
			Shallow	5
6.	Depth to water level (m)	6	11-14	10
			9-11	8
			7-9	6
			4-7	4
			2-4	2
7.	Specific Electrical Conductance (μmhos/cm)	5	<500	10
			500-800	8
			800-1100	6
			1100-1400	4
			>1400	2

Table 5.3 Weightage of different parameters for suitable site for artificial recharge in the Kethan basin

Distance to lineament on a lineament buffer is a quantitative measure of the lineaments in relation to the increasing distance. This theme has been used in the Boolean logic model. In the present study, analysis of the quality of the groundwater has not been attempted. However, specific electric conductance

(EC) theme has been generated to incorporate the quality of groundwater in this analysis. The quality of groundwater should be pure in the artificial recharge sites. Of course, it has lower importance relative to all the parameters discussed above, because those parameters decide the possibility of the recharge phenomenon. If favorable conditions in all the parameters are satisfied, then comes the consideration for the quality of water. The parameters and their classes are discussed below.

(a) Slope

Slope is a very important factor in controlling the hydraulic gradient for the movement of water. Generally, a flat area is preferred for artificial recharge sites by many. Karale et. al. (1990) preferred plain relief in a remote sensing based study on site selection of artificial recharge in the Nagpur district, Maharashtra. In the present study, it has been observed that the Kethan tank is situated over a very gentle slope instead of null slope, which helps to maintain the steady hydraulic gradient and it is provides better recharge conditions. Hence a slope of 2°-5° has been given the highest weightage of 10 followed by a slope of 0°-1°. Steep slopes are given the lowest weightage, as water does not have the chance to infiltrate, and flows downstream as runoff.

(b) Geomorphology

Channel fills provide the highest potential for recharge due to the presence of unconsolidated material. It has been discussed in chapter 4 that these are the areas that receive the highest recharge from rainfall as estimated by the Thornthwaite–Mather model. Alluvial plains have good prospects except in the areas of yellow clay layer (which hinders the flow of water into the sub surface). Pediment has lower potential in comparison to the alluvial plain and receives lower weightage. Basalt hills and Vindhyan upland have very poor prospect for recharge except in the jointed areas. They are given the lowest weightage. The dissected part has better prospect than the basalt hill and assigned a weight of 2.

(c) Lineament

High lineament density indicates highly fractured rocks in this area. The higher the value, the better is the prospect for recharge. Hence, the areas having no lineament have been considered unsuitable for artificial recharge and assigned 0 weightage. The highest value of lineament density class (>2.6m/k.m^2) receives highest weightage of 10, weights gradually decrease with decreasing value.

(e) Soil

Slightly deep black soil, having water holding capacity 150-200 mm/m, is present in the valley plains. This is given the highest weightage. The shallow black soil covering the hilly parts, provides much space for storage of water. It has moderate water holding capacity of 100-150mm/m. This is given a weightage of 5.

(f) Depth to water level

The valley part has deep water level, up to 14 m b.g.l., as compared to the hilly part, where the average depth to water level is 2-4 m b.g.l. Deep water table is given the highest weightage. Average depth to water level surface has been generated from the average of depth to water level data of 24 years. In the Kethan basin water level is quite deep in the valley parts, going down up to 13m (Figure 5.13). In the western hilly part, water level is up to a depth of 4-5 m b.g.l. In the Narayan basin, the maximum depth reaches up to 6-7 m in the valley portion, whereas in the hilly areas it is very shallow (Figure 5.15).

(g) Water quality

It is important that the quality of groundwater should be pure at the artificial recharge area. Specific electrical conductance (EC) in µs/cm has been taken as the criteria for quality of water. EC values range from 350 – 1650 in the Kethan basin (Figure 5.14). In the Narayan basin, EC value is lower, ranging from 400-750 (Figure 5.16). Low values of EC are preferred for artificial recharge sites and assigned the highest weightage.

5.5.2 WEIGHTED INDEX OVERLAY

All the information layers discussed are combined using weighted index overlay method to give rise to zones of suitability for artificial recharge structures. Figure 5.17 shows the output map of this analysis in the Kethan basin and Figure 5.18 for the Narayan basin. The most suitable zones are along the channel fills and the foothills of the basalt hills in the north-eastern part. On the basalt plateau and hills, suitability is poor. In the Narayan basin, the suitable zones are along channel fills and in the foothill regions of basalt hills in the southeastern part. Elsewhere, in the basalt hills and Vindhyan, suitability is very poor, except around lineaments. Now, in order to suggest the exact location for an artificial recharge structure, Boolean logic and conditional methods are employed.

Sensitivity analysis has been performed in order to know which information is most sensitive to the model results. It is done by varying the weights of different layers and observing the results through running the model multiple times. Statistical methods are also used in sensitivity analysis. In the present study, sensitivity has been tested by varying the weights of the parameters. The model has been run with different combinations of weights for several times. It has been observed that, changing the weight of the layer geomorphology produces the greatest change in the result.

5.5.3 BOOLEAN LOGIC ANALYSIS

The first task in this method is to identify the criteria and to formulate the set of logical conditions to extract the suitable zones. In this case, the output will have only two classes – suitable or unsuitable. Where the defined conditions of the information layer fulfilled together, a value of 1 is given. The remaining part

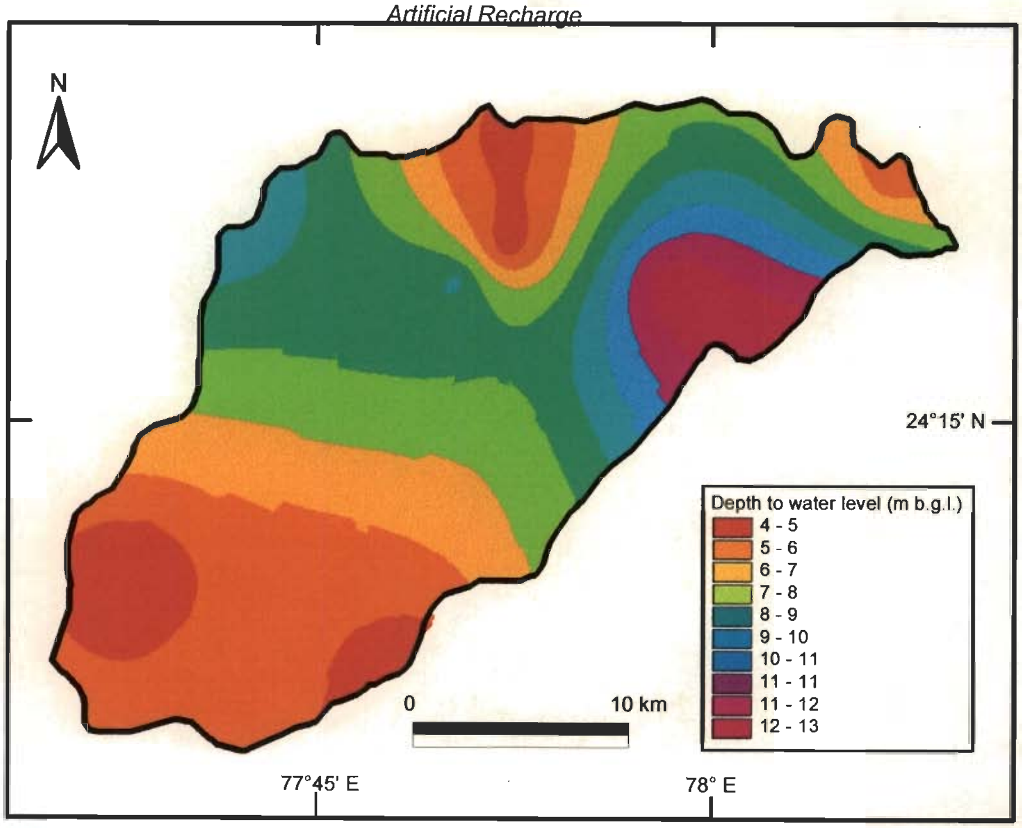

Figure 5.13. Average depth to water level map of the Kethan basin. In the central part the water level is deep.

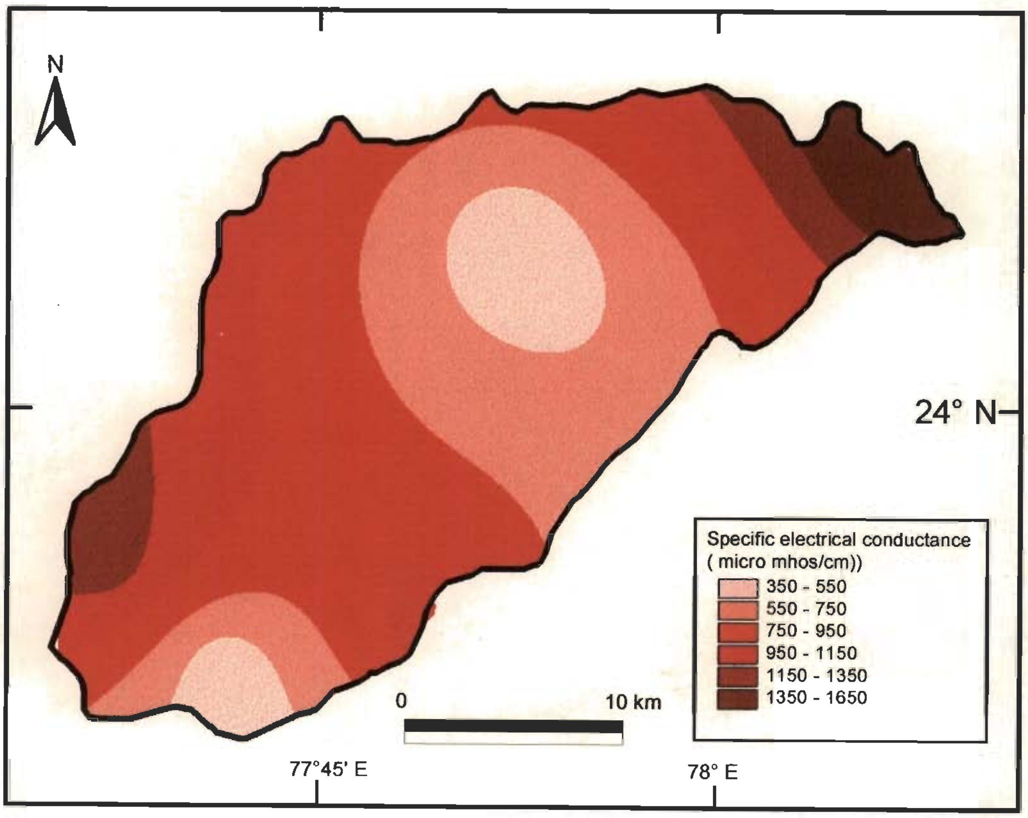

Figure 5.14. Specific Electrical Conductance (EC) map of the Kethan basin. The central part has lower value of EC.

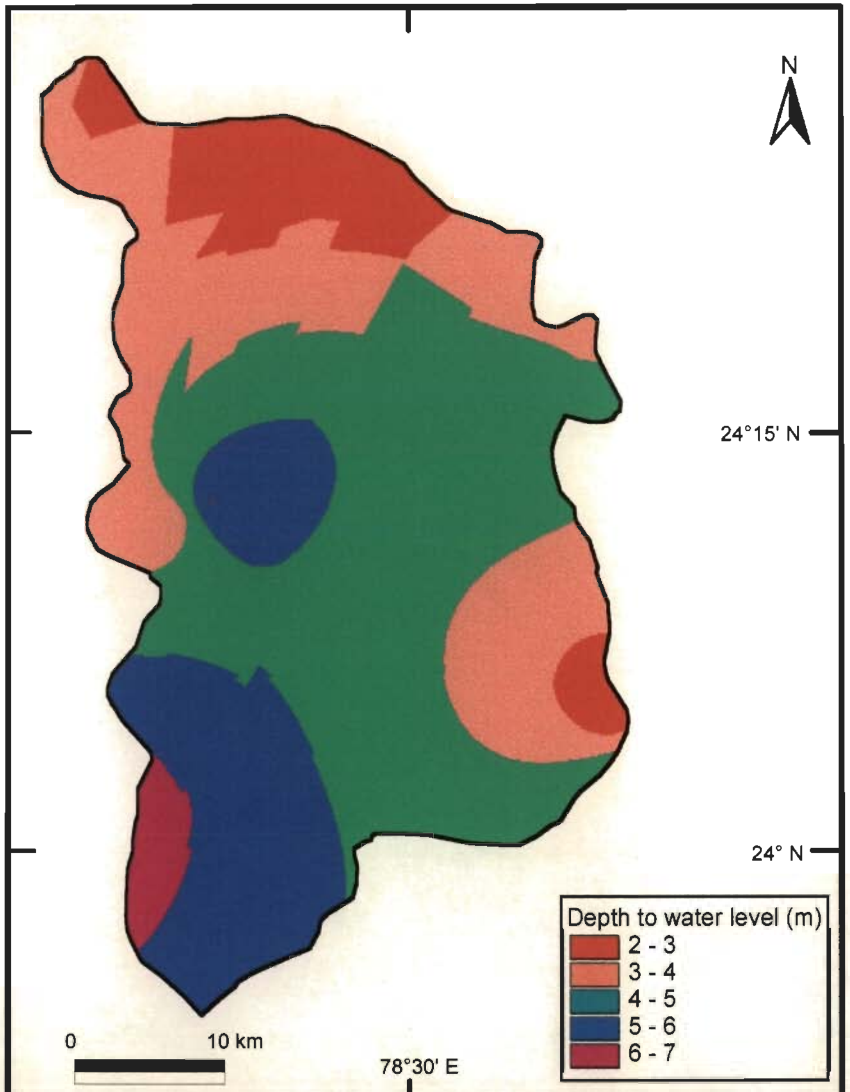

Figure 5.15. Average depth to water level map of the Narayan basin. The hilly parts have shallow depth to water level.

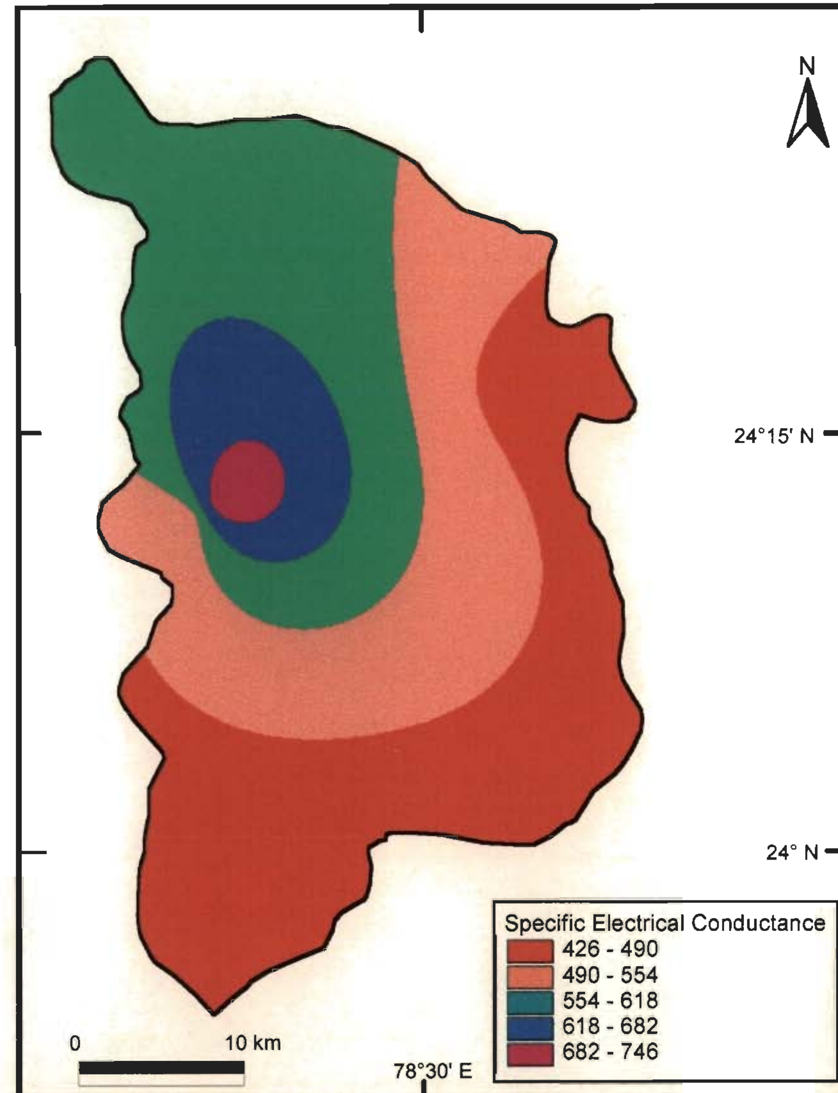

Figure 5.16. Specific electric conductance map of the Narayan basin.

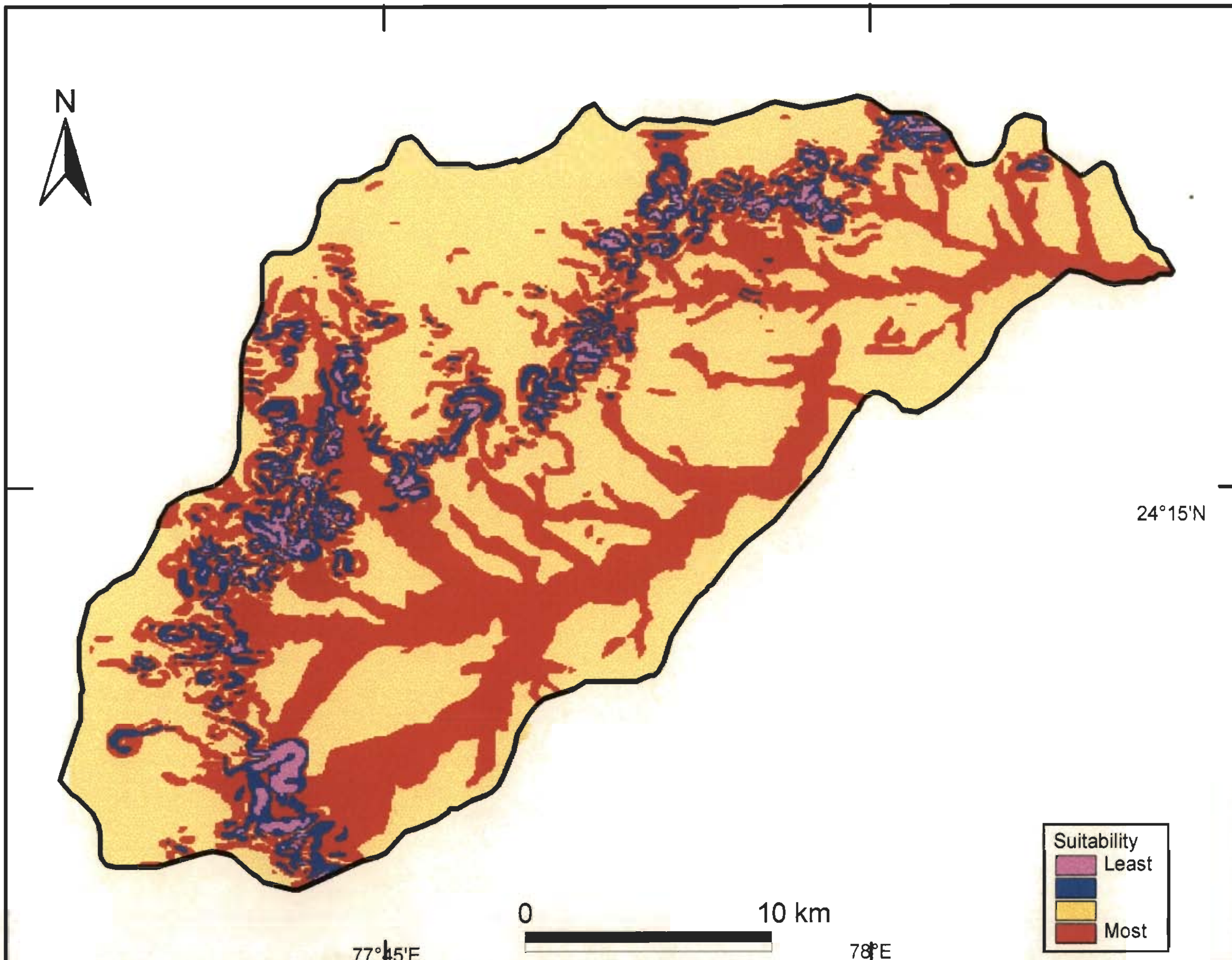

Figure 5.17. Suitable zones for future artificial recharge structures in the Kethan Basin, derived from weighted index overlay analysis.

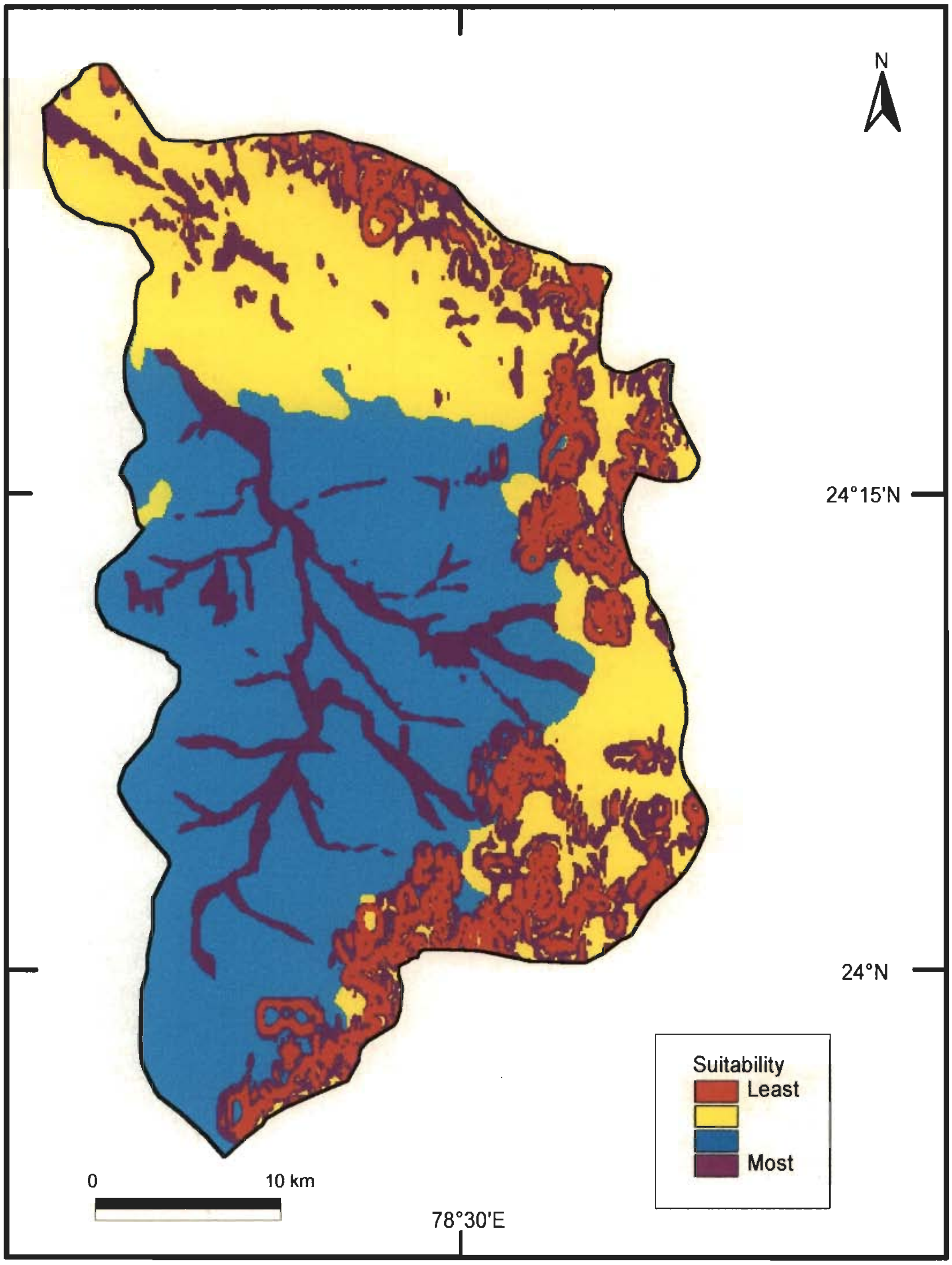

Figure 5.18. : Suitable zones for artificial recharge in the Narayan basin, derived by weighted index overlay analysis.

will have a zero value. This analysis is suitable for objective criterion but is not suitable to show gradational values. In order to have a comparison of the results with weighted indexing method, suitability analysis has been done using Boolean logic model. The criteria for site selection are:

1. The sites should be over a slope of 2°-5°.
2. The sites should be over weathered basalt.
3. The sites should be on channel fills of alluvial plains.
4. The sites should have high lineament density.
5. The sites should be on moderately deep black soil with high water holding capacity.
6. The depth to water on the sites should be in the range of 6-12 m b.g.l.
7. The sites should be within a distance of 100m from a lineament.
8. The quality of water on the sites should be pure, having low EC (<500).
9. The sites should be on the 2nd or 3rd order stream.

It has been noticed that very little spatial overlap occurs with all these parameters fulfilling the criteria. As a result, most of the area comes as zero value. Therefore, a combination of weighted indexing and Boolean logic model has been adopted. The most suitable class of the result of weighted index overlay is assigned a value of 1, indicating suitable, and rest of the pixel as zero, indicating not suitable, by the method of map query. This map is combined with other binary weight maps on stream order, proximity to lineament. The following criteria are considered:

The artificial recharge area should be located:

1. on a stream of 2nd order OR on a stream of 3rd order in order to have a minimum catchment area and to avoid submergence AND
2. within a distance of 100m from a lineament AND
3. on a non-cultivable land AND
4. should be located where there is no yellow clay layer on the surface

Yellow clay has been identified from the FCC (Figures 5.3 & 5.6) as dark green patches on the residual hills. Borehole information indicates that there is a surfacial clay layer, about 1m thick, at some places within the weathered basalt. It may be hindering the flow of water into the soil zone and groundwater by creating a perched water table. As visible on the remote sensing image, this layer is not continuous. Available borehole information is not sufficient to generate a thematic information on the yellow clay. Hence, the first three criteria are used and combined through Boolean logic with the most suitable zone calculated through weighted indexing. The output map thus generated has been overlaid on the FCC in order to exclude those sites that are situated over the yellow clay, as identified from FCC. Finally, the suitable sites for artificial recharge have been suggested (Figures 5.13 & 5.14).

Now, different artificial recharge methods are suitable for different conditions. Detailed study on the choice of a method is beyond the scope of this study as it also involves consideration from civil engineer's point of view. However, an attempt has been made to suggest a few methods for the proposed sites through GIS analysis. Recharge tanks are suitable for the tributaries having a gentle slope. These collect the runoff to facilitate gradual seepage into the groundwater. It has been observed from the existing tanks that recharge tanks suit very well in a narrow valley with a gentle slope. Hence, sites 1,2,3 and 4 in the Kethan and 1 in the Narayan basins (Figure 5.19 & Figure 5.20) may be considered for recharge tank. Subsurface dykes are suitable for forested areas along tributaries. This can avoid the problem of forest submergence and at the same time provide recharge to groundwater. Sites 5 and 6 in the Kethan basin and 2, 3 and 7 in the Narayan basin may be considered suitable for subsurface dyke. Check dams are suitable in areas of high runoff on the main stream to check the runoff. Sites 7 and 8 in the Kethan basin, and sites 4, 5 and 6 in the

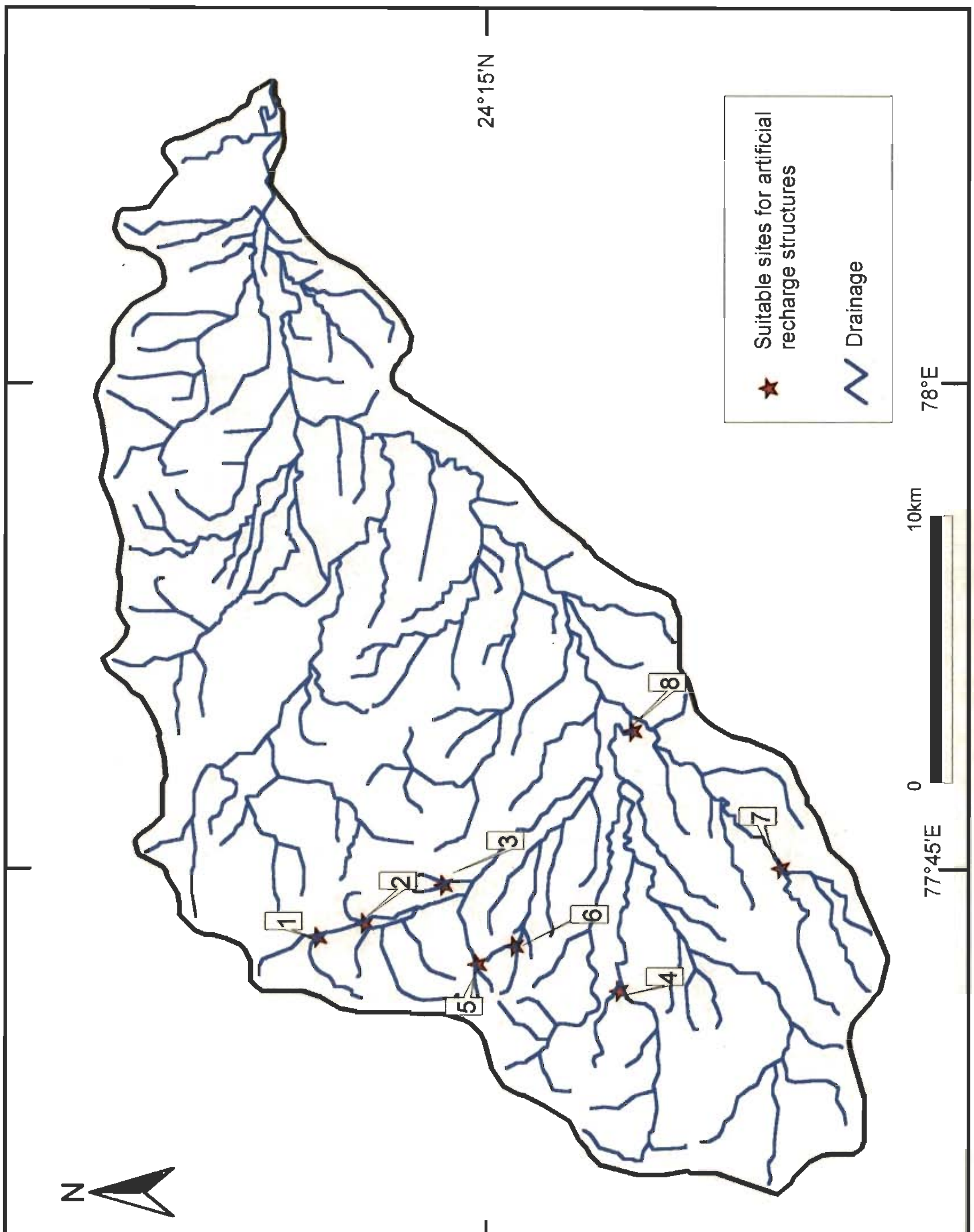

Figure 5.19. Suitable sites for artificial recharge structures in the Kethan basin. This map is the output of Boolean logic model for suitability analysis.

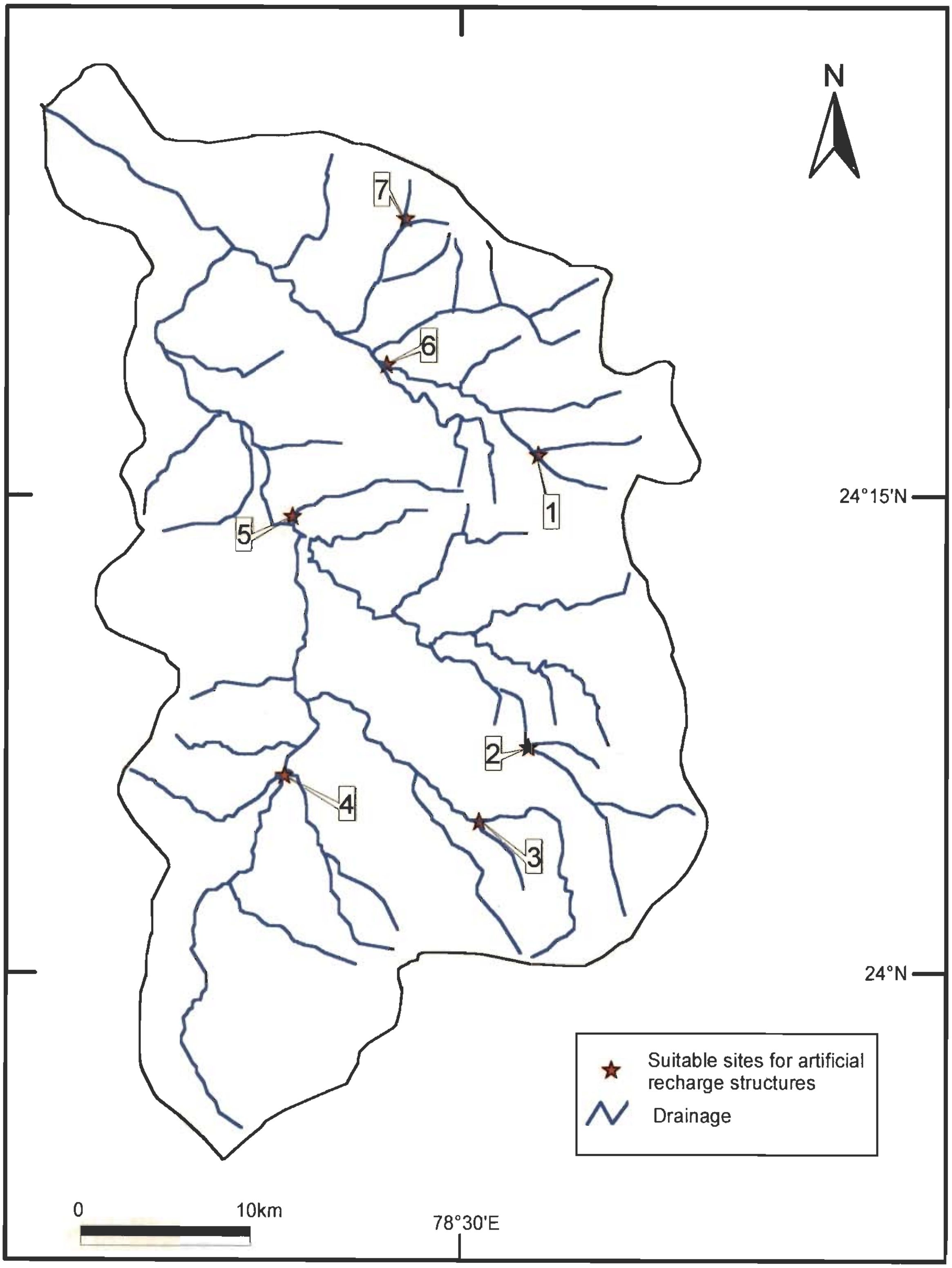

Figure 5.20. Suitable sites for future artificial recharge structures in the Narayan basin. This map has been prepared through Boolean logic model for suitability analysis.

Narayan basin can be suitable for check dams. Of course, detailed field investigation of the sites is necessary for implementation of these methods.

The integrated analysis through a combination of weighted indexing and Boolean logic method has been found to be very suitable for selection of suitable sites for artificial recharge. Of course, detailed litholog information and geophysical data of the proposed sites, and the surrounding areas, will improve the results of this analysis. 3D-perspective views give a clear picture of the terrain features. Further, GIS has immense potential to simulate the future scenario. Integrated remote sensing and GIS can simulate recharge tank at a particular site and also evaluate the effect of an artificial recharge structure in a particular area.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Groundwater is a precious resource of limited extent in hard rock areas. It is the source of water supply and irrigation in these areas. Due to urbanization and industrialization, groundwater level is depleting in many parts of India, and the situation is moving towards one of acute water scarcity in the next century. This alarming situation calls for a cost and time-effective technique for proper evaluation of groundwater resources and management planning. Groundwater development program needs a large volume of data from various sources. Integrated remote sensing and GIS can provide the appropriate platform for convergent analysis of large volume of multi-disciplinary data and decision making for groundwater studies. In the present study, an integrated remote sensing and GIS based methodology has been developed and demonstrated for evaluation of groundwater resources of a hard rock area in a part of the Betwa basin, in the state of Madhya Pradesh, India. Suitable sites for artificial recharge, to improve groundwater conditions in the area, have also been suggested. The remote sensing and GIS based methodology developed here has applications in hard rock terrains where generally groundwater is scarce.

The study area comprises mainly Deccan Trap basalt and partly Precambrian sedimentary rocks of the Vindhyan Supergroup. Groundwater occurrence in basalt is restricted to the weathered and fractured parts. In this area, monsoon groundwater recharge can not meet the demands for groundwater throughout the year. Artificial recharge is necessary to improve the groundwater conditions in the area. In this area, much thought has not been given to utilize artificial recharge methods at suitable locations. The present work is an attempt in this direction.

The main objectives of the study have been as follows:

- to develop and test an integrated remote sensing and GIS technique for evaluation of groundwater resources in a hard rock terrain,
- to identify the interrelationship of recharge areas with geology, geomorphology and structure of the area,
- to have qualitative and quantitative assessment of groundwater recharge,
- to delineate the groundwater potential zones in the area, and
- to suggest suitable sites and methods for artificial recharge to augment groundwater recharge in the area.

The following data sets have been used for the study:

(a) IRS-LISS-II data (27-02-95 & 21-03-95) and IRS-LISS-III data (20-02-98),

(b) Survey of India topographic maps at 1:250,000 & 1:50,000 scale,

(c) Existing maps on geology, landuse, soil etc.,

(d) Groundwater data e.g. depth to water level data (1976-1998), and

(e) Meteorological data e.g. rainfall, evaporation etc.

The time of acquisition of remote sensing data has been carefully chosen. Immediately after monsoon, data are dominated by reflectance of vegetation and the geologic, geomorphic features and structure are suppressed. On the other hand, during the end of dry season, the vegetation cover is generally very low. Hence, the data of February and March, the harvesting time for winter crops, have been used. In these data, a balanced response of vegetation, geologic and structural features is found.

The Vindhyan sediments were deposited during Pre-Cambrian and Cambrian time over the Bundelkhand Granite, which forms the basement in the area. However, granite is not exposed anywhere in the area. During Upper Cretaceous time, a series of successive lava flows erupted, covering the whole area. Subsequent weathering of basalt gives rise to the present day configuration of the area. Extensive weathering of basalt gave rise to the formation of light brown silty clay, locally known as Muram (yellow clay) in the plain areas. Black cotton soil develops over weathered basalt, yellow clay being the parent material. The hard and compact remnant of the basalt flows forms residual hills and plateaus.

IRS-LISS-II and LISS-III sensors acquire data in the visible, NIR and SWIR regions of the electromagnetic spectrum. LISS-II and LISS-III have spatial resolution of 36.25 m and 23.5 m respectively. These data have been processed using suitable digital image processing methods. These include various combinations of false colour composite, spatial filtering, band ratioing, and principal component analysis. Principal component composite has been found very useful in delineating different geomorphic features, namely channel fill, alluvial plain, residual hills and pediments. Yellow clay soil can be readily recognised on the remote sensing images by its high reflectance in the visible band (0.62-0.68 μm), as compared to vegetation. This is seen as dark green patches on the FCC of LISS-II bands 4, 3, 2 and LISS-III bands 3, 2, 1 in RGB. Thematic information layers on geology, geomorphology, lineament, soil etc. have been generated from digitally processed images supported by ancillary information.

Remote sensing images facilitate discrimination of basalt exposure, mainly in the hilly areas, from weathered basalt in the low- lying areas, due to their different spectral characteristics. Weathered basalt provides the shallow aquifers in the area. Various combinations of FCC supported by DEM enable delineation of the geomorphic features and their interrelation with geology and topography. Basalt forms residual hills and plateaus along the western margin of the Kethan basin. Pediments are formed over gentle slope bordering the basalt plateau. Alluvial plains develop in the low-lying areas in the Kethan and the Narayan basin. Alluvial plains are discriminated by their high reflectance in the visible band (0.52-0.56 μm). Depth of weathering is more in case of the Kethan basin. This is expressed by the development of wide channel fills along the Kethan river compared to the thin patches of channel fill material along the Narayan river. The channel fills are the sites for potential groundwater.

A wealth of hydrogeologic information can be extracted from the DEM, generated from elevation contours. Slope is a very important parameter in groundwater studies. Further, tracing the path of the steepest slope of eight neighbours, the drainage network has been derived from the DEM data. This method is based on the assumption that there is no upward or downward loss of water due to precipitation. Hence, there is a misfit between the actual surveyed drainage and simulated drainage. In hilly areas, there is a good match between the actual surveyed drainage and simulated drainage. In flat areas, parallel channels develop due to low gradient. Excluding the flat areas, this misfit has been utilized to link with recharge areas. Overlay analysis of surveyed drainage and simulated drainage with information layers on geology, soil, lineament, geomorphology reveals that the these are the areas (a) covered by weathered basalt, (b) having greater soil depth, (c) having high lineament density and (c) having channel fills. Further, recharge estimation shows that these are the areas receiving higher recharge. Evapotranspiration shows uniform pattern in this area. Hence, it may be concluded that the misfit is an indicator of recharge areas. The higher grounds, covered by the hard and compact basalt or Vindhyan sandstones show a good match. These areas are relatively not favourable for recharge, as compared to weathered basalts and valley fills.

Lineaments in this area represent joints and other fractures, which impart permeability to the basalts and Vindhyan sandstones. Lineaments have been mapped from directionally filtered NIR band and principal component 1 (PC1). Groundwater potential is more in the fractured areas. Lineament density and buffer zone maps have been generated to represent the intensity and the proximity to lineament. Weighted index overlay method is found suitable for mapping groundwater prospective zones. Criteria for the analysis have been defined on the basis of the knowledge gained from integrated analysis supported by ground truth. Each parameter has been assigned with a weightage, and each class of the parameters is assigned with a weightage on the basis of its relative contribution in controlling the occurrence of groundwater in the area. For weightage assignment, a scale of 1-10 has been used, indicating least suitable to most suitable. 0 (zero) indicates not suitable. Geology receives the highest weightage followed by geomorphology, lineament, slope and soil properties. In general, the Kethan basin holds a better prospect for groundwater than the Narayan basin.

Remote sensing images of this area brought to light valuable information on the artificial recharge provided by irrigation reservoirs/ tanks. LISS-II images of February and March 1995 show good vegetation growth downstream the tanks. Dry season vegetation is an indicator of groundwater. It can be inferred that the tanks are augmenting groundwater recharge in the area. There are four medium sized tanks in the Kethan basin along with some small ones. All the tanks are contributing to recharge. The extent of recharge is different due to difference in size, capacity and hydrogeological conditions. The effective area receiving recharge from larger tanks is about 8-10 km^2, whereas smaller tanks provide recharge to 1-2 km^2 area. Integrated GIS analysis indicates that recharging capability of these tanks depends on the following factors: porosity and permeability of the rock and soil cover, topography, geomorphology, structural features and landuse. Other conditions remaining same, topography plays a very important role. 3D- perspective view of the terrain reveals that the Kethan tank, situated in a narrow valley in between two hills over a gentle slope, provides recharge to a larger area, in spite of being smaller in size than the Naren tank. The Jassia tank along with the tank on the Kuri river do not provide appreciable recharge. These tanks are situated on 4^{th} and 5^{th} order streams where the catchment area is larger. By the time rain water reaches these higher order streams, the runoff velocity is quite high. The area is covered by unweathered basalt where lineament density is also very poor and there is little chance of infiltration. On the other hand, the downstream area of the Kethan tank is covered by weathered basalt. Lineament density is also quite high indicating presence of fractures, thus facilitating infiltration. A field study confirms the remote sensing and GIS based interpretation. A large area around the Kethan tank is benefiting from this tank for drinking and agricultural purposes. Based on these observations, a suitability analysis has been performed to suggest suitable sites for future artificial recharge structures. Weighted index overlay analysis has been performed to extract the zone of suitability using the following parameters: slope, geomorphology, geology, lineament, soil properties, depth to water level and specific electrical conductance. Then, the output map is combined with stream order, landuse and lineament buffer zone maps through Boolean logic model in order to locate the suitable site. The sites on yellow clay soil are excluded, by overlay analysis with FCC, as it acts as an impermeable layer, obstructing the downward movement of water. The recharge tanks are suggested on tributaries with gentle slope on valley bordered by hills. Subsurface dykes are suggested in the forested areas. Check dams are suggested in the areas of high runoff in the main stream to check runoff.

In this study, an integrated remote sensing and GIS technique has been developed for identification of groundwater potential zones and for selection of suitable artificial recharge sites and has been tested for the Kethan and the Narayan basin. To conclude with, the following remarks can be made.

- An analysis approach based on comparative study of the surveyed drainage vs simulated drainage for identification of recharge areas has been developed and tested in the present study. The results obtained from this approach are in match with other derived information on groundwater recharge.
- The present study has demonstrated that the reservoirs situated on a gentle slope and lower order streams are providing artificial recharge to a larger area.
- Combination of weighted index overlay and Boolean logic model has been found very useful in the selection of suitable sites for artificial recharge.
- Moderately high resolution remote sensing data (IRS-LISS-II and LISS-III) provide details of the terrain, as well as a synoptic overview, to visualize the general groundwater condition indirectly.
- The methodology developed may be applied to similar terrain conditions, with some local considerations and modifications.
- Incorporation of geophysical data can enrich the interpretation. The future scenario for artificial recharge can be also generated through GIS analysis.

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