

Chapter 6

Application of Remote Sensing and Geographical Information System in Groundwater Study



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1 Introduction

The availability of water, both in quantity and quality is the prime factor in deciding the sustainable growth of mankind and also for the development of towns and cities. With the advance in space technology, now it is possible to employ remote sensing techniques to estimate surface and subsurface water over large areas. The need for remote sensing based groundwater survey is necessary to define all possible features connected with localization of groundwater. Satellite data provide quick and beneficial baseline information about numerous factors that directly or indirectly control the occurrence and movement of groundwater such as geomorphology, soil types, slope, land use/land cover, drainage patterns, lineaments, etc. (Jha et al. 2007). These features are extracted from the appropriate satellite data products and integrated with the thematic details obtained from topographic sheets of the desired scale. The use of conventional techniques (e.g., geophysical, geostatistical, numerical modelling, etc.) for groundwater management, is often limited by the lack of adequate data. Frequent and long-term monitoring of groundwater and vadose zone systems by using all these conventional methods is expensive, laborious, time-consuming and destructive (Jha and Chowdary 2007). Therefore, innovative technologies, such as remote sensing (RS) and Geographic Information Systems (GIS), have an immense role to play (Jha and Chowdary 2007). Airborne and spaceborne imagery have also become better and increasingly detailed. The recent development of viewers like Google Earth, Bhuvan ISRO Portal etc. with very high resolution has allowed users to explore 2D/3D representation of the surface of the Earth more accurately. The application package ‘WARIS’ (Web enabled Water Resources Information System)

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171

developed by ISRO provides a comprehensive, credible and contextual view of India's water resources data along with allied natural resources data and information. It will allow users to search, access, visualize, understand, analyze and look into context and study spatial patterns.

The traditional use of remotely sensed images and their interpretations lies in qualitative characterization of hydrogeological mapping units (Meijerink 2000). For about three decades, the application of remote sensing technology in groundwater resources evaluation has been practised. Remote sensing is without doubt the backbone of hydrogeological reconnaissance in areas of the world where the coverage of detailed geological maps and field data are insufficient (Hoffmann and Sander 2007). These data, in conjunction with ground truth information, provide details on geology, geomorphology, structural pattern and recharge conditions, which ultimately define the groundwater regime. The groundwater prospect/potential maps can show the range in groundwater yield at different depths, besides indicating probable sites for recharging aquifers. GIS provides a means for introducing information and knowledge from other data sources into the decision-making process and help in handling and management of large and complex data bases. RS combined with GIS facilitates better data analysis and interpretation.

Even though remote sensing has proved to be a useful tool in providing data for GIS to study various environmental aspects including groundwater, a number of factors must be considered before using this data in GIS. Among these factors are those summarised by Baban and Luke (2000), which include the spatial resolution, the spectral resolution and the temporal resolution. In summary, satellite data can provide reliable up-to-date information on land cover, land use, geology, vegetation, geomorphology etc. which will provide an improved understanding of the hydrogeological system.

This chapter tries to outline how RS and GIS technologies are used for groundwater studies and the various approaches related to groundwater potential assessment in geological (consolidated and unconsolidated) formations using RS and GIS.

2 Development of Groundwater Mapping Using RS

Hydrogeologists were late to use satellite data for an obvious reason; groundwater lies in the subsurface. Also, the radar and radiometer based satellite has very few centimetres penetration capability into the ground. In spite of this apparent obstacle, RS holds tremendous potential for regional groundwater flow studies (Becker 2006). The remote-sensing data, with its ability for synoptic view, repetitive coverage with calibrated sensors to detect changes, and observations at different resolutions, provide a better alternative for natural resources management as compared to traditional methods (Lillesand et al. 2004; Chandra and Ghosh 2007; Ranganath et al. 2007; Mukherjee 2008). Remotely sensed indicators of groundwater may

provide important data where conventional alternatives are not available. An example of measured data includes groundwater heads, changes in groundwater storage, heat signatures, and subsidence data (Becker 2006). Ground-based RS (geophysics) is usually more expensive than space and airborne RS but is still more accurate and cheaper than invasive methods (drilling) (Meijerink 2007). These indicators include vegetation, surface water, water discharging to the surface carrying heat energy and runoff (Becker 2006). Satellite technology is reviewed in Table 6.1 with respect to its ability to measure groundwater potential, storage and fluxes. Continuous advancement in satellite sensor technology over the years has led to the availability of metre and sub-metre ground resolution.

2.1 Some Benefits of Using Satellite Data in Groundwater Mapping

The utility of remotely sensed data as an efficient tool for groundwater exploration and mapping in different lithological, structural and geomorphological features of various rock types has been well established through a number of studies worldwide (Krishnamurthy et al. 1996, 2000; Ai et al. 1998; Saraf and Choudhury 1998; Murthy 2000; Dhiman and Keshari 2002; Shahid et al. 2000; Sikdar et al. 2004; Chandra et al. 2006; Sultan et al. 2007; Vijith 2007; Sharma and Thakur 2007; Dhakate et al. 2008; Madrucci et al. 2008; Ganapuram et al. 2009; Suja Rose and Krishnan 2009; Dar et al. 2010; Pothiraj and Rajagopalan 2012; Waikar and Nilawar 2014; Ramamoorthy and Rammohan 2015) which are as follows:

1. For extracting the drainage network information from multisensor, multisatellite images such as Landsat-3, Return Beam Vidicon (RBV), Landsat-5 Thematic Mapper (TM) with SPOT Panchromatic Linear Array (PLA) stereo pairs as well as topographic sheets showed that satellite images can be used effectively.
2. The TanDEM-X (TerraSAR-X add-on for digital elevation measurement) mission was launched by the German Space Agency in June 2010 is expected to provide a globally standardized and accurate three-dimensional (3D) digital elevation model of Earth with a measuring point density of 12 m to obtain the depth to groundwater level from the digital elevation model which is more advance than shuttle radar topography mission (SRTM) data set.
3. For lineament extraction Landsat TM combining with SPOT-MS and SIR (Sub-surface Interface Radar) images were used extensively because reflection on Landsat TM imagery shows as straight to curvilinear topographic breaks. At present, the HRSI (High Resolution Satellite Image) clearly depicts minor faults and lineaments, and provides highly accurate spatial information products such as orthoimages, DEM, linear feature extraction and terrain modelling.

Table 6.1 Selected list of active space-based sensors that report data of potential use for investigations of groundwater resource

Sensor	Launch year	Ground resolution (m)	Precipitation	Surface temp	Soil moisture	Water storage	Snow water	Land cover	Topography
AMSR-E	2002	5400 – 56,000	X	X	X		X		
ASTER	1999	15,30,90		X				X	
AVHRR	1991–2003	1100	X	X	X		X		
GRACE	2002	300,000				X			
ENVISAT- RA	2002	1000		X					X
Landsat-7	1999	30,60		X				X	
MODIS	1999	250, 500, 1000		X				X	
Orb View-2	1997	1100		X				X	
Orb View-3	2003	1,4		X				X	
RADARSAT-1	1995	10,30,100			X				
SRTM	2000	30,90			X				X
IKONOS-2	2000	1,4						X	
Quick Bird-2	2009	0.6,2.4						X	
KOMPSAT-2	2006	1,4						X	
EROS-B1	2006	0.7						X	
Cartosat-2	2016	1			X			X	
GeoEye-1	2008	0.4,1.65						X	
WorldView-2	2009	0.52, 2.08						X	
Pleiades-HR 1 & 2	2011, 2012	0.7, 2.8						X	
KOMPSAT-3	2012	0.7						X	X

4. The recent data from the GRACE (Gravity Recovery and Climate Experiment) Satellite are available to assess changes in terrestrial water over larger areas. GRACE is a twin-satellite mission used to identify mass changes due to variations in water storage, assist in determination of groundwater depletion and residual basin-scale estimates of evaporation or validation of hydrological models. GRACE data are expressed in mm equivalent to water.
5. Microwave or radar images have several applications in hydrogeological studies. Radar altimetry for detecting lake levels is important for the groundwater heads and flow studies around lakes. Moreover, Digital Elevation Models (DEMs) and precise measurement of land subsidence can be done by radar data.
6. Meteosat thermal, Landsat optical and Modis normalized vegetation index (NDVI) data along with GIS have been extensively used by various scientists all over the world to identify land-surface features that control location of groundwater recharge and discharge areas in a large data-scarce, semi-arid basin.

3 Development of Groundwater Mapping Using GIS

The growth and use of GIS in groundwater investigations is increasing tremendously. It is used for groundwater potential (Krishnamurthy et al. 1996) and vulnerability assessment (Laurent et al. 1998), groundwater modelling (Watkins et al. 1996; Pinder 2002) and management (Patra et al. 2016). In regional scale, it requires to handle large volume of geo-referenced (spatial) and attribute (aspatial) data. GIS is an ideal problem solving environment where RS data and interpretations can be merged with discrete and continuous data from various primary and secondary sources (Burrough 1986; Manap et al. 2013; Rahmati et al. 2014; Deng et al. 2016).

GIS uses both operational and analysis tools for generating thematic maps. There are several commercial GIS packages available in the industry, namely Arcinfo, Integrated Land and Water Information System (ILWIS) and Earth Resource Data Analysis System (ERDAS), Geomatica, ENVI, TNTmips, QGIS etc. developed by various software vendors.

A GIS approach comprises three distinct phases: (1) data acquisition, (2) data processing, and (3) data analysis. The data acquisition phase includes establishing control of the data quality, which consists of positional accuracy, and reliability of observations. There are several ways of digitizing map data for inserting in a GIS. The data can be directly digitized from the map using a digitizing table or it can be digitized by tracing the outline of required classes on a transparent overlay in image processing software. A general approach to prepare different thematic maps for the development of a GIS database for hydrogeological mapping is shown in Fig. 6.1.

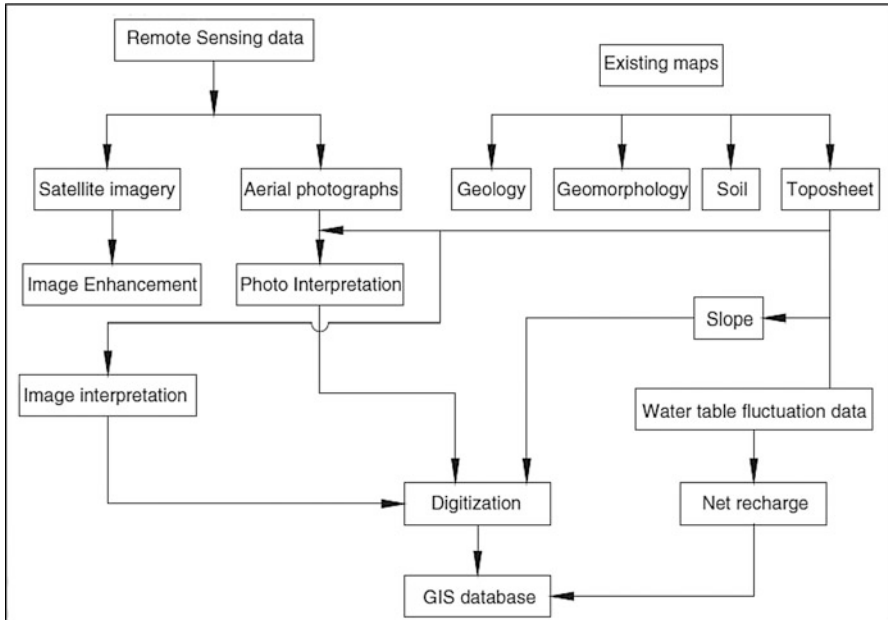


Fig. 6.1 Preparation of thematic map

4 Benefits of Using GIS

Some benefits of using GIS in groundwater mapping are as follows:

1. Teeuw (1995) proposed an integrated approach of RS and GIS techniques to improve the site selection for borehole drilling.
2. Nagarajan and Singh (2009) and Chowdhury et al. (2009) highlighted the importance of coupling RS and GIS in groundwater potential assessment studies.
3. Gosain and Sandhya (2004) used GIS as a pre-processor to the SWAT (Soil and Water Assessment Tool) model for assessment of existing and anticipated water uses and water shortages in chronically drought prone area. The output from the model was combined with water availability, sediment yield, demographic and socio-economic data in the GIS environment for prioritization of sub-watersheds for water-resources planning. Using GIS capabilities the possible locations of water-harvesting structures were identified for future development.
4. Elewa and Qaddah (2011) integrated Enhanced Thematic Mapper Plus (ETM+) images, GIS, a watershed modelling system (WMS) and weighted spatial probability modelling (WSPM) to identify the groundwater potential areas.
5. Dawoud et al. (2005) developed a GIS-based model to simulate the water resources in the Western Nile Delta. GIS was used to manage the spatially distributed input parameters such as the time invariant spatial data and outputs of the model.

Table 6.2 MCDA mapping studies relevant to groundwater recharge applications

Study	Country of application	MCDA
Rahman et al. (2012)	Portugal	AHP, WLC and OWA
Chowdhury et al. (2010)	West Bengal	AHP
Sargaonkar et al. (2011)	India	AHP
Srivastava and Bhattacharya (2006)	India	AHP
Machiwal et al. (2011)	India (Rajasthan)	AHP
Anane et al. (2008)	Tunisia	AHP and Boolean

- Lubczynski and Gurwin (2005) applied GIS cross-overlay procedure to merge different component maps and weight information relating to controls on recharge processes. The mapping of relative recharge rates has been applied to studies in aquifer vulnerability modelling, i.e. using the DRASTIC approach.
- Hajkowitz and Higgins (2008) suggested that multi-criteria decision analysis (MCDA) is a very efficient tool for groundwater assessment, and one of the most widely used MCDA types is the Analytic Hierarchy Process (AHP) method. It is implemented within GIS, which defines weights for criteria in many environmental and groundwater management problems. Table 6.2 shows some of the studies that used AHP as a MCDA method and Weighted Linear Combination (WLC) and Ordered Weighted Averaging (OWA) techniques to select site for groundwater recharge.

The AHP approach was used by Chowdhury et al. (2010), and Srivastava and Bhattacharya (2006) for deriving criteria weights, whilst Rahman et al. (2012) used WLC and OWA techniques to select the optimum sites for groundwater recharge, Machiwal et al. (2011) and Anane et al. (2008) used an AHP approach to support decision making, incorporating AHP to identify site for groundwater recharge.

5 Preparation of Groundwater Potential Maps Using RS and GIS

For the purpose of systematic and controlled development and planning of groundwater resources, groundwater mapping is one of the major tool used by many scientists. These maps are extensively used by engineers, planners and decision makers in order to govern the planning and development of groundwater resources and their optimum utilization as formulated in the National Water Policy by the Ministry of Water Resources, Government of India (NWP 2012). Jaiswal et al. (2003) proposed a schematic plan for exploitation of groundwater by integrating a number of thematic maps (Fig. 6.2) in a GIS environment for depicting village-wise groundwater prospect zones. Thematic maps such as topographical, geological,

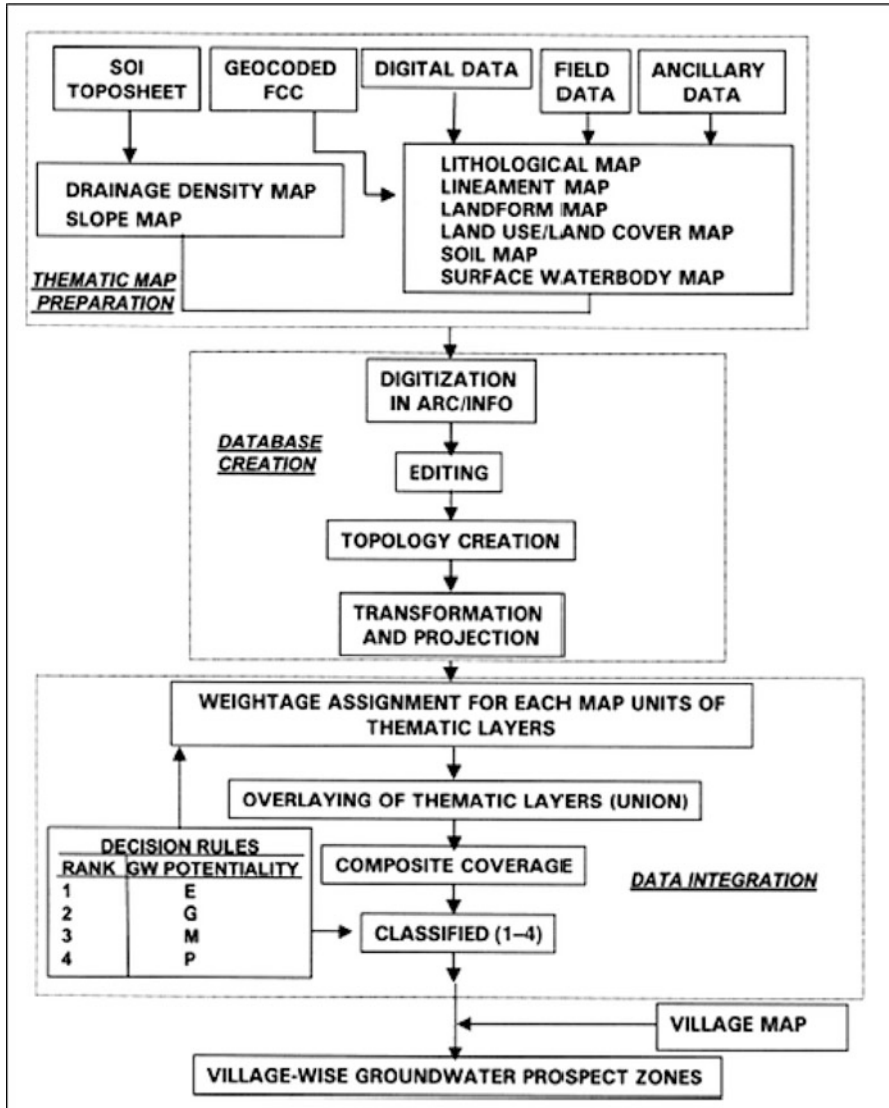


Fig. 6.2 Approach for delineating groundwater prospect zone (Adapted from Jaiswal et al. 2003).

hydrographical, hydrological, hydrochemical, drainage density and lineament density were prepared using the Indian Remote Sensing (IRS) data. The feature-based categorizations of thematic maps and the exact weightage were assigned to each of the thematic features based on their relative merit and demerit with respect to groundwater occurrence.

These maps were based on determining the most important contributing parameters that control groundwater storage. These parameters include the following:

1. Slope, which controls the runoff of water or remains on the ground surface for time long enough to infiltrate (SI),
2. Stream network, which influences the distribution of runoff and groundwater recharge (Dr),
3. Lineament, which enhance significantly the permeability by inducing secondary porosity and hence vertical water percolation to recharge the aquifers (Lin),
4. Lithology or rock type, which determines the soil and exposed rocks infiltration capabilities and govern the flow and storage of water (Geo), and
5. Topographical map layers (top).

These input layers were combined together mathematically by the equations (6.1) and (6.2) using the Raster Calculate Module in a GIS model to produce the final groundwater prospective zones of the investigated area. Each thematic map has been given a weight value depending on its strength of influence/contribution with respect to the groundwater storing.

$$GWP = \sum Wi \times CVi \quad (6.1)$$

where the GWP = groundwater potential, Wi = map weight and CVi = capability value (weight of inter-map class).

$$GWP = \sum (Dr, Lin, SI, Geo, top) \quad (6.2)$$

where Dr = stream network class, Lin = lineaments density class, SI = slope class Geo = lithology class and top = topography/elevation class.

6 Applications of RS and GIS in Consolidated and Unconsolidated Formations for Groundwater Studies

Groundwater is extracted from either consolidated rock formations or unconsolidated loose sediments. The occurrence of groundwater in a geological formation and the scope for its exploitation primarily depends on its porosity and permeability (Kesavulu 1993). A detailed methodology regarding the groundwater exploration in India has been summarized by the National Remote Sensing Agency (1993, 2008) and RGNDWM Project Team (2009). The steps includes:

1. Preparation of drainage map showing surface-water bodies, drainage channels, paleochannels (buried as well as abandoned) and flood plains.
2. Preparation of lineament map showing faults, fractures, dykes and lineament intersections.

3. Preparation of landuse/landcover map from RS data by incorporating observations on vegetation, landforms and topography.
4. Collection of soil, geology, water level and precipitation data and preparation of respective thematic maps.
5. Assigning suitable weights for each layer depending on their contribution to groundwater potential.
6. Integration in GIS environment.

Various groundwater exploration studies were successfully attempted by combining RS and GIS in the semi-arid, arid and hard rock geological formations of the world (Murthy 2000; Shahid et al. 2000; Krishnamurthy et al. 2000; Majumdar and Pal 2005; Kamla et al. 2006; Galonos and Rokos 2006; Vijith 2007; Sultan et al. 2007; Dhakate et al. 2008; Agarwal and Kachhwaha 2009; Kushwaha et al. 2010; Ganapuram et al. 2009; Dar et al. 2010; Khodaei and Nassery 2011; Madani and Niyazi 2015).

The studies by these authors suggest that the most important themes necessary for groundwater assessment in consolidated formations are lineament, geomorphology, slope, drainage density and land use/land cover. The major themes necessary for groundwater assessment in unconsolidated formations are lithology, geomorphology, slope, drainage density, soil type and land use/land cover. Further, themes such as rainfall intensity, surface-water bodies, topographic elevation and net recharge have also been considered in various studies and found to have improved the accuracy. The following salient features of the landscape have been used for assessing groundwater condition from RS data (Table 6.3).

Various models such as logical conditioning overlay analysis, weighted-index method, groundwater-potential index and multi-criteria analysis, overlay analysis, water-balance techniques, and correlation with NDVI values all in combination with remote sensing and GIS were attempted to arrive at the promising zones of groundwater potential in unconsolidated formations. A comparative study between these methods was not possible as the methods are site specific.

7 Case Studies

7.1 *Assessment of Groundwater Potential in Hard Rock Area through RS and GIS*

The Raniganj area of West Bengal has a long history of coal mining starting from 1744. This has resulted in major change in land use pattern and high groundwater abstraction leading to drinking water crisis especially during the pre-monsoon period.

Sikdar et al. (2004) investigated landuse/landcover change over the period of 26 years (1972–1998), geology and geomorphic set up and also groundwater potential zoning for future development using RS and GIS in Raniganj area, West Bengal. The study indicated that land covered with vegetation and settlement has

Table 6.3 Salient features of the landscape used for assessing groundwater condition from remote-sensing data

Features	Classification	Groundwater potential
Topography		The local and regional relief setting gives an idea about the general direction of groundwater flow and its influence on groundwater recharge and discharge
Slope	Low slope (0–5°)	High groundwater potential
	Medium slope (>5–20°)	Moderate groundwater potential
	High slope (>20°)	Poor groundwater potential
Vegetation	Phreatophytes	Shallow groundwater under unconfined conditions
	Xerophytes	Deep groundwater under unconfined conditions
	Halophytes	Shallow brackish or saline groundwater under unconfined conditions
Geologic landform	(a) Modern alluvial terraces, alluvial plains, floodplains and glacial moraines	(a) Favourable sites for groundwater storage
	(b) Sand dunes	(b) Presence of underlying sandy glacio-fluvial sediments indicating the presence of groundwater
	(c) Thick weathered rocks	(c) Moderate groundwater potential
	(d) Rocks with fractures/fissures	(d) Very good or excellent potential for groundwater
	(e) Rocks without fractures/fissures	(e) Unfavourable sites for groundwater occurrence
	(f) Hillocks, mounds and residual hills	(f) Unfavourable sites for groundwater existence
Lakes and streams	Oxbow lakes and old river channels	Favourable sites for groundwater extraction
	Perennial rivers and small perennial and intermittent lakes	High to moderate potential of groundwater
Drainage density	High	Unfavourable for groundwater availability
	Moderate	Moderate ground water potential
	Less/no	High groundwater potential
Drainage pattern	Gives an idea about the joints and faults in the bedrock which, in turn, indicates the presence or absence of groundwater	
Drainage texture	Coarse	Favourable site for groundwater storage
	Medium	Moderate groundwater occurrence
	Fine	Unfavourable site for groundwater storage

(continued)

Table 6.3 (continued)

Features	Classification	Groundwater potential
Lineaments	In pediplain or valley fill	Groundwater occurrence
	In denudational hills, residual hills, in areas of high-drainage density, high-slope areas, clay zones	Less significant for groundwater availability
Spring type	Depression springs, contact springs, and artesian springs.	Presence of potential aquifer
	Moist depressions, seeps and marshy environments	Presence of shallow groundwater under unconfined conditions

Adapted from: Jasmin and Mallikarjuna (2011)

decreased at the expense of mining activity. For delineating groundwater potential zone overlay analysis using multi-criteria such as drainage, texture, geomorphology, lithology, land use and steepness of slope were utilized to understand the potentiality of groundwater for future development.

The following data sources and methods were used to delineate groundwater potential zones for Raniganj area.

7.1.1 Data

- Survey of India Toposheet (73 M/2)
- The corresponding satellite imagery IRS-ID LISS-III geocoded FCC of 1998 on 1:50,000 scale, and geological map of the Geological Survey of India.

7.1.2 Methodology

The methodology used consists of following steps:

- Visual interpretations of satellite imagery to delineate the geology, drainage, geomorphologic units, lineament and land use/land cover.
- Field verification of interpreted units.
- Preparation of various thematic maps using GIS (ILWIS 3.3 Academic version).
- Preparation of slope map using Digital Elevation Model (DEM).
- Preparation of landuse/landcover change map over the period of 26 years.
- Preparation of groundwater potential zone map using overlay analysis in GIS platform.

7.1.3 Preparation of Thematic Maps

All the thematic maps were prepared in 1:50,000 scale with a spatial resolution of 0.1 km² using GIS package ILWIS to find out the potential groundwater bearing zone (Figs. 6.3 and 6.4, Table 6.4).

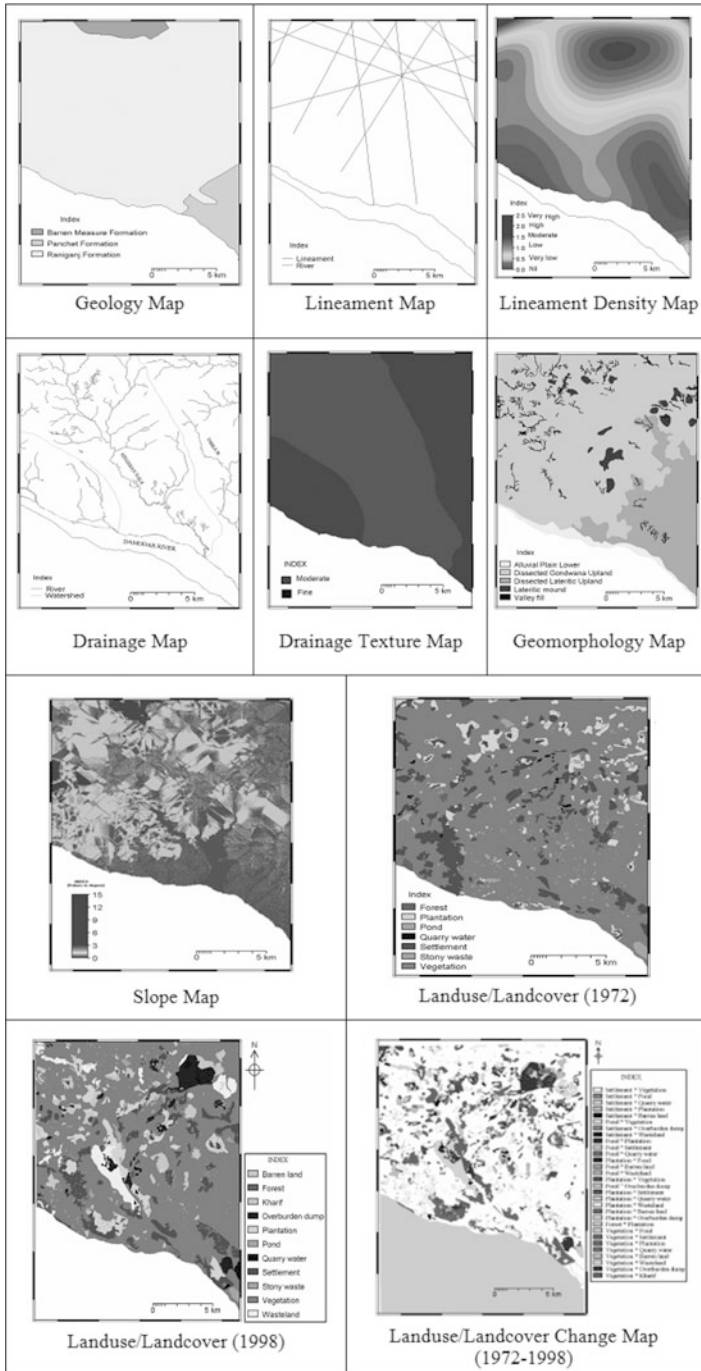
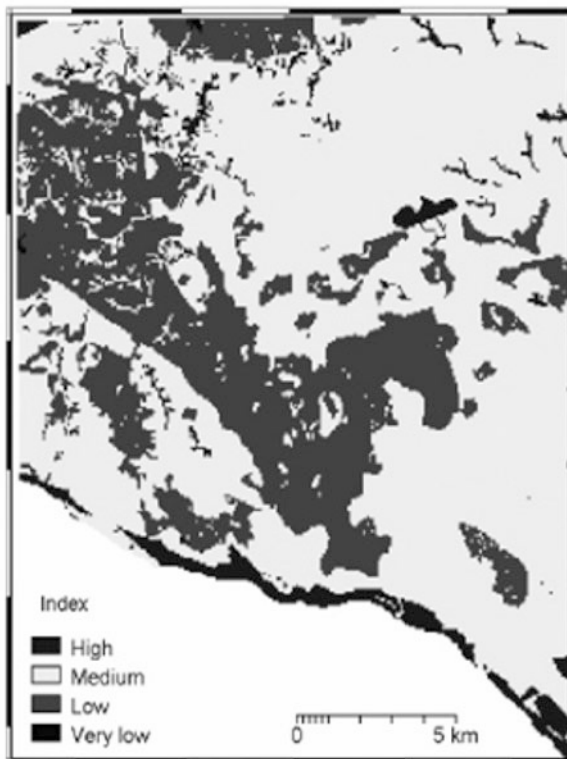


Fig. 6.3 Thematic maps of various layers (Adapted from Sikdar et al. 2004)

Fig. 6.4 Groundwater potential map of Raniganj area (Adapted from Sikdar et al. 2004)



7.2 Assessment of Groundwater Potential in Soft Rock Area through RS and GIS

Shahid et al. (2000) applied GIS to demarcate the groundwater potential zone in a soft rock area in Midnapur District, West Bengal, India which falls under the Gangetic West Bengal region. He used seven hydrogeologic themes on the basis of its direct control on the groundwater which include lithology (L), geomorphology (G), soil (S), net recharge (R), drainage density (D), slope (S) and surface water bodies (W). Each theme was assigned a value from 1 to 7. Each feature of an individual theme was ranked in the 1–10 scale in the ascending order of hydrogeologic significance. The Ground Water Potential Index (GWPI) for an integrated layer was calculated using GIS as

$$GWPI = (LwLr + GwGr + SwSr + RwRr + DwDr + EwEr + WwWr) / \sum w$$

where the index 'w' represents the weight of a theme and 'r' the rank of a feature in the theme. GWPI is a dimensionless quantity that helps in indexing the probable groundwater potential zones in an area. All the thematic maps were prepared in the

Table 6.4 Area covered by different groundwater potential zone

Category	Area covered (km ²)	Percentage of the total area	Yield range (m ³ /hr)	Depth/thickness of aquifer	Groundwater structures feasible
High	14.70	5.2	50–100	Unconfined 15–25 m	Dug wells fitted with low power pumps and tubewell fitted with hand pump and submersible pump
Medium	184.33	64.8	25–50	Confined 45–60	Dug well, dug-cum-bored well and tube well fitted with hand pump
Low	85.38	29.9	<25	Unconfined <15 m	Dug well, dug-cum-bored well
Very low	0.19	0.1	<25	Unconfined <15 m	Generally groundwater structures will not be successful. Dugwell, dug-cum-bored well may be constructed. Surface water should be harnessed and rooftop rainwater harvesting schemes may be adopted
Total	285.10	100			

Adapted from Sikdar et al. (2004)

1:50000 scale with a spatial resolution of 0.1 km² using the GIS package ARC/INFO. The evolved GIS-based model of the study area was found to be in strong agreement with available borehole and pumping test data. The field verification of this model also established the efficacy of the GIS in demarcating the potential groundwater areas in soft rock terrain.

8 Conclusion

This chapter highlights the capability of RS with suitable sensors to generate informations on the spatial and temporal domain and significance of GIS technology in managing large and complex databases for groundwater assessment and management studies. This chapter also focuses on the integration of RS and GIS based analysis and models in finding groundwater potential areas in the form of thematic maps in consolidated and unconsolidated formations. These maps are used by engineers, planners and decision makers to allocate, develop and manage groundwater resources. Satellite data derived geological and hydro-geomorphologic features, preparation of corresponding thematic maps, assigning appropriate weights and integration in a sophisticated GIS platform assist in prospecting the groundwater resources to plan recharging of aquifer, constructing water harvesting structures and drinking water sources. The use of advance high resolution satellite and aerial data in the future will remarkably augment the remote sensing services extending it to infrastructure, planning and management.

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