Remote Sensing

4

4.1 Introduction

Remote sensing, encompassing the study of satellite data and aerial photographs, is an extremely powerful technique for earth resources exploration, mapping and management. It involves measurements of electromagnetic (EM) radiation in the wavelength range of about 0.4 μm–1 m, from sensors flying on aerial or space platforms to characterize and infer properties of the terrain. Remote sensing has evolved primarily from the methods of aerial photography and photo-interpretation used extensively in 1950s–1960s. The technique has grown rapidly during the last four to five decades. In the context of groundwater studies, remote sensing is of great value as a very first reconnaissance tool, the usual sequence of investigations being: satellite images—aerial photographs—geophysical survey—drilling. Geological interpretation derived from aerial photos/remote sensing has been extensively used for the purpose of identification of lineaments or fracture zones along which flow of groundwater may take place and for landform investigations suitable for groundwater prospecting particularly in hard rocks (e.g., Mabee and Hardcastle 1997; Moore et al. 2002; Salama et al. 1994).

Fundamental Principle The basic principle involved in remote sensing is that each object, depending upon its physical characteristics, reflects, emits and absorbs varying intensities of radiation at different EM wavelength ranges. The curves depicting relative intensity of light reflected/absorbed/emitted by the objects at different wavelengths are called spectral response curves (Fig. 4.1). Using information from one or more wavelength ranges, it is possible to discriminate between different types of ground objects, e.g. water, dry soil, wet soil, vegetation, etc., and map their distribution on the ground. A generalized schematic of energy data/flow in a typical remote sensing programme is shown in Fig. 4.2.

Advantages and Limitations The chief advantages of remote sensing technique over other methods of data collection are due to the following:

1. Synoptic overview: remote sensing permits delineation of regional features and trends.
2. Feasibility: in some inaccessible areas, remote sensing may be the only way to get the information.
3. Time saving: The technique saves time and manpower as information about a large area is quickly gathered.
4. Multidisciplinary applications: the same remote sensing data can be used by workers in different disciplines of natural sciences.

Though remote sensing provides direct observations and inputs to all other components of hydrological cycle, viz. oceanic, atmospheric and surface water, there are limitations in remote sensing applications to groundwater, chiefly arising from the fact that the EM radiation have a limited depth of penetration—say fraction of a millimeter in the visible range to a couple of meters (in dry desert conditions) at the most in the microwave region. Therefore, interpretations on subsurface hydrogeology have to be based on indirect surface evidences and features such as landform, lithology, structure, vegetation, soil, drainage, land use, surface anomalies etc. (see Sect. 4.7).

The implementation of satellite remote sensing techniques to hydrogeological problems in developing countries has faced constraints in the past due to several factors such as high costs of satellite sensor data, expensive software tools, and lack of proper expertise/training etc. (Jha and Chowdary 2007). However,

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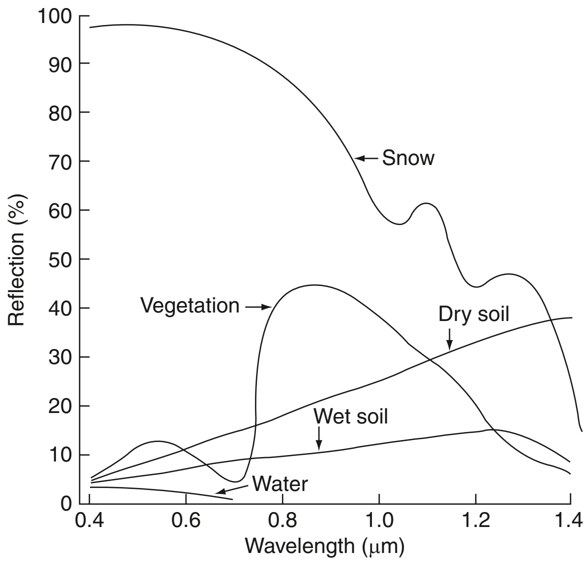

Fig. 4.1 Spectral response curves of selected objects

the above issues now appear to be resolved, at least in part, by the availability of free downloadable data (e.g. Landsat TM and ETM), free software packages (e.g. ILWIS), and several tutorials available on the web.

4.2 Physical Principles

EM Spectrum and Sources of Radiation Electromagnetic spectrum is the ordering of EM radiation according to wavelength, or frequency, or energy. The nomenclature used for different parts of the EM spectrum is shown in Fig. 4.3c.

For remote sensing purposes, the sensors may utilize either naturally available radiation from the Sun or the Earth or artificial radiation. The technique involving artificial illumination is called active, in contrast to the one utilizing naturally available radiation, which is termed passive. Solar reflected radiation dominates in the ultraviolet—visible—near-infrared parts of the spectrum (Fig. 4.3a), which, therefore, is called solar reflection region. The Earth-emitted radiation dominates in the 3–20 µm wavelength region, and this spectral region is therefore called thermal IR. Besides, artificial illumination using radar is frequently used in the microwave region.

Atmospheric Interactions The EM radiation while passing through the Earth's atmosphere interacts with atmospheric constituents and is selectively scattered, absorbed and transmitted. Raleigh scattering is the most important type of scattering and leads to haze and low-contrast pictures in the UV-blue parts of the EM spectrum. Further, selective absorption of the EM radiation takes place by atmospheric gases such as H_2O-vapour, CO_2 and O_3 etc. The spectral regions of least atmospheric absorption are called atmospheric windows, as these can be advantageously used for looking at the Earth's surface from aerial/space platforms. Major atmospheric windows occur in the visible (VIS), near-IR (NIR), shortwave-IR (SWIR), thermal IR (TIR), and microwave regions (Fig. 4.3b).

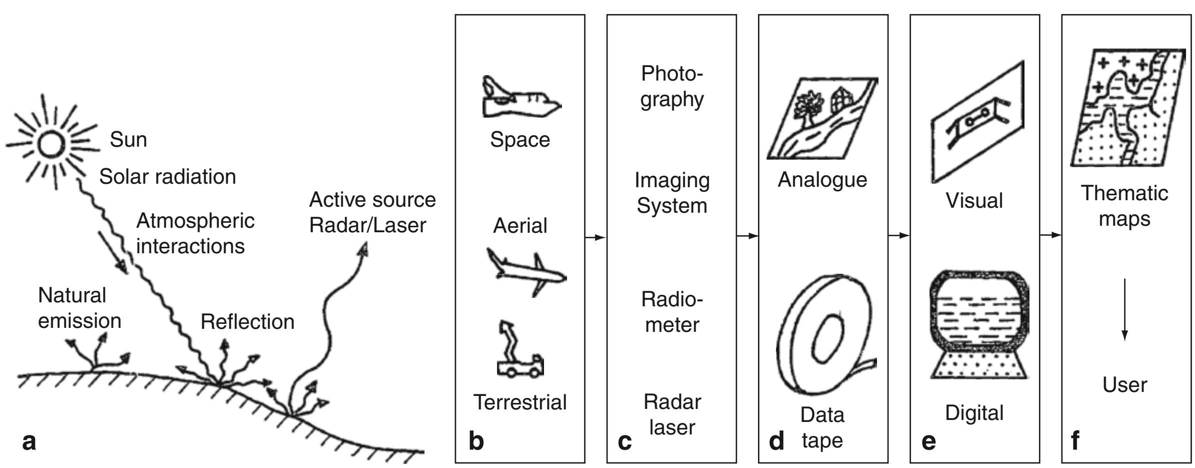

Fig. 4.2 Schematic data flow in a typical remote sensing programme

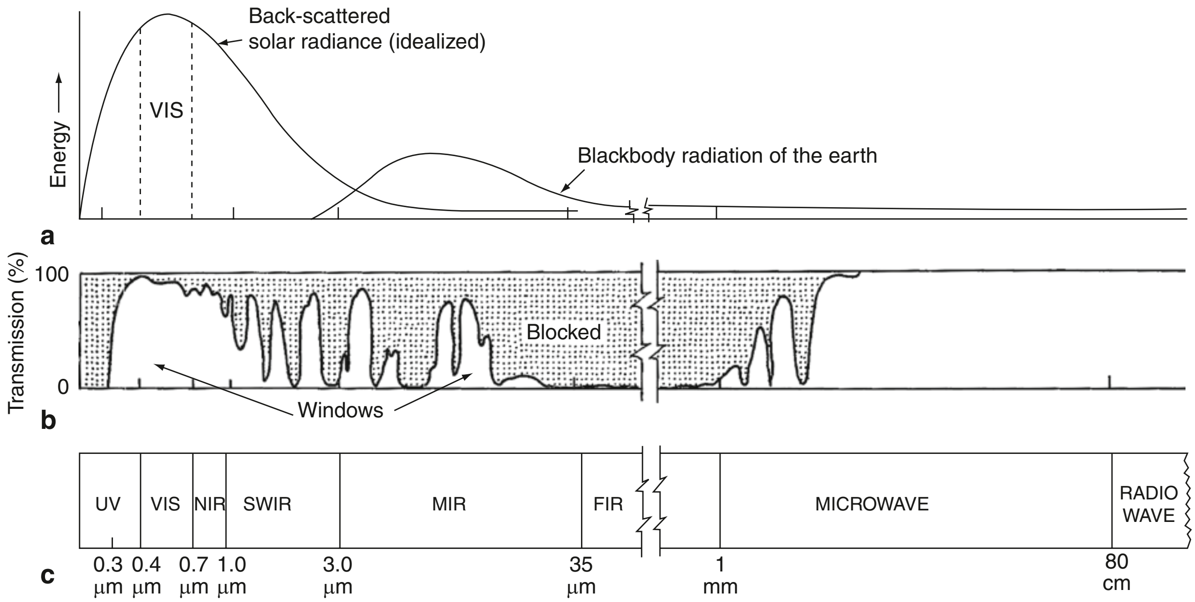

Fig. 4.3 **a** Backscattered solar radiation (idealised) and black body radiation of the earth, **b** atmospheric windows, **c** EM spectrum and nomenclature

Platforms Sensors for EM radiation can be operated from airborne, spaceborne or ground based platforms (Fig. 4.2b). Some of the typical airborne platforms are helicopters, aircrafts and balloons, whereas satellites, rockets and space shuttles constitute the space platforms. The hydraulic platforms and hand-held field instruments are used for collecting ground truth, to help better interpret aerial and space remote sensing data.

4.3 Remote Sensors

A sensor is a device to measure radiation intensity. It comprises optical components and detectors. A wide variety of sensors operate in various parts of the EM spectrum. For a comprehensive discussion on remote sensors, the reader is referred to other texts (Sabins 1997; Lillesand et al. 2007; Gupta 2003). Keeping in mind the operational aspects for groundwater investigations in fractured rocks, we consider here four main types of remote sensors: (a) photographic systems, (b) line scanning systems, (c) digital cameras, and (d) imaging radar systems.

4.3.1 Photographic Systems

Perhaps, the most familiar remote sensing systems have been photographic. Main advantages of photographic systems have been good geometric accuracy and high resolution, whereas chief limitations include logistics related to the retrieval of films from spacecrafts and limited spectral range of operation. A standard film is panchromatic black-and-white and gives output in shades of gray. Other films are colour out of which colour infrared film (CIR) is most important for resources investigations. Filters permit sensing in selected wavelengths of light and form an integral part of modern photographic system.

The photographic systems can be deployed from space, aerial or terrestrial platforms. From aerial platforms, the vertical photography with an overlap of 70–75% for stereo viewing has been a standard technique in remote sensing (e.g. Wolf 1983) and its unique advantage of stereo viewing with good geometric accuracy has not been taken-over by any spaceborne remote sensing technique till date. Aerial photographs normally at of 1:20000–1:50000 scales are used, the larger scale photography being ideally employed for detailed site selections.

4.3.2 Line Scanning Systems

Multispectral line scanning systems have been the most important device for remote sensing from satellite platforms. A scanner is a non-photographic device and generates digital data on intensity of ground radiance. The entire scene is considered to be comprised of a large number of smaller cells. Radiation from each unit cell is collected and integrated by the scanning system, to yield a brightness value, or digital number (DN), which is ascribed to the unit cell (Fig. 4.4). This process is called scanning. There are several advantages of scanners over photographic techniques related to retrieval of data and sensing in extended wavelength range with high spectral, spatial and radiometric resolutions. Further, the digital information from scanners is amenable to computer processing enhancement etc., and for integrated interpretation in GIS.

Resolution of a sensor is an important parameter and is given in terms of spatial, spectral, radiometric and temporal aspects. Spatial resolution implies the ground resolution and corresponds to a pixel on the image. Spectral resolution means the span of wavelength range over which a spectral channel operates. Radiometric resolution generally implies the total number of quantization levels used in the sensor. Temporal resolution refers to the repetivity of observations over an area.

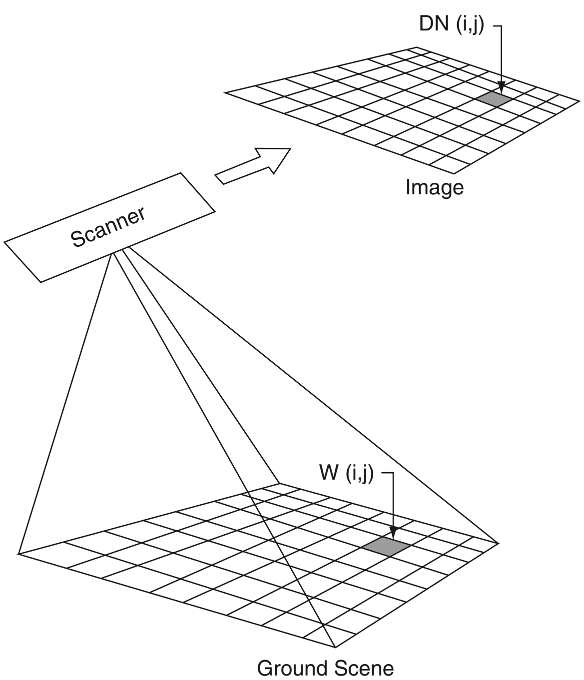

Fig. 4.4 Working principle of a scanner. The ground radiance $W_{(ij)}$ from a ground cell is converted into a digital number $DN_{(ij)}$ at the corresponding position in the image

Types of Line Scanners There are two basic types of line scanners: 1. opto-mechanical (OM) line scanners and 2. charge-coupled device (CCD) line scanners. The OM line scanners have been extensively used from aerial and space platforms in multispectral mode at a wide range of wavelength from visible, near-IR, SWIR to thermal-IR. In this, the collector optics includes a moving plane mirror to reflect radiation from the ground which is collected and directed on-to the filter and detector assembly for quantization. The MSS, TM and ETM+ on Landsats are typical OM line scanners. The CCD line scanners are solid-state scanners and utilize photoconductors as the detector material. In a CCD line scanning system, a linear array of CCDs comprising several thousand detector elements is placed at the focal plane of a camera system to sense the radiation and convert the same into electrical signal. Typically, for each spectral band there is one CCD line array viewing the entire swath, simultaneously. Thus, there is no moving part in the sensor. The CCD line scanning system has been used in many earth-observation satellites sensors, such as SPOT-HRV, IRS-LISS, JERS-OPS etc.

4.3.3 Digital Cameras

Digital imaging camera constitutes a rather recent development in remote sensing technology and provides high-definition images at reduced costs. A digital camera employs a solid-state area-array (using CCDs or CMOS) with millions of photo-sensitive sites, which produces a two-dimensional digital image. Thus, the basic difference between a film-based photographic camera and a digital imaging camera is that in the latter the film is replaced by solid-state electronics. The incident light is focused by the optical device on the photo-sensitive area array that generates a signal which is quantized and recorded. The main advantages of digital imaging cameras arise from their direct digital output, fast processing, higher sensitivity, better image radiometry, higher geometric fidelity and lower costs. A major limitation is imposed by detector technology that limits its usability in the wavelength range from visible to near-IR, presently. The development and growth of digital imaging technology by using area-arrays has been very fast. Space sensors using this technology include all the modern high-resolution satellite sensors such as IKONOS, QuickBird, CARTOSAT, GEOEYE etc.

4.3.4 Imaging Radar System

The electromagnetic spectrum range 1 mm–100 cm is commonly designated as microwave. The atmosphere is nearly transparent at these wavelengths. Basically, the microwave technique is of two types: (a) passive, and (b) active. The passive microwave radiometry has a major limitation of coarse spatial resolution (about 10–20 km^2). We therefore, in the context of groundwater applications, restrict this discussion to active microwave remote sensing, also called imaging radar.

Radar (Radio Detection and Ranging) basically operates on the principle that artificially generated microwaves sent in a particular direction collide with objects and are scattered. The back-scattered radiation is received, amplified and analyzed to determine location, electrical properties and surface configuration of the objects. The radar has all-time and all-weather capability, independent of solar illumination and atmospheric-meteorologic factors.

For imaging purpose, the radar is mounted in the configuration of Side-Looking Airborne Radar (SLAR), at the base of the sensor platform (Fig. 4.5). The radar transmits short pulses of microwave EM energy, illuminating narrow strips of ground, perpendicular to the flight direction. The radiation back-scattered from the ground is recorded to give information about the objects on the ground. As the sensorcraft moves forward, a two-dimensional image is generated.

Two basic types of imaging radars have been used: (a) real aperture and (b) synthetic aperture (e.g. Trevett 1986). Synthetic aperture radar (SAR) utilizes advanced data processing algorithms to yield higher spatial resolution and is employed in modern remote sensing programmes. Commonly, the SAR systems have a ground resolution of the order of 5–30 m, depending upon the altitude and sophistication in data processing. A number of SAR experiments have been conducted from aircrafts and spacecrafts. Important spaceborne SAR missions have been SEASAT, ERS-1/2, JERS (FUYO)-1, RADARSAT, ENVISAT-1 and DAICHI (ALOS).

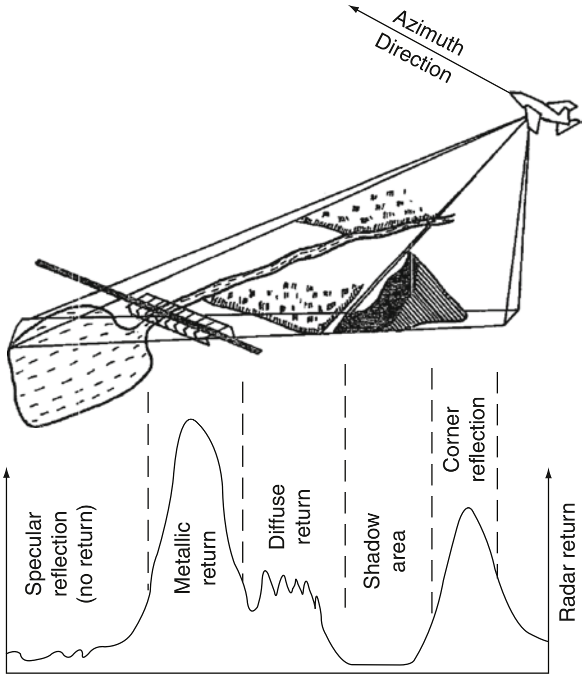

Fig. 4.5 Principle of side-looking airborne radar and typical radar returns. (Modified after Sabins 1997)

Geometry of SAR imagery is fundamentally different from that of photographs and scanner images because of the oblique viewing configuration of the imaging radar system. Several serious geometric distortions arise due to image displacement, particularly in mountainous areas. Further, shadows and look-direction effects are also prominently manifested on SAR images.

The backscattered signal received at the SAR antenna is called "radar return" and carries information about the properties of the object. It depends upon numerous factors, such as radar wavelength, EM beam polarization, local incidence angle, target surface roughness and complex dielectric constant. Thus, it has to be kept in mind during interpretation that the radar response is governed by a complex interplay of radar system and ground terrain factors.

4.4 Important Spaceborne Sensors

LANDSAT Program Till date, the Landsat program of NASA has provided the most extensively used remote sensing data, the world over. Its chief plank has been in delivering unrestricted global data of good geometric accuracy at rather low costs. Starting 1972, till date, seven satellites (Landsat-1, 2, 3, 4, 5, 6 and 7) have been launched under the Landsat program. These satellites have been placed in near-polar, near-circular, sun-synchronous orbit. In this configuration, as the satellite orbits in the nearly north–south plane, the Earth below spins around its axis, from west to east (Fig. 4.6). Thus, different parts of the globe are 'seen' by the satellite during different north–south passes and entire globe is scanned. Remote sensing data are generally acquired in the descending node, i.e. as the satellite moves from the north to the south. The Landsats-1, 2, 3 were placed at an altitude of 918 km with a repeat cycle of 18 days, and L-4, 5, 6 and 7 at an altitude of 705 km with a repeat cycle of 16 days.

Fig. 4.6 Typical near-polar orbit of an earth observation satellite such as Landsat, IRS etc. As the satellite revolves in N–S orbit, the earth spins from W to E; therefore different parts of the earth are observed by the satellite in different N–S passes

For remote sensing, the Landsats have used OM-line scanners producing ground scenes of nominally 185 × 185 km size. Initially, the Multispectral Scanning System (MSS) was used which provided excellent multispectral data in four spectral bands and made the remote sensing experiment a tremendous success. The Thematic Mapper (TM) was an improved OM scanner yielding data in seven spectral bands with higher spectral, spatial and radiometric resolutions. Enhanced Thematic Mapper Plus (ETM+) being used on Landsat 7 is a further improved version yielding data in eight spectral bands (Table 4.1).

SPOT Program Under the French remote sensing program, a series of five satellites (SPOT-1, 2, 3, 4, and 5) have been launched since 1986, all being in near-polar sun-synchronous orbit. The SPOT program has used CCD linear array devices for remote sensing. The first sensor was called HRV (High Resolution Visible) used in SPOT-1, 2, 3 and yielded data in panchromatic and multispectral modes. Further, it could be tilted to acquire data in off-nadir viewing mode enabling more frequent repetitive coverage and stereoscopy. The HRV sensor was modified as HRVIR sensor on SPOT-4 improving on resolution and more number of spectral bands. The latest HRG (high resolution geometrical) sensor is a further improved version being used on SPOT-5. It provides high spatial resolution in panchromatic band and four multispectral bands in green, red, near-IR and SWIR bands (Table 4.1).

IRS Program Commencing 1988, the Indian Space Research Organisation (ISRO) has launched a series of land observation satellites, naming the series as Indian Remote Sensing Satellite (IRS) program. All these satellites have been placed in near-polar, sun-synchronous orbit. The sensors used have been typically CCD linear arrays to yield data in multispectral mode and called Linear Imaging Self Scanning (LISS-I, -II, -III, and -IV). LISS-I and LISS-II were used on initial IRS-1A and -1B platforms to yield data in blue, green, red, and near-IR spectral ranges. LISS-III is an improved version used on IRS-1C and -1D and provides data in green, red, near-IR and SWIR bands. LISS-IV is a multispectral sensor on RESOURCESAT platform and provides relatively good spatial resolution (5.8 m)

Table 4.1 Comparison of spatial resolutions of selected spaceborne remote sensors (all data in m)

		Panchromatic	Blue	Green	Red	Near IR	SWIR I	SWIR II	Thermal-IR
LANDSAT	MSS*	–	–	79×79	79×79	79×79	–	–	–
	TM*	–	30×30	30×30	30×30	30×30	30×30	30×30	120×120
	ETM+	15×15	30×30	30×30	30×30	30×30	30×30	30×30	60×60
IRS	LISS I*	–	72×72	72×72	72×72	72×72	–	–	–
	LISS II*	–	36×36	36×36	36×36	36×36	–	–	–
	LISS III	–	–	23×23	23×23	23×23	70×70	–	–
	Pan	5.8×5.8	–	–	–	–	–	–	–
	WiFS	–	–	–	188×188	188×188	–	–	–
	LISS IV	–	–	5.8×5.8	5.8×5.8	5.8×5.8	–	–	–
	CARTOSAT-1	2.5×2.5	–	–	–	–	–	–	–
	CARTOSAT-2A	0.8×0.8	–	–	–	–	–	–	–
SPOT	HRV-Pan*	10×10	–	–	–	–	–	–	–
	Multi*	–	–	20×20	20×20	20×20	–	–	–
	HRVIR-HR*	–	–	–	10×10	–	–	–	–
	Multi*	–	–	20×20	20×20	20×20	20×20	–	–
	HRG	2.5×5	–	10×10	10×10	10×10	20×20	–	–
JERS-OPS*		–	–	18×24	18×24	18×24	18×24	18×24	–
DAICHI (ALOS)									
	PRISM	2.5×2.5	–	–	–	–	–	–	–
	AVNIR	–	10×10	10×10	10×10	10×10	–	–	–
CBERS		20×20	20×20	20×20	20×20	20×20	–	–	–
TERRA	ASTER	–	–	15×15	15×15	15×15	30×30	30×30	90×90
IKONOS	Pan	1×1	–	–	–	–	–	–	–
	Multi	–	4×4	4×4	4×4	4×4	–	–	–
QuickBird-2	Pan	0.6×0.6	–	–	–	–	–	–	–
	Multi	–	2.5×2.5	2.5×2.5	2.5×2.5	2.5×2.5	–	–	–
FORMOSAT		2×2	8×8	8×8	8×8	8×8	–	–	–
KOMPSAT		1×1	4×4	4×4	4×4	4×4	–	–	–
WorldView-1		0.55×0.55	–	–	–	–	–	–	–
GEOEYE-1	Pan	0.4×0.4	–	–	–	–	–	–	–
	Multi	–	–	1.65×1.65	1.65×1.65	1.65×1.65	–	–	–

*Archive data may be available from these sensors

data in green, red and near-IR multispectral bands. A high resolution panchromatic band (Pan) with stereo capability has also been included in all but the initial programs (Table 4.1).

FUYO (JERS) and DAICHI (ALOS) Programs The Japanese earth resources remote sensing satellite programs, FUYO and DAICHI, both have included an optical sensor as well a SAR sensor on the same platform. The satellites have utilized near-circular, sun-synchronous and near-polar orbit. The Japanese Earth Resources Satellite-1 (Fuyo-1) (1992) employed an optical sensor (OPS) using CCD linear arrays that yielded data in green, red, near-IR and SWIR bands. The Fuyo-1 SAR operated at 23.5 cm wavelength and provided data with a ground resolution of 18 m. The DAICHI (Advanced Land Observation Satellite, ALOS) carries two optical sensors—one called PRISM, that provides stereo data with 2.5×2.5 m spatial resolution, and another called AVINIR, that provides multispectral data in blue, green, red and near-IR bands with 10×10 m spatial resolution. In addition to the optical sensors, ALOS also carries an L-band SAR sensor called PALSAR.

TERRA-ASTER Sensor A very important sensor for geoscientific applications is the ASTER (Advanced Spaceborne Thermal Emission and Reflection) radiometer, launched by the NASA as a part of the Earth Observation Satellite program aboard TERRA platform

Table 4.2 Salient characteristics of selected spaceborne SAR systems

Spaceborne system Parameter	Altitude (km)	Wavelength (cm)	Band	Swath Width (km)	Azimuth resolution (m)	Range resolution (m)
Seasat* (USA)	795	23.5	L-band	100	25	25
SIR-A* (USA)	259	23.5	L-band	50	40	40
JERS-1* (Japan)	568	23.5	L-band	75	18	18
ERS-1/2* (ESA)	777	5.7	C-band	100	28	26
Radarsat* (Canada)	~800	5.7	C-band	10–500	9–100	10–100
Envisat-1 (ESA)	777	5.7	C-band	100	25	25

*Archive data available

in 1999. ASTER carries moderate resolution (15 m, 30 m, 90 m) imaging sensors in a wide range of 14 spectral bands lying in the visible—near infrared—SWIR—thermal infrared parts of the EM spectrum. The spectral bands are such that they are sensitive to broad chemical-mineralogic constituents (e.g. contents in terms of Fe–O, argillic, carbonates, silica, felsic vs. mafic etc.) and can be used to derive broad mineralogic compositional information (for more details, see e.g. Ninomiya et al. 2005; Hook et al. 2005; Rowan et al. 2003).

High Spatial Resolution Space Sensors A general trend in the evolution of spaceborne remote sensing systems has been the deployment of multispectral bands, one each in green, red and near-IR bands, with good spatial resolution to allow generation of high-resolution CIR composites. This may be with or without one still higher spatial resolution panchromatic band with stereoscopic capability. AB selected list is given in Table 4.1.

SAR Programs During the past three decades, a number of spaceborne SAR sensors have been launched by various agencies for resources investigations. Salient specifications of these sensors are listed in Table 4.2. The first spaceborne SAR sensor was the SEASAT (1978) which operated for about 100 days. A series of Shuttle Imaging Radar (SIR-A,-B,-C) yielded radar images of selected parts of the earth in different radar imaging modes on experimental basis. The European Resources Satellite (ERS-1/2) was a very important SAR mission that provided global data and has been particularly useful for SAR interferometry. JERS-1 and RADARSAT-1 also yielded useful SAR images from space.

Currently, data may be available from *ENVISAT-ASAR*, ALOS-PALSAR and TerraSAR-X. The ENVISAT-ASAR can operate in alternate polarization mode. The *ALOS-PALSAR* is the first fully polarimetric L-Band spaceborne sensor. The *TerraSAR*-X is the first commercial SAR sensor to provide up-to 1 m resolution. It can operate in alternate polarization mode, provide polarimetry data and along track interferometry. Planned sensors include *RADARSAT-2*, *Sentinel-1* (follow-on to the ENVISAT), and *TerraSAR-L (Cartwheel)* and *Tandem-X*, that are novel concepts in SAR imaging to provide single pass along-track and cross-track interferometry.

4.5 Interpretation Principles

To commence a study, first, the remote sensing photographs and images are indexed to provide information on location, scale, orientation and extent of the area covered. Mosaicking provides a bird's-eye view of the entire area. Overlapping photographs and images may be studied stereoscopically. Products of a multispectral set can be combined in colour mode. Digital data can be processed for enhancement, classification and interpretation. It can also be combined with ancillary geodata in a GIS approach, for a comprehensive interpretation.

Several photo recognition parameters are used to study and interpret features on photographs and images. These are called elements of interpretation and geotechnical elements (Table 4.3) (for details see e.g. Colwell 1960; Mekel 1978). Convergence of evidence is a general underlying principle in photo and image interpretation. It implies integrating all the photo-evidences and analyzing where all the photo-parameters are leading to, collectively.

Ground truth is necessary for reliable interpretation of remote sensing data. It aims to provide a reference

Table 4.3 Elements of photo-interpretation and geotechnical elements

A. Elements of photo-interpretation	
1. Tone	It is a measure of the relative brightness of an object in shades of grey
2. Colour	Appropriate terms are used to describe the colour; use of colour dramatically increases the capability of subtler distinctions
3. Texture	It means tonal arrangements and changes in a photographic image; it is the composite effect of unit features too small to be discerned individually
4. Pattern	It refers to spatial arrangement of features, like drainage, vegetation, etc.
5. Shadow	Shadow helps in studying the profile view of objects, and is particularly useful for man-made objects
6. Shape	Outline of an object in plan
7. Size	Size of an object is related to scale
8. Site/association	Mutual association of objects is one of the most important guides in photo/image interpretation
B. Geotechnical elements	
1. Landform	Constructional and depositional landforms are associated with various natural agencies of weathering and erosion, and are extremely helpful in identifying hydrogeomorphological characteristics of the site
2. Drainage	It is one of the most important geotechnical element and includes the study of drainage density, valley shape and drainage pattern
3. Soil	Soil characteristics depend upon the bedrock material and agencies of weathering. They have characteristic hydrological properties which govern surface run-off vis-à-vis infiltration
4. Vegetation	Vegetation distribution and type may be related to lithology and subsurface seepage zone

base for interpretation, as also to verify anomalous responses, if any. Parameters for field survey may include: rock/soil type, geological structure, soil moisture, vegetation type and density, land use, groundwater level etc. Often, ground truth observations are made by field-checking. At times, adequately large-scale photographs and images may also serve as ground truth for smaller-scale satellite image data.

4.6 Interpretation of Remote Sensing Data

The discussion here is divided into the following:

1. Panchromatic photographs and images
2. Multispectral image data
3. CIR photographs and composites
4. Thermal IR image data, and
5. SAR imagery.

4.6.1 Panchromatic Photographs and Images

Panchromatic sensors are broad-band sensors operating in the visible range (0.4–0.7 μm wavelength) and carry a major advantage of high spatial resolution in comparison to that of multispectral sensors (Table 4.1). Panchromatic photographs and images may be obtained from a variety of platforms or sensors and may differ in their geometry and scale; however, they are quite similar as far as the spectral characters are concerned, and therefore, their interpretation must follow the same line of logic. The technique of air photo-interpretation has been described in numerous standard publications (e.g. Colwell 1960; Miller and Miller 1961; Ray 1965). Numerous factors such as atmospheric condition, topography, slope, aspect etc. affect the image data (Table 4.4). Target reflectance i.e. albedo and its variation across the scene is very important, and deciphering this parameter holds the key to remote sensing applications. Spectral characteristics and identification features of selected features are described below.

On panchromatic products, deep and clear water body appears dark; on the other hand, turbid and shallow water body appears in shades of light gray to gray. Vegetation appears dark gray to light gray, depending upon the density and type of foliage. Soils appear in various shades of gray, the variation being related to moisture content, organic matter and grain size of the soil. Cultural features such as cities, settlements, roads and railway tracks can often be recognized by their shapes and outlines.

Stereo aerial black-and-white photographs have been routinely used for the study of landforms,

Table 4.4 Salient factors affecting image data in the solar reflection region

Primary variables	Secondary variables	Comments
1. Atmospheric factors	Composition of the atmosphere leading to absorption; particulates and aerosols, leading to scattering; relative humidity, cloud cover, rain etc.	May vary within a scene from place to place
2. Topography and slope aspect	Goniometric aspects, landscape position and slope direction; sun-sensor look angle	Vary from place to place within a scene, depending upon sun-local topography relation
3. Target reflectance	Albedo of the object; surface texture and coating	Deciphering this attribute holds the clue in remote sensing

lithology, structure, lineaments, soil, vegetation etc. Identification of rock types is based on convergence of evidence derived from a number of parameters (Sect. 4.8.8). Interpretation of panchromatic data can provide valuable inputs in geohydrological studies, particularly in the context of runoff, evaporation and groundwater recharge (e.g. Colwell 1960).

4.6.2 Multispectral Image Data

Multispectral image data in the solar reflection region are available on a routine basis from a number of space-sensors such as LANDSAT-ETM+, SPOT-HRG, IRS-LISS-III/LISS-IV, TERRA-ASTER, IKONOS, QUICKBIRD, and GEOEYE etc. (Table 4.1). As spectral distribution of these sensors is quite comparable, interpretation of image products from these sensors must follow a common line of argument. Spectral characters of common objects on multispectral bands are briefly mentioned below (Table 4.5).

Water exhibits different characters, depending upon its suspended load and the depth of the water body. Clear and deep water bodies are generally dark, and turbid and shallow water bodies reflect in the shorter wavelengths (blue/green). In the NIR and SWIR, all water bodies appear black. Vegetation in general appears medium-dark in the VIS and bright in the NIR. Cropland is medium gray and is marked by the characteristic field pattern. Soils and fallow fields (dry) are light in the VIS and medium gray in the NIR—SWIR bands. Moist ground is medium gray in the VIS but very dark in the NIR and SWIR. Rocky terrain (bare) is usually brighter in the VIS than in the NIR and SWIR, and may be characterized by landforms and structures. Clayey soils are medium to light toned in the VIS, NIR and SWIR-I, but are very dark in the SWIR-II, due to strong absorption by the hydroxyl anions. Snow is bright in the VIS—NIR and exhibits typical absorption in the SWIR-I. Clouds appear bright in the all the bands due to non-selective scattering. The multispectral data have opened vast opportunities for mapping and monitoring of surface features for hydrogeological investigations and a multitude of other applications.

4.6.3 CIR Photographs and Composites

Colour infrared (CIR) photography has been carried out from aerial platforms world over, as also from selected space missions (e.g. Skylab, Metric Camera and Large Format Camera etc.). False colour composite (FCC) is an extensively used technique for combining

Table 4.5 Response characteristics of important multispectral bands

Blue	Green	Red	NIR	SWIR-I	SWIR-II
Very strong absorption by vegetation and Fe–O; good water penetration; high scattering by suspended particles	Some vegetation reflectance; good water penetration; scattering by suspended particles	Very strong absorption by vegetation; some water penetration; scattering by suspended particles	High reflectance by limonite and vegetation; total absorption by water	General higher reflectance; insensitive to moisture contained in vegetation or hydroxyl bearing minerals; absorption by water, snow	High absorption by hydroxyl-bearing minerals, carbonates hydrous minerals vegetation, water and snow

multispectral images of the same area through colour coding. In an FCC, three images of a multispectral set are projected concurrently, one each in a different primary colour, and geometrically superimposed to yield a colour composite. This optical combination carries information from all the three input images, in terms of colour variation across the scene. As these colours are not shown by the objects in nature, these products are called false colour composites (FCC's). Though, as such, any spectral band may be coded in any primary colour, a standard FCC uses a definite colour coding scheme as follows:

- Response in green wavelength range—shown in blue colour.
- Response in red wavelength range—shown in green colour.
- Response in NIR wavelength range—shown in red colour.

This is also called CIR composite as the colour coding scheme is analogous to a CIR photograph. On these products, vegetation appears in shades of red; deep and clear water bodies are dark, whereas shallow-silted water bodies are cyanish; dry sands are white-yellow while wet fields are cyanish-light grayish. Bare rocky slopes appear in shades of gray.

4.6.4 Thermal IR Image Data

The EM wavelength region of 3–25 μm is popularly called thermal infrared (TIR) region. Any sensor operating in this wavelength region would primarily detect the thermal radiative properties of ground materials. Out of this the 8–14 μm region has been of greatest interest, as this is characterized by the peak of the Earth's blackbody radiation and an excellent atmospheric window (Fig. 4.3). The thermally radiated energy is a function of two parameters: surface temperature, and emissivity. The surface temperature is governed by a number of physical properties, among which thermal inertia is most important in governing the diurnal temperature variations. If thermal inertia is less, diurnal temperature variation is more and vice-versa.

A typical thermal IR remote sensing experiment uses a set of pre-drawn (night) and day (noon) passes. Commonly, TIR image is a simple (radiant) temperature image. Other processed images, like a diurnal temperature difference image or thermal inertia image can also be generated through data processing and used for interpretation.

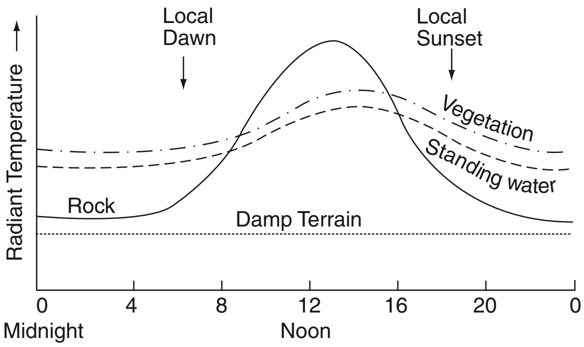

Fig. 4.7 Thermal response of rock, vegetation, standing water and damp terrain in a diurnal cycle

Topographic features are enhanced on day-time thermal images due to differential heating and shadowing. However, on night-time images, the topography gets subdued. All objects on the ground surface undergo cyclic heating and cooling in the day/night cycle, thus showing systematic temperature variations in a diurnal cycle (Fig. 4.7). Standing water appears brighter (relatively warmer) on the night-time image and darker (cooler) on the day-time image. Soils with higher moisture are cooler than those with lower moisture content. Shallow groundwater conditions are marked as zones of cooler temperatures on night-time thermal images (Heilman and Moore 1982). Soil moisture estimation has practical utility in agriculture and water budgeting. Temperature contrasts of the order 5–10°C could be produced by soil moisture variation. Effluent seepage would also lead to cooler ground surface. Drainages are also well shown on thermal data. Vegetation in general, is warmer on the night-time and cooler on the day-time image, in comparison to the adjoining unvegetated land.

Structural features like folds, faults etc. may be manifested due to spatial differences in thermal characters of rocks. Bedding and foliation planes appear as sub-parallel linear features due to thermal contrasts of compositional layering. Faults and lineaments may act as conduits for groundwater flow and may be associated with springs. This would lead to evaporative cooling along a line or zone producing linear features (Fig. 4.17a). Therefore, thermal data can be used for exploration of shallow aquifers and water-bearing fractures. In general, the spatial resolution of sensors is an important aspect in applications. The aerial thermal scanners have spatial resolution of the order of 2–6 m, quite suitable for such applications. In contrast, the available imagery from spaceborne thermal IR sensors is generally of coarser resolution (90 m for ASTER), which has put constraints the applicability of space-acquired TIR imagery for such applications.

4.6.5 SAR Imagery

As mentioned earlier, the radar return carries valuable information about the physical, geometric and electrical properties of ground objects. On a SAR image, intensity of radar return is shown in shades of gray, such that areas of higher backscatter appear brighter (Fig. 4.5). For common visual image interpretation, the black-and-white radar image is widely used, but the data can also be combined with other geodata sets in a GIS approach.

Commonly on a SAR image, most of the area is dominated by diffuse scattering caused by rough ground surface and vegetation (Fig. 4.5). Very strong radar return is caused by metallic objects and corner reflectors (hills and buildings). Specular reflection is produced by smooth surfaces, such as quiet water bodies, playa-lakes etc and there is little return at the SAR antenna.

Study of drainage network is often the first step in radar image interpretation. The waterways are generally black to very dark on the radar images, as water surface leads to specular reflection. However, in semi-arid to arid conditions, the valley bases are often vegetated, and appear bright on the radar images (Fig. 4.25). General terrain ruggedness is an important geotechnical element and orientation of individual landform facet in relation to look direction is very important for SAR image interpretation. Soil moisture is another important parameter as the radar return is governed by complex dielectric constant (δ) of objects. Water has very high δ, as compared to dry soil and rock. With increase in soil moisture content a regular increase of backscattering coefficient of the mixture takes place (Fig. 4.8), and this variation can be used to broadly estimate soil moisture on the ground.

Owing to the fact that minor details are suppressed, SAR images have value for regional landform studies. SAR images are found to be immensely useful for structural delineation. Lineaments are extremely well manifested on SAR images. The lithologic interpretation on radar image has to be based on indirect criteria like surface roughness, vegetation, soil moisture, drainage, relief, and special features like sinkholes etc.

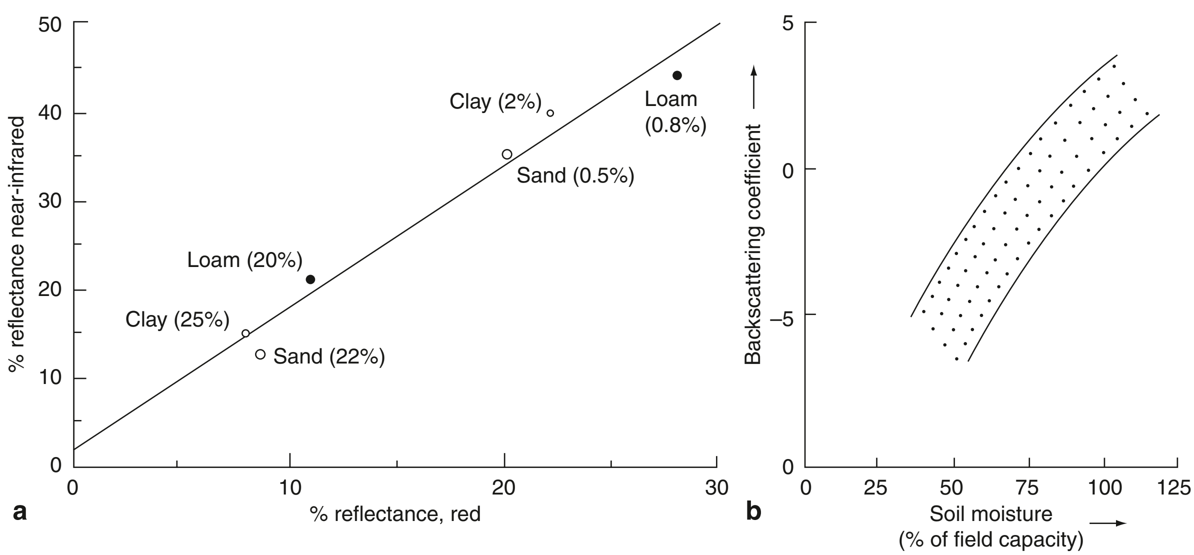

Fig. 4.8 **a** Reflectance of soils of different texture and moisture content (after Belward 1991), **b** Increase in radar backscattering coefficient with rise in soil moisture. (Redrawn after Bernard et al. 1984)

The radar image texture is an important parameter in deciphering lithological units.

Depth penetration is another important point in the context of geological-geohydrological applications. Ground penetration of the imaging radar depends upon the wavelength and increases with longer wavelengths as shorter wavelengths undergo a sort of "skinning effect". Further, the depth penetration is inversely related to complex dielectric constant (δ). Higher surface moisture inhibits depth penetration, whereas some limited depth information can be obtained in hyper-arid regions (Figs. 16.1, 16.2). It is generally accepted that in dry desertic condition, the depth of penetration of imaging radar is limited to <0.5 m for C-band and <2.0 m for L-band.

4.7 Groundwater Indicators on Remote Sensing Data Products

As mentioned earlier, remote sensing data provides primarily surface information, whereas groundwater occurs at depth, may be a few metre or several tens of metres deep. The depth penetration of EM radiation is barely of the order of fraction of a mm in visible part of the EM spectrum, to hardly a few metres in microwave region, at best. Therefore, remote sensing data is unable to provide any direct information on groundwater in most cases. However, the surface morphological—hydrological—geological regime, which primarily governs the subsurface water conditions, can be well studied and mapped on remote sensing data products. Therefore, remote sensing acts as a very useful guide and efficient tool for regional and local groundwater exploration, particularly as a forerunner in a cost-effective manner.

In the context of groundwater exploration, the various surface features or indicators can be grouped into two categories: 1. first-order or direct indicators, and 2. second-order or indirect indicators. The first-order indicators are directly related to groundwater regime (viz. recharge zones, discharge zones, soil moisture and vegetation). The second-order indicators are those hydrogeological parameters which regionally indicate the groundwater regime, e.g. rock/soil types, structures, including rock fractures, landform, drainage characteristics etc. (Table 4.6).

Table 4.6 Important indicators of groundwater on remote sensing data. (After Ellyett and Pratt 1975; Gupta 1991)

1. First-order or direct indicators
   (a) Features associated with recharge zones; rivers, canals, lakes, ponds etc.
   (b) Features associated with discharge zones; springs etc.
   (c) Sol moisture
   (d) Vegetation (anomalous)
2. Second-order or indirect indicators
   (a) Topography
   (b) Landforms
   (c) Depth of weathering and regolith
   (d) Lithology
   (e) Geological structure
   (f) Lineaments, joints and fractures
   (g) Faults and shear zones
   (h) Soil types
   (i) Soil moisture
   (j) Vegetation
   (k) Drainage characteristics
   (l) Special geological features, like karst, alluvial fans, dykes and reefs, unconformities, buried channels, salt encrustations etc. which may have a unique bearing on groundwater occurrence and movement

Image Data Selection Selection of remote sensing data for groundwater applications has to be done with great care as detection of features of interest is related to spatial resolution and spectral band width of the sensor as well as seasonal conditions of data acquisition. For example, small-scale image data are good for evaluating regional setting of landforms and regional structure, whereas large-scale photographs/images are required for locating actual borehole/structural sites. Similarly, an understanding of spectral response of objects is crucial for selecting spectral bands of remote sensing data. Further, temporal conditions (rainfall, soil moisture, vegetation etc.) may affect the manifestation of features on a particular data set. Figure 4.9 gives an example of the same area (granitic terrain in Central India) imaged by the same sensor (IRS-LISS-II) in two different seasons: post-monsoon and pre-monsoon. The post-monsoon image shows presence of a widespread thin vegetation cover, and therefore the distribution of various landforms and lineaments is not clear on this image. On the other hand, on the summer (pre-monsoon) image, the various landforms like buried pediments, valley fills and lineaments are clearly brought out.

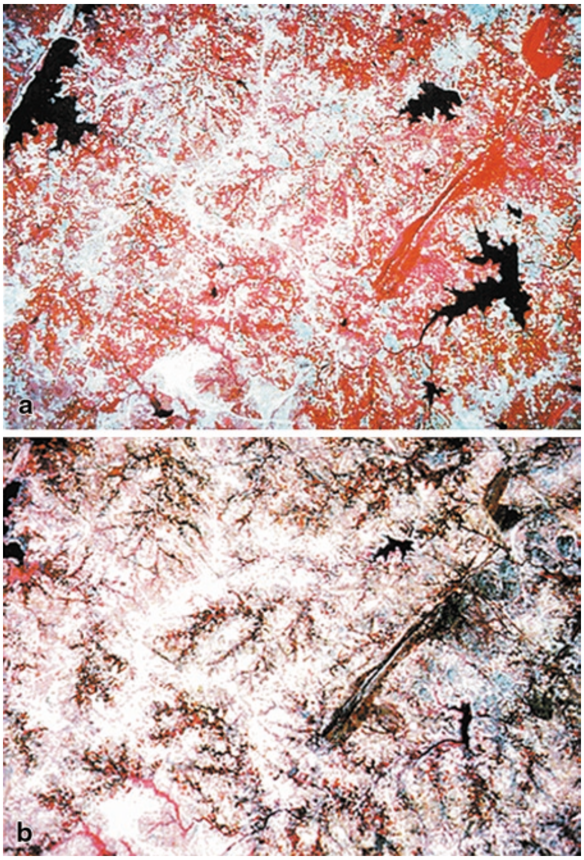

Fig. 4.9 A set of **a** post-monsoon (dated 13 October 1996) and **b** pre-monsoon (7 April 1997) IRS LISS-II FCCs of a part of Bundelkhand granites in Central India. Note that the various landforms (buried pediments, valley fills etc.) and lineaments are better deciphered on the pre-monsoon (summer) image

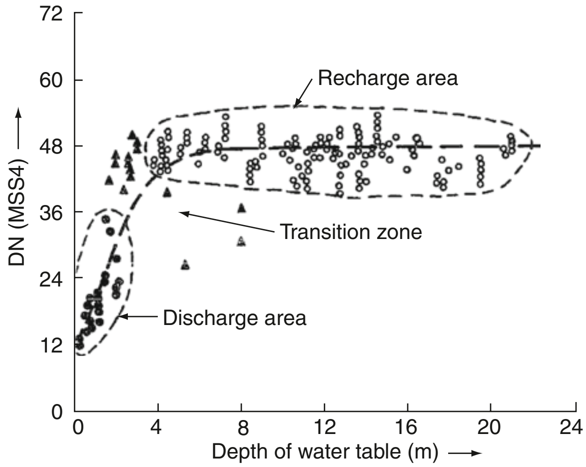

Fig. 4.10 Relationship between NIR reflectance (MSS4 DN values) and depth of water-table; the distribution of groundwater discharge and recharge areas is indicated. (Modified after Bobba et al. 1992)

4.8 Thematic Applications

Application potential of remote sensing technique based on various groundwater indicators is briefly discussed in the following paragraphs, with examples.

4.8.1 Features Associated with Recharge Zones

Surface water bodies constitute an important source of groundwater recharge and hence their identification is useful. Water bodies such as streams, canals, ponds, reservoirs are often very well marked on all types of optical and microwave image data. However, certain spectral bands such as near-infrared, thermal infrared and microwave are highly sensitive to surface moisture. Figure 4.10 is a plot of NIR reflectance against depth of water-table and shows that the groundwater discharge zones have shallow water-table and lower reflectance than the recharge zones.

Multispectral image data depicting spatial characteristics, patterns and shapes of surface water bodies can indicate whether they are recharging the groundwater. For example Fig. 4.11 is a Landsat image of

Fig. 4.11 Features associated with groundwater recharge in the sub-Himalayas; the thinning of streams towards downstream indicates influent seepage. (Landsat MSS4 image)

a region marked by an overall low drainage density. The streams appear to get thinner and thinner towards downstream; evidently, they are losing water into the ground implying influent groundwater seepage.

4.8.2 Features Associated with Discharge Sites

Springs or effluent groundwater seepage may be detected on panchromatic images, multispectral image data and thermal IR data due to the fact that higher surface moisture may result in abnormal lower ground reflectance, anomalous local vegetation or temperature distribution. Quantitative estimates of groundwater discharge in lakes/streams etc. is difficult to obtain as remote sensing provides qualitative indicators of groundwater discharge.

In the area shown in Fig. 4.12, a number of springs and gradual building-up of streams southwards is due to effluent groundwater seepage. Another example of springs in coastal areas is shown in Figs. 15.13, 15.14 detected by thermal IR data. Effluent seepage may also be detected by SAR, as the microwaves are sensitive to surface moisture and vegetation. Remote sensing has been utilized to estimate spring discharge from areal extent of swamps and vegetation. When groundwater contains minerals, there may occur chemical deposits, staining or mineral alterations at points of water springs and seeps, which can be detected by high-spatial resolution remote sensing.

4.8.3 Soil Moisture

Soil moisture content influences the response of soil to EM radiation, throughout the EM spectrum. On the panchromatic band, a higher moisture in soils leads to darker photo-tones. As the infrared reflectance is highly sensitive to moisture content, the soil moisture variation can be detected using the NIR and SWIR bands. For example, very high reflectance in the visible and NIR bands and low drainage density point towards near dry surface conditions, absence of vegetation and deep water-table conditions. The waterlogged areas are also easily identified on NIR band. Figure 4.13 shows quartzite ridges and intervening waterlogged phyllite valleys. Reflectance of soil is influenced by soil texture and moisture content (Belward 1991) (Fig. 4.8a); therefore, reflectance data can hardly be used for quantitative estimation of soil moisture content in a general way. The thermal-IR region is also sensitive to surface moisture. The wet areas are sites of evaporative cooling and appear cooler (darker) than the adjacent dry areas.

As far as application of microwave part of the EM spectrum for soil moisture studies is concerned, imaging SAR response is also broadly related to soil

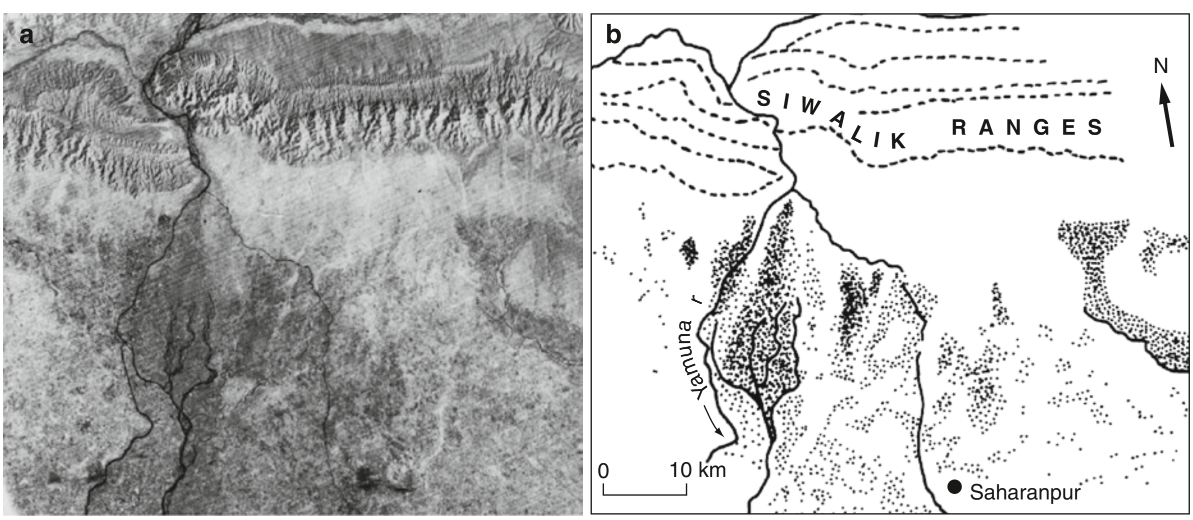

Fig. 4.12 Features associated with groundwater discharge: **a** Landsat MSS4 image, and **b** interpretation map. Note the building up of streams due to effluent seepage

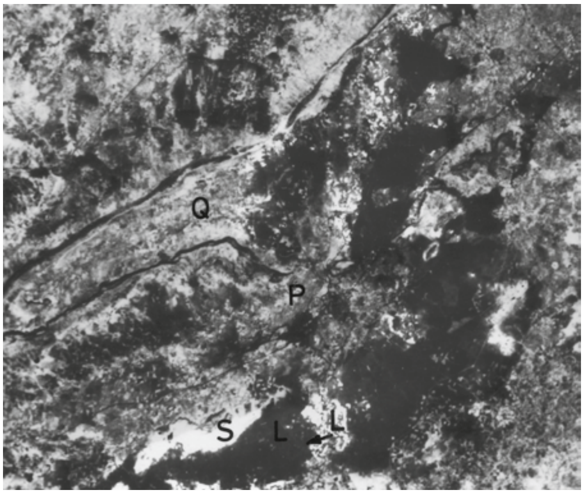

Fig. 4.13 IRS-LISS-II image of a part of northern Rajasthan, (India). The region is underlain by quatzite (*Q*) (ridges), and phyllits (*P*) (valleys). The valleys are waterlogged (*L*); white patches are salt encrustations (*S*)

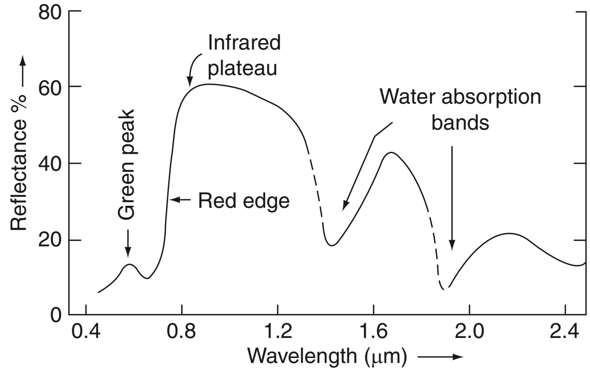

Fig. 4.14 Spectral reflectance curve of healthy vegetation in the solar reflection region

moisture variation (Fig. 4.8b). However, precise estimation is made difficult by the fact that SAR response is affected by soil moisture as also by a number of parameters such as surface roughness, topography, and vegetation density and vegetation wetness. Passive microwave sensing has good scope for soil moisture studies but with coarse spatial resolution. Soil moisture estimates with spatial resolution of about 20 km are obtained from satellite sensor passive sensing in microwave frequencies of C-band (6.9 GHz) and X-band (10.7 GHz). The goal of such data is to obtain global soil moisture estimates with about 25–50 km spatial resolution and regional maps of soil moisture are available on the internet. A new satellite program called Hydros is under consideration for launch in about 2010 to estimate soil moisture in shallow (about 5 cm) soil zone, and is primarily based on microwave sensors (Entekhabi et al. 2004).

4.8.4 Vegetation

Vegetation forms an important general guide for groundwater investigations, and anomalous vegetation may serve as a direct guide for groundwater. Remote sensing data, particularly of dry seasons, may bring out vegetation anomalies as water-bearing fractures may sustain vegetation even under dry/drought conditions.

Vegetation can be studied on panchromatic and/or multispectral images, thermal-IR images and SAR data. The spectral response curve of healthy vegetation is shown in Fig. 4.14. In the visible part of the EM spectrum, the pigments in leaves govern the reflectance; therefore, vegetation is generally darker than the adjacent rock or soil on panchromatic, and multispectral blue, green and red bands. Healthy vegetation is strongly reflective in the NIR and this character helps in discriminating healthy vis-à-vis diseased/decaying vegetation. In the SWIR region, the reflectance is governed by leaf water content and this spectral band has importance in evaluating vegetation stress. On SAR images, dense canopy leads to a more intense scattering and a corresponding higher radar return (Fig. 4.23).

Suitably large-scale stereo pairs may yield information on the type of plants to indicate groundwater conditions in the area. For example, presence of xerophytic plants indicate dry arid conditions, whereas phreatophytic vegetation (plants taking water directly from the water-table) denotes shallow water-table. In such conditions, proliferation of water resistant plant species can also be observed on remote sensing data (e.g. Bacchus et al. 2003). Palm trees indicate shallow water-table but highly mineralized water, and mangroves flourish along the sea shore.

4.8.5 Topography and Digital Elevation Model

Surface topography has pronounced influence on groundwater occurrence. Topography also governs basin boundaries. The regional topography is best studied on stereo photographs/images. Besides, topographic maps, multispectral images and radar images are also useful for the study of topography.

Digital Elevation Model (DEM) forms a very basic and important input in any study of the earth's surface features. DEM can be obtained in many ways. Digitization of topographic maps followed by interpolation has been a widely used practice for generating DEM. However, the major short-comings of this are lower accuracy due to deformation of topographic map paper and many generalizations during topographic map preparation.

The shuttle radar topographic mapping (SRTM) mission has provided DEM of a large part of the land surface that can be downloaded. The SRTM global coverage has so far been restricted to 3-arc-sec (about 90 m) but for certain parts 1-arc-sec (about 30 m) DEM is available. In general, the absolute height accuracy is about 15 m and the relative accuracy is <10 m.

Digital photogrammetry developed for stereo aerial photography can also be applied to the stereo satellite image data and stereo data from space sensors such as SPOT, ASTER, IRS can be used. The principle of parallax (relief displacement) is applied and the amount of parallax is proportional to the relief. Various software packages are available for generating DEM. For ASTER data, the accuracy of DEM is normally considered to be around 15–40 m depending upon the terrain. High-resolution stereo-systems such as Cartosat, Quick-Bird, Ikonos etc. allow generation of DEM with higher accuracy (≈1–2 m).

Elevation data can also be downloaded from GoogleEarth which provides point data up-to an accuracy of 1 m in relatively flat areas. This data if downloaded in grid-form can also be converted into DEM. LIDAR surveys yield vertical accuracy in the range of 10–30 cm; however there are problems in data processing due to vegetation cover.

4.8.6 Landforms

One of the widest applications of remote sensing image data, particularly of stereo photography, has been in the study of landforms, because: (a) remote sensing particularly with stereoscopic capability gives direct information on the landscapes, involving slopes, relief and forms, and (b) landforms can be better studied on a regional scale provided by remote sensing data, rather than in the field. Some special landform features such as karst, buried channels, dykes, alluvial fans etc. are of particular interest in groundwater studies, and they are discussed separately at relevant places in this book. Genetically, the landforms are divided into two broad groups: 1. erosional landforms, and 2. depositional landforms.

1. *Erosional landforms:* Erosional landforms are typically associated with the resistant hard rock terrains and they are discussed in more detail in Chap. 13. From the point of view of groundwater occurrence, valley fill is the most important landform unit in such a geologic setting. Often, it may be difficult to distinguish between buried pediments and valley fills on panchromatic images and other raw data. However, dedicated image processing of multispectral data could lead to better discrimination of such landform features, as illustrated in Sect. 4.9.
2. *Depositional landforms:* Depositional landforms are a result of depositional processes of various natural agencies, viz. river, wind, and glacier etc. They differ in form, shape, size, occurrence, composition, association, and hence also in their groundwater potential. However, as they may also occur in the regional setting of fractured hard rock terrains, they play an important role for groundwater development for local needs. These are discussed in Chap. 16.

4.8.7 Depth of Weathering and Regolith

In hard rock terrains, the depth of weathering and thickness of regolith are important considerations in locating dugwells in rural areas. Spatial distribution of rock outcrops can give a reasonable idea of the likely thickness of regolith/overburden, and depth to bedrock. Thickness of regolith is also related to landform and is likely to be more at lower slopes and valleys. For this purpose, studies of stereo photographs and CIR composites of multispectral images are particularly useful (Fig. 4.19).

4.8.8 Lithology

Different lithologic units, i.e. rock types can be inferred indirectly based on the rock structures and landforms. The first task is to identify the terrain, i.e. fractured hard rocks vs. unconsolidated sediments. On photographs and images, the hard rock areas are characterized by the presence of a number of features such as compositional bandings, bedding, foliation, fractures, folds etc. Further, they have the characteristic erosional landforms, as described earlier. The unconsolidated sediments are marked by the absence of the rock structures and presence of various depositional landforms such as alluvial fans, point bars, moraines, dunes etc. From the point of view of hydrogeological investigations, the fractured hard rocks have been divided into four groups in this work: (a) crystalline rocks, (b) volcanic rocks, (c) carbonate rocks, and (d) clastic rocks. Their salient photocharacters are summarized in Table 4.7.

4.8.9 Geological Structure

Remote sensing images and photographs have found extensive applications for structural studies, to decipher planar discontinuities in the terrain, and understand their disposition and mutual-relations. The discontinuities may be visible on simple photographs and images, or remote sensing data may be processed specifically to enhance certain structural features. In general, remote sensors (photographic cameras, line scanners, digital cameras etc.) provide plan-like information, the data being collected while the sensor views the earth vertically from the above. Vertical and steeply dipping planar discontinuities are therefore prominently displayed on these images and photographs. On the other hand, gently dipping or subhorizontal

Table 4.7 Photocharacters of broad lithologic groups

Crystalline rocks
Widely different weathering characters are exhibited, depending upon composition, structure, and climate; more prone to weathering in humid, warm climates than in cold, dry climates; commonly occur as large size bodies (plutons) forming low-lying or undulating terrains; in arid conditions, sometimes show woolsack weathering in which isolated outcrops protrude through the weathered mantle. Drainage is generally medium density; massive rocks have dendritic pattern while jointed and foliated rocks exhibit angular-rectangular patterns; plutonic igneous rocks are massive; metamorphic rocks show foliation; lithological layering in gneisses leads to bandings. Several sets of joints may be present; granites also exhibit sheeting joints. Vegetated cover is variable. Spectral characters depend upon weathering, soil and vegetation; generally fresh rock surfaces are lighter toned. Also generally, if acidic they are lighter toned than basic and ultrabasic rocks.
Carbonate rocks
These are highly susceptible to solution by water; in humid climates, carbonate rocks show karst topography. In arid regions, the carbonates form ridges and hills. Drainage density in both arid and humid terrains is low; internal drainage is high in humid areas. Bedding may be weakly developed; intercalations of other lithologies may enhance lithological layering. Generally 3–4 sets of well-developed joints are observed; joint surfaces may become curved due to solution activity. Light coloured, thin calcareous soil is often observed in carbonate terrain; removal of carbonates may result in an iron oxide layer called terra-rosa. Vegetation is variable, depending upon weathering and climate. Carbonate rocks usually appear light toned; very often exhibit mottling due to variation in surface moisture.
Volcanic rocks
These are highly susceptible to weathering, which obliterates characteristic landforms and features in older flows. Drainage is highly variable; absent or very coarse due to high porosity in newer flows; often older flows display high drainage density and dendritic drainage. Foliation or bedding is absent in volcanic rocks; successive flows interbedded with weathered material and non-volcanic sediments may resemble coarse bedding (pseudo-bedding) shown on the scrap faces. Joints may be well developed; columnar joints are typically present in basaltic flows. Acidic flows have light toned soil cover and basaltic flows have darker toned soil cover. Vegetation is sparse on younger flows; weathered areas may support vegetation and cultivation. Tonal characters are related to composition, age, weathering, soil moisture and vegetation.
Clastic rocks
Sandstones are resistant to weathering, whereas shales are incompetent and easily eroded. Sandstones from hills, ridges, scarps, and topographically prominent features; shales form valleys and lower hill slopes. Sandstones have low to medium drainage density, and rectangular-angular pattern; shales have high drainage density and dendritic drainage; intercalated sequences of sandstone-shale produce trellis pattern. Bedding is often very prominent. Sandstones often exhibit compositional layering; massive and pure varieties lack compositional layering. Shales are less commonly exposed, as they are usually covered under weathered debris. Several sets of joints may be developed. Soil cover is variable. Shales usually possess thick soil cover. Vegetation bandings may be present, sandstones being vegetated and shales used as agricultural grounds. Tone is highly variable, depending upon vegetation and soil moisture.

structural discontinuities are comparatively subdued, and are difficult to delineate, especially in the rugged mountainous terrain.

Geological structures include bedding, foliation, folds, joints, lineaments, faults and shear zones etc. In this section, the discussion is confined to bedding/foliation and folds. Bedding is the primary discontinuity in rocks and is due to compositional layering. On remote sensing images, bedding appears as regular and prominent linear features, which may be marked by differential weathering, tone, texture, soil and vegetation; the linear features due to bedding appear longer, even-spaced and more regular, in contrast to those produced by foliation and joints.

Orientation of bedding or foliation is important. The strata may be sub-horizontal, inclined or vertical, and may form segments of larger fold structures. The outcrop pattern on photographs and images is influenced by structure and relief in the area. Folds can be delineated by tracing the bedding/marker horizon along the swinging strike and recognition of dips. Broad, open, longitudinal folds are relatively easy to locate on satellite images than tight overturned isoclinal folds, owing to the small areal extent of hinge areas, which may provide the only clues of their presence. Therefore, such folds need to be studied on appropriately larger scales.

4.8.10 Lineaments Including Joints and Fractures

Lineament studies are most important for groundwater investigation in hard rock terrains. The technique of mapping fracture traces and local lineaments from aerial photographs for locating zones of higher permeability in hard rock terrain was developed by Parizek (1976); also Lattman and Parizek (1964), and the same has now been extended to satellite imagery. It has been shown that wells located on or close to fracture traces yield many times more water than the wells away from the fracture traces, and they are more consistent in their yield when located on lineaments than under other conditions.

What Is a Lineament? The photolinears, i.e. linear alignment of features are one of the most obvious features on aerial photos and satellite images. The term lineament is now used, by and large, in a geomorphological sense, as "a mappable simple or composite linear feature of a surface whose parts are aligned in a rectilinear or slightly curvilinear relationship, and which differs distinctly from the pattern of the adjacent features, and presumably reflects a subsurface phenomenon" (O'Leary et al. 1976). Hence, this category includes all structural topographical vegetational, soil and lithological alignments, which are very likely to be the surface expression of buried fractures and structures. This definition seems to be the most practical in the context of remote sensing image interpretation.

Manifestation of Lineaments Lineaments occur as straight, curvilinear, parallel or en-echelon features (Fig. 4.15). Generally, lineaments are related to fracture systems, discontinuity planes, faults and shear zones in rocks (Fig. 4.16). The term also includes fracture traces described from aerial photographic interpretation by some workers. Dykes and veins may also appear as linear features but these can be identified in field or large-scale photographs. In some cases, fractures may be covered under regolith. The pattern of a lineament is important on the image. Lineaments with straighter alignments indicate steeply dipping surfaces and by implication, they are likely to extend deeper below the ground surface.

Ground element corresponding to a lineament would depend on the scale of remote sensing image. Both small-scale and large-scale images are useful and ought to be used in a complimentary manner for hydrogeological studies. On regional scales (say 1:100 000), lineament features may be more than ca. 2 km in length, and represent longer valleys and complex fractured zones; such data can facilitate regional selection. On larger scales (say 1:20 000 scale), shorter, local, minor drainage features, individual fracture traces etc. are represented as lineament features; such data are useful in detailed investigations, e.g. for well siting.

Different types of fractures and their characteristics have been described earlier (Chap. 2). The distinction between dilational and shear fractures is very important for groundwater studies as the former are more productive. This distinction can sometimes be made on remote sensing images on the basis of two

Fig. 4.15 Mapping of various types of fractures on IRS-1C LISS-III FCC of Cuddapah region, India. (Courtesy D.P. Rao, A. Bhattacharya and P.R. Reddy)

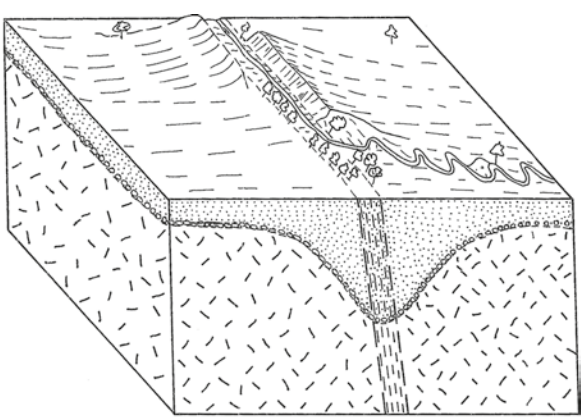

Fig. 4.16 Schematic showing surface manifestation of lineament in terms of topographic/drainage/vegetation alignment. The lineament zone is marked with greater depth of weathering

considerations: (a) relative movement along an individual discontinuity, and (b) orientation and statistical distribution of lineaments. It is always desirable if both these types of evidences are mutually supportive. Sometimes, relative movements along lineaments could be seen to indicate faults and shear fractures (Fig. 4.15); in contrast, lineaments related to dilational fractures would not show any relative displacement. Further, in areas of less complex deformation, statistical analysis of lineament trends could help distinguish between fractures of shear origin and tensile origin. It is always better if such interpretations are supported by evidences of relative movement observed in field or remote sensing data. Hydrotectonic models have also been attempted by some work-

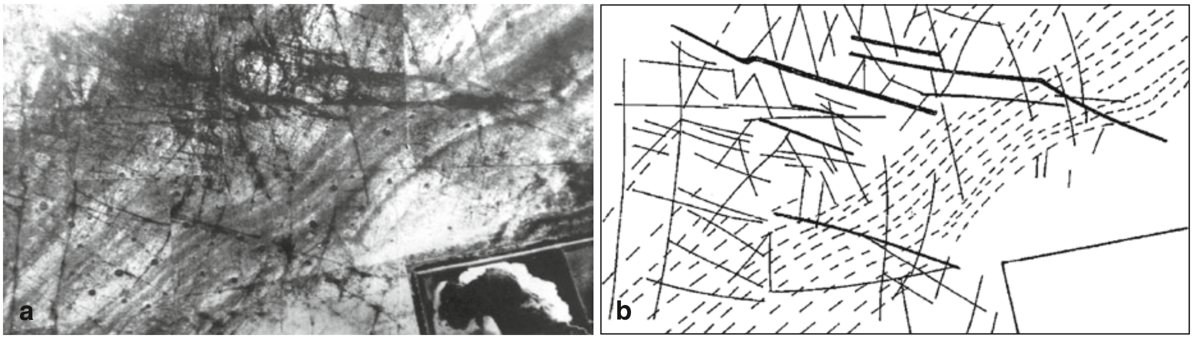

Fig. 4.17 **a** Thermal IR image showing numerous structural features such as bedding and lineaments, **b** interpretation map (Stilfonstein area, Transvaal, South Africa). (After Warwick et al. 1979)

ers to interpret the erstwhile stress field and thence identify tensile fracture trends as they are believed to be more productive.

On an image, the lineaments can be easily identified by visual interpretation using tone, colour, texture, pattern, association etc. Alternatively, the automatic techniques of digital edge detection can also be applied for lineament detection. However, these techniques have found limited application due to the cropping up many non-meaningful linears. Therefore, the visual interpretation technique is preferred and extensively applied, although it involves some degree of subjectivity, due to human perception (e.g. Sander et al. 1997).

Mapping of lineaments can be done on all types of remote sensing images: stereo panchromatic photographs and various images. The panchromatic, NIR SWIR, and thermal IR images contain information of near-surface, whereas SAR images may provide limited depth penetration (of the order of a few metres at best) in arid conditions. Manifestation of lineaments is related to ground conditions and the sensor spectral band. Figure 4.17 shows an example where aerial thermal IR image exhibits a number of structural features (bedding planes and fractures), which are not seen on the panchromatic band aerial photograph. The structural features appear dark due to evaporative cooling along them. Further, often lineaments are better manifested on SAR images than on panchromatic photographs, owing to the fact that radar response is intensely affected by surface roughness, micro-relief, vegetation and surface moisture. Figure 4.18 shows a comparison of lineament features observed on air photos and SAR images of the same area in Brazil.

Lineaments can be mapped on original data products, as well as on enhanced images. Further, a variety of digital techniques to enhance linear features can also be applied, in the form of isotropic and anisotropic filters (Sect. 4.9). An anisotropic filter can be used to enhance linear information in a certain preferred

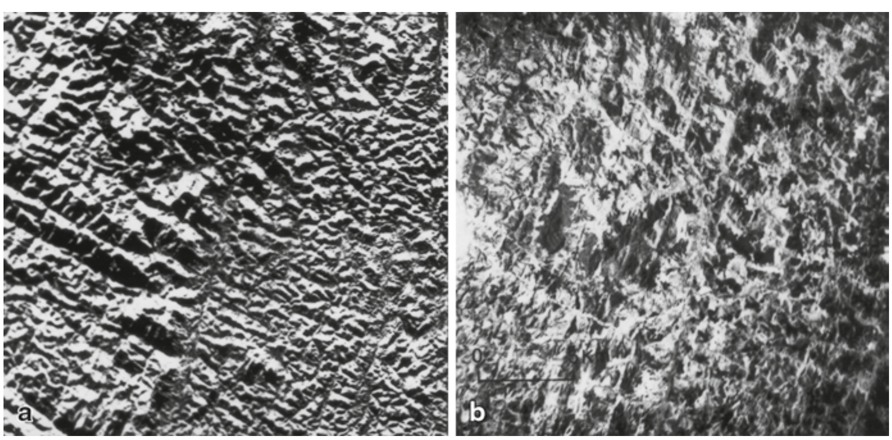

Fig. 4.18 **a** X-band radar image of an area in Bahia, Brazil, and **b** aerial photograph of the same area. Note that the structural features are better manifested on the radar image than on the aerial photograph. (Courtesy A.J. Pedreira)

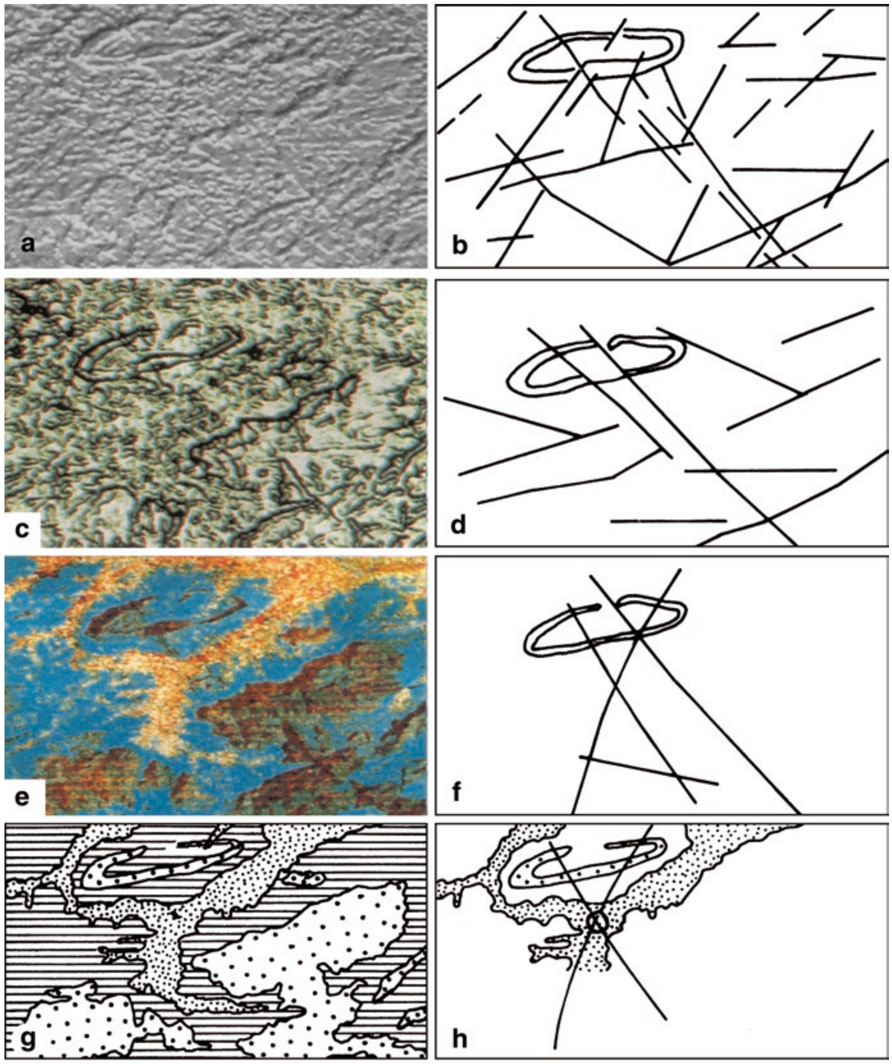

Fig. 4.19 Image processing and dedicated interpretation of a region in the Athur valley (India) using Landsat data. **a**, **c** and **e** are Sobel-filtered, Roberts-filtered and hybrid FCC's respectively, **b**, **d**, and **f** are their respective lineament interpretation maps, **g** is a landform interpretation map, **h** shows selection of groundwater potential targets based on lineament and landform interpretations. ((a), (c) and (e) courtesy of A. Perumal) (for (c) and (e))

direction; however, due to the presence of artificats, interpretation of such filtered products has to be done cautiously (e.g., Fig. 4.19).

Statistical Treatment of Lineament Data There are a number of ways to assess the statistical distribution of lineaments in an area. One is by considering the number of lineaments per unit area; the second, by measuring the total length of lineaments per unit area; and the third, by counting the number of lineament intersections per unit area. The method of lineament intersection per unit area (density) is generally faster and convenient. The intersections of two (or more) lineaments are plotted as points. The number of points falling within a specified grid area is counted. The data are contoured to give the lineament intersection density contour map (Fig. 4.20) showing zones of relative intensity of fracturing in the area.

Relation of Lineaments with Other Features As lineaments frequently represent fracture zones in the rock, they are generally associated with zones of greater weathering, thicker soil cover, denser vegetation, higher moisture and valley alignments (Fig. 4.15). They are therefore also, often characterized by lower electrical resistivity values. Correlation between lineament and vegetation anomalies has been shown in several areas (e.g. Gustafsson 1993). Figure 4.21 illustrates that a strong correlation between lineament and vegetation anomalies in fractured rocks may exist even for long linear stretches of 5–10 km.

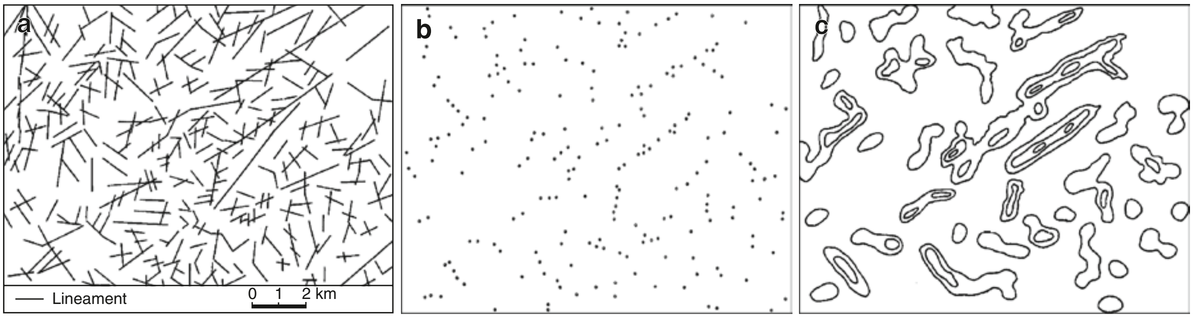

Fig. 4.20 **a** Lineament interpretation map of the area shown in Fig. 4.10, **b** lineament intersection density point diagram, **c** contour diagram from (b)

Lineament density and drainage density maps can also be combined for regional groundwater exploration; the target zones are usually marked by higher lineament density (representing greater fracturing) and lower drainage density (implying greater infiltration) (see Fig. 13.16).

Lineaments together with other features like landform and drainage have to be considered for delineating groundwater potential areas and for siting of wells. For example, in an area the groundwater potential targets may be marked by the intersection of lineament and valley-fill (Fig. 4.19). Further, it may also be recalled that often lineament traces appear as surface drainage ways but it is advisable to locate boreholes away from drainage lines to avoid chances of flooding.

Lineaments detected on satellite images often correspond to wide zones on the ground, which may be debris/soil covered. Therefore, delineating the main zone of fracturing (lineament) is often necessary and can be best accomplished using geophysical tools. Zeil et al. (1991) describe a case study from Botswana in which they geometrically coregistered Landsat TM and geophysical (EM) data to locate lineament-fracture zone more accurately in the field. Further, intersection of tensile and shear fractures in association with geophysical anomalies and suitable landforms may produce exceptionally high yields (Boeckh 1992, Fig. 17.10). Integration of remote sensing data and geophysical data (e.g. aeromagnetic) can be highly useful in identifying regional exploration targets (e.g. Ranganai and Ebinger 2008). An additional example of use of lineament conjunctively with other data in a GIS approach for groundwater exploration is discussed in Sect. 6.4.3. Examples of well yield as related to lineaments are given in Sect. 13.5.1 for crystalline rocks and Sect. 15.7 for carbonate rocks.

4.8.11 Faults and Shear Zones

Characteristics of faults and shear zones have been discussed in Chap. 2. Chief criteria for delineating faults

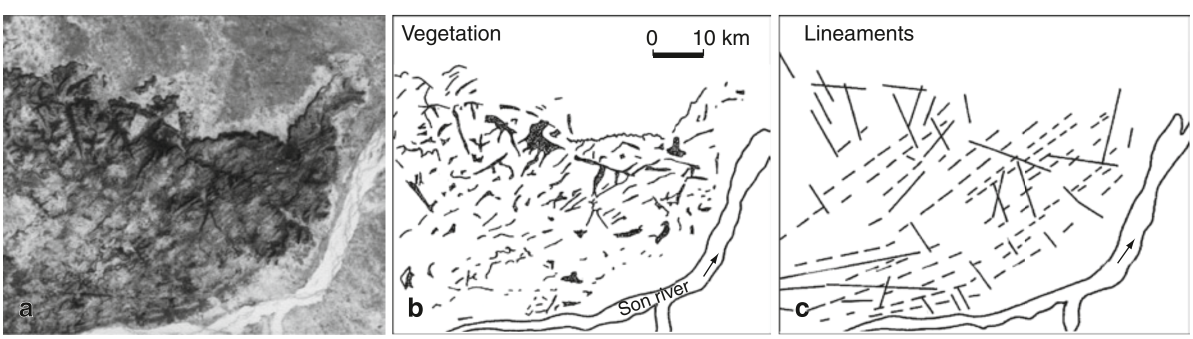

Fig. 4.21 Preferential alignment of vegetation for tens of kilometres along lineaments in the Son river area in Central India. **a** Landsat MSS2 (red band) image, **b** and **c** interpretation maps showing vegetation and lineaments respectively

an remote sensing images are: 1. displacement of beds or key horizons, 2. truncation of beds, 3. drag effects, 4. presence of scarps, 5. triangular facets, 6. alignment of topography including saddles, knobs etc., 7. offsetting of streams, 8. alignment of ponds or closed depressions, 9. spring alignment, 10. alignment of vegetation, 11. straight segment of streams, 12. waterfalls across stream courses, 13. knick points (local steepening of stream gradient), 14. disruption of channels and valleys, etc.

As such, a distinction between faults and lineaments is difficult to make, the main difference being that faults show evidences of movement (Fig. 4.15). On remote sensing images, faults with strike-slip movement are more readily discerned than those with only dip-slip movement. Like lineaments, faults can be delineated on all types of remote sensing images—panchromatic, multispectral, thermal IR, and SAR data. Figure 4.22 (Landsat infrared image) shows the presence of nearly E–W trending prominent extensive Recent fault marked as a lineament. The block on the south of the fault is frequently invaded by coastal waters, playas and salinas and forms the downthrow side.

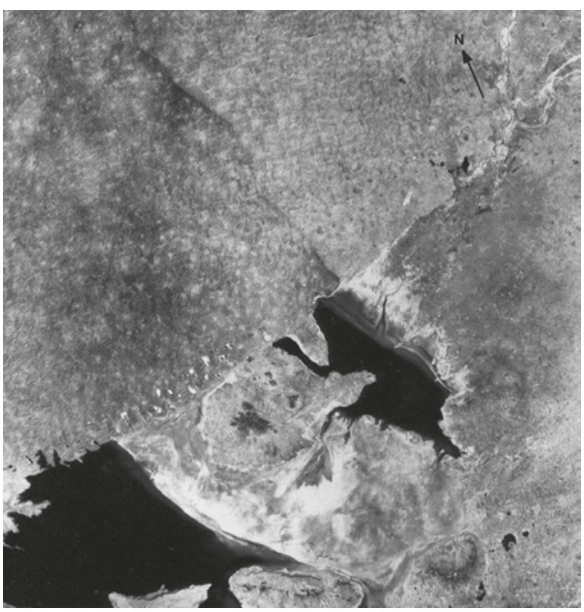

Fig. 4.22 Landsat infrared image showing the presence of nearly E–W trending prominent extensive Recent fault marked as a lineament. The block on the south of the fault is frequently invaded by coastal waters, playas and salinas and forms the downthrow side. The northern block is covered with dunes. The terrain is dry, bare of vegetation and quite uninhabited. Also note the artificial Indo-Pak boundary running through the dunes

4.8.12 Soil Type

Soil types and humus content can be estimated from remote sensing data, particularly panchromatic photographs. Soil types are intimately related to the bedrock. For example, sandy soils originate from arenaceous and siliceous rocks; clayey soils develop from argillaceous rocks; basalts typically produce black cotton soils. Coarse grained soils and sandy soils are generally light toned. Saline soils are light coloured due to salt encrustation. Fine grained soils and clayey soils are moisture-rich and generally dark toned. Clayey soils also exhibit absorption bands in the SWIR region. Humus content in soils is related to vegetation and moisture which leads to darker tones.

4.8.13 Drainage Characteristics

For hydrogeological investigations, drainage is a very important parameter of study. Drainage channels are characterized by the typical serpentine-sinuous shape and pattern. They may appear differently on different spectral bands depending upon depth of water, turbidity, vegetation cover etc. Condition of the channel including its pattern and density may give a good idea of the hydrogeological characteristics of the terrain. Figure 4.9 shows an IRS-LISSII image of the granitic area, Central India, where drainage is controlled by fractures and the channels are marked by good vegetation (dark tones on the red band image); there is little surface water. Figure 4.23 is a SAR image of basaltic

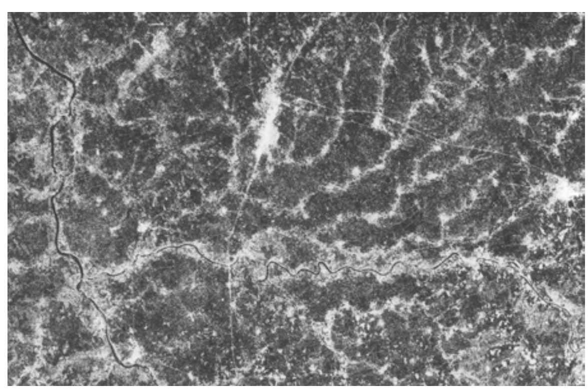

Fig. 4.23 SAR image from Shuttle Imaging Radar-A of a part of Central India. On the SAR image vegetated channels are bright due to higher radar returns whereas water bearing channels are dark due to specular reflection

terrain from Central India showing dendtritic drainage pattern; the drainage-ways are mostly vegetated (bright) with little surface water.

4.8.14 *Special Geological Features*

Some geological features may be locally important from hydrogeological point of view, such as karst features (in carbonate rocks), alluvial fans and buried channels (in clastic formations), dykes and reefs (in volcanic and crystalline rocks), and unconformities. These are discussed in appropriate lithology chapters.

4.9 Digital Image Processing

4.9.1 *Introduction and Methodology*

Digital image processing is carried out for image data correction, superimposing digital image data, enhancement and classification. A digital image is an array of numbers, in the form of rows and columns, depicting spatial distribution of a certain parameter, usually intensity of EM radiation in the case of remote sensing images.

Image processing can be carried out for various purposes; for detailed information, the reader is referred to standard texts (e.g. Mather 2004). Digital image processing for geological applications has been discussed by Sabins (1997); Gupta (2003) among others. The general sequence of digital processing of remote sensing data includes: image correction, registration, enhancement, visual interactive interpretation, and finally output.

Image correction is also called image restoration. Several types of radiometric errors and anomalies, including striping, bad data lines and atmospheric scattering effects etc., and geometric distortions such as those related to the Earth's rotation may be present in the image data. These are rectified before further processing. Registration is the process of superimposing images, maps, or data-layers over one-another with geometric congruence.

Image enhancement is the modification of an image to alter its impact on the viewer and render it more interpretable. A wide variety of enhancement techniques are available. Salient features of a few commonly used techniques are summarised in Table 4.8. Contrast enhancement deals with rescaling of gray tones to improve the image contrast and is almost invariably carried out. Edge enhancement is basically a process whereby borders of objects get enhanced. Main applications of edge-enhancement filtering are:

Table 4.8 Common types of digital image enhancements

Name	Description
1. Contrast enhancement	Rescaling of grey levels to improve the image contrast
1.1 Linear stretch	Range of image values is uniformly linearly expanded to fill the range of display device
1.2 Histogram equalized stretch	Assigning new image values on the basis of their frequency of occurrence, resulting in a uniform population density of pixels in the new image, also called ramp stretch; this results in a very high image contrast
1.3 Logarithmic stretch	Image data stretched using a logarithmic function; useful for enhancing features in the lower DN-range
1.4 Exponential stretch	Image data are stretched using an exponential function; useful for enhancing features in the upper DN-range
2. Edge enhancement	Application of a filtering technique to obtain a sharper image; information on local variations, which may be related to local morphology, soil, vegetation, moisture, fractures etc. are enhanced
3. Addition and subtraction	Simplest method to combine multi-image data; pixel-wise addition or subtraction is carried out to generate a new image
4. Ratio images	Generated by dividing the pixel value in one band by the corresponding pixel value in another band for each pixel. On ratio images, effects of illumination/topography are reduced
5. Colour enhancement	Uses colour display; pseudocolour is for a single image at a time such that grey scale is sliced into several ranges and each range is displayed in a separate colour; colour composites are often generated to combine multiple images by concurrently projecting them in different colours (RGB).

(a) to obtain a sharper image with more information on local characters, and (b) to enhance fractures, structural features and lineaments, over-all, or alternatively in a certain preferred direction (e.g. Fig. 4.19).

Addition and subtraction is the simplest method to digitally combine multiple image data sets. After digitally registering image sets, pixel-wise addition of two or more bands produces a new addition image. In a similar manner, pixel-wise subtraction of one image data from another generates a new subtraction image. In general, addition produces a high contrast image and is good for a general study. On the other hand, a difference image has a reduced contrast. A difference image is particularly useful for change detection; for example, change in vegetated area, flood area, or wet ground area etc., between two dates of satellite passes may be detected by this method.

Ratio images are generated by dividing the pixel value in one band by the corresponding pixel value in another band, for each pixel. Ratio images are made to reduce the effects of illumination variation due to topography and enhance spectral information. Ratioing is particularly useful in estimating vegetation density (see Fig. 4.24).

Colour enhancement is a very powerful technique of feature enhancement. Pseudo-colour and RGB (red-green-blue) coding are the two basic techniques of colour enhancement. Pseudo-colour is applied to enhance differences within a single image. On the other hand, RGB coding is applied on a set of three co-registered images; the three images are co-projected for concurrent display and coded in blue, green and red primary colours. Such colour displays have been found to be extremely useful for geoscientific investigations and terrain evaluation.

Fig. 4.24 Ratio NDVI image of a part of the area shown in Fig. 4.9. Brighter tones correspond to greater density of vegetation

Classification is carried out to construct thematic maps, where each pixel is assigned to a particular class by name. The methods of image classification are based on digital image pattern recognition. For subsurface geological exploration, the classification approaches have rather limited applications, and enhancement has been a more rewarding approach for subsurface geological-hydrogeological investigations (c.f. Siegal and Abrams 1976; Gupta 2003).

4.9.2 Digital Image Enhancement of Groundwater Indicators

It may be stated at the outset that there is no universal best digital image processing technique for enhancing all the groundwater indicators, in all conditions. Many combinations have to be attempted by trial and error, and in general, the convergence of evidence principle is very helpful. In these paragraphs some important guidelines for enhancing groundwater indicators are outlined.

1. Structure, faults and lineaments
   For mapping of various structures, viz. faults and lineaments on remote sensing images, the following types of processing are useful:
   (a) NIR band image, suitably, edge-enhanced, contrast-stretched.
   (b) FCCs utilizing edge-enhanced and contrast-manipulated images.
   (c) Difference image of NIR-Red bands, particularly when vegetation is associated with lineaments.
   (d) Hybrid FCCs of SAR image and optical (Red band and NIR band) images.
2. Lithology
   Lithologic discrimination is usually based on indirect evidences such as landform, drainage, soil and vegetation. Therefore, the enhancement of all the geotechnical features is useful.

3. Vegetation
   For vegetation studies, the following procedures of digital image enhancements are generally found to be more useful:
   (a) Red and NIR band images, suitably edge-enhanced contrast-manipulated.
   (b) CIR composite where vegetation is displayed in shades of red-magenta due to higher reflectance in the NIR band.
   (c) The health and vigour of vegetation is indicated by a spectral ratio, involving Red to NIR bands; frequently the ratio is computed as [(NIR−Red)/(NIR+Red)], called normalized difference vegetation index (NDVI). NDVI has higher values for vegetated areas and lower for barren areas (see Fig. 4.24).
4. Landform and Drainage
   Landforms and drainage are best studied by streoscopic techniques. Further, the general image quality is vital for such studies. The following techniques of image processing may be particularly helpful:
   (a) CIR composites of edge-enhanced contrast-manipulated Green–Red-NIR bands.
   (b) Hybrid colour composites involving optical images and SAR images.

4.10 Application of Remote Sensing in Estimating other Hydrological Parameters

The importance of remote sensing in estimating surrogate hydrological data has been emphasized by a few workers and well reviewed by Meijerink et al. (1994). In this way, remote sensing can contribute substantially in groundwater budgeting and modelling (Brunner et al. 2007). Main applications of remote sensing data could be of the following types:

1. *Topography and DTM:* In areas where accurate base maps are not available, topographic data and Digital Terrain Model (DTM) can be generated from stereo photos and images. DTM may be subjected to filtering to produce slope map, flow path map etc., with GIS functions.
2. *Rainfall:* In areas of rainfall <1500 mm per year, regional vegetation patterns are related to spatial rainfall patterns. Therefore, NDVI image can be related to rainfall distribution. As rainfall pattern is affected by topography, local DTM can also provide some information on spatial variation in rainfall. Thus, field data from rain gauge stations, local DTM, and vegetation pattern can be merged in GIS to yield a more realistic isohyetal map.
3. *Snow cover extent:* Owing to synoptic overviews and repetitive coverages, the satellite data are extremely useful for mapping snow cover area and delineating snow cover depletion pattern.
4. *Evaporation and soil moisture:* are important hydrological parameters, governing soil moisture retention and infiltration. Remote sensing data can be used to generate maps showing variation in soil moisture.
5. *Interception and infiltration:* Interception of surface water is affected by vegetation while rooting depth of plants governs infiltration. Remote sensing data can be used to generate maps of various land cover categories for estimating coefficients of infiltration.
6. *Water bodies:* Repetitive remote sensing data is highly useful in mapping temporal variation of surface water bodies, zones of influent/effluent seepage, flooding, etc.

4.11 Emerging Developments and Applications

Future developments and emerging new applications of remote sensing in groundwater may include the following (e.g. Becker 2006):

1. High-resolution gravity survey
   High-resolution gravity surveys may be used to estimate groundwater storage (Pool and Eychaner 1995). Gravity surveys measure mass occurring below the satellite that exerts a gravitational pull on the satellite and have no vertical resolving power. Hence, mass of entire vertical column (including that of water at depth in saturated and unsaturated zones, vegetation and atmosphere) affects gravity data and adequate processing is required for accurate/reliable interpretation. The NASA's Gravity Recovery and Climate Experiment (GRACE) satellite is being considered as a possibility. Rodell

and Famiglietti (2002) used computer simulations and anticipated GRACE performance parameters to estimate that groundwater level changes as small as about 8–9 mm could be possibly deciphered. However, observational errors and local atmospheric variability limit the applicability of the GRACE data to only very large basins of hundreds of square kilometre area (Swenson et al. 2003). A follow-on mission of GRACE with a higher resolution might provide practical useful data in monitoring water storage changes.

2. Satellite-borne laser altimetry
   Laser altimetry involves illumination of the ground by artificially generated laser beams which strike the target and are back-scattered; distance estimation is carried out from the two-way travel time measurements (Fig. 4.25). Aerial laser altimetry has been found to be a powerful tool for various land surface applications where high-resolution terrain mapping/digital elevation models are required, e.g. in detailed town planning.
   Measurement of water-level elevation (stage) in rivers and lakes is important from a hydrogeologic point of view as surface water can be considered to represent surface manifestation of groundwater discharge (Winter et al. 1998). River stage measurement in lean season can be used to estimate groundwater discharge. Satellite-borne radar altimetry has been used to measure water-levels in large lakes and rivers. For example, Birkett (1998) (Birkett et al. 2002) used data from the TOPEX/Poseidon satellite to measure water-levels in large lakes and rivers, with vertical accuracies of 11–60 cm, though only in wide sections (>1 km). Laser altimetry has a much smaller ground footprint and a higher vertical accuracy. For example, ICESAT satellite has a laser sensor with footprint of ~70 m and vertical resolution of 15 cm. Therefore, satellite-borne laser altimetry appears to possess good potential for measuring changes in water-levels in river/lake.
3. SAR interferometry
   SAR Interferometry, also called Interferometric SAR (InSAR), is a relatively new technique of remote sensing. It involves imaging the same target from two different angles at different times by Synthetic Aperture Radar (Fig. 4.26). Measurements of phase in SAR return beams yield data on elevation changes to sub-wavelength accuracy. The InSAR data are affected by atmospheric water vapour, and it is generally found that the accuracy of InSAR is ~10 cm in humid regions and ~1 mm in dry regions. In this perspective, InSAR application has a very high potential in arid to semi-arid regions. Applications of InSAR in groundwater studies include the following:

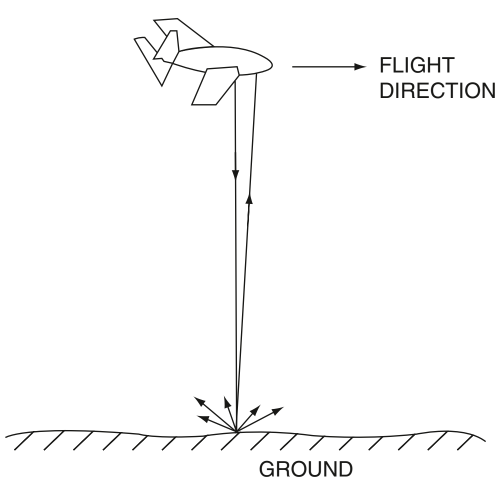

Fig. 4.25 Schematic arrangement of an active laser remote sensing system

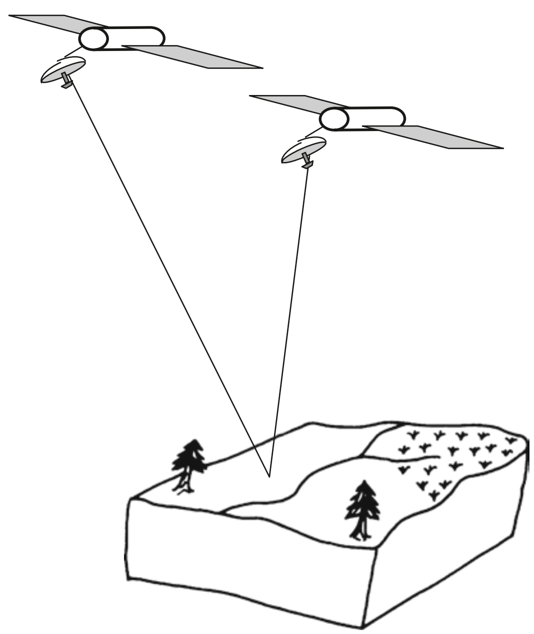

Fig. 4.26 Configuration of data acquisition for SAR interferometry; the same ground/target is sensed from two different angles at different times by the Synthetic Aperture Radar

(a) Monitoring of land subsidence due to groundwater withdrawal: Groundwater withdrawal may lead to compaction of sediments in the aquifer system which may cause elastic or inelastic deformation resulting in surface elevation changes that can be detected by InSAR (e.g. Galloway et al. 1998; Lu and Danskin 2001; Watson et al. 2002; Hoffmann et al. 2003; Schmidt and Burgmann 2003). Further, spatial pattern of subsidence due to groundwater withdrawal may be also influenced by neotectonic Quaternary faults, as revealed by InSAR (Smith 2002).
(b) As InSAR permits monitoring of ground surface elevation changes associated with discharge-recharge of aquifers, using numerical groundwater models it is possible to estimate regional storativity value and its spatial variation using InSAR (e.g. Lu and Danskin 2001; Hoffman et al. 2001; Hoffman et al. 2003).
(c) InSAR has also been proposed as a tool for measuring stream stages (water-level) in rivers (Alsdorf et al. 2003), which in turn is related to groundwater discharge.

Summary
Remote sensing involves measurements of intensity of electromagnetic radiation reflected or emitted from the ground by sensors flying on aerial or space platforms to infer terrain properties. In groundwater studies, remote sensing is a common first reconnaissance tool. Design of remote sensing systems is constrained by spectral characteristics of the atmosphere, energy available for sensing and sensor technology. Four main types of remote sensors are: photographic systems, line imaging systems, digital cameras, and imaging radars. Data from a numerous space sensors are now available that may vary in ground resolution from about 80 m to better than 1 m and could be multispectral and or stereoscopic. The remote sensing data in terms of reflectivity, temperature or radar backscatter can yield valuable information on physical attributes of the ground. Digital image processing techniques can be used to enhance and classify features. In the context of groundwater, the various ground features/parameters of interest are: springs, and discharge zones, areas of recharge, canals, lakes etc., soil moisture, vegetation distribution and density, topography and DEM, landforms, thickness of regolith and weathering, lithology, geological structure, lineaments, faults, joints and fractures, soil types, drainage characteristics, and special geological features such as karst, alluvial fans, buried channels, dykes, reefs, unconformities, ground subsidence etc.

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