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Groundwater Prospecting and Management

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Preface

Several books are available in the market on various groundwater development and management issues. The need for a comprehensive book on different practical aspects of groundwater studies has long been felt by geologists, geophysicists, civil and agricultural engineers with an eye to understand the groundwater system and targeting the aquifers under different geologic, terrain and geomorphic conditions.

Use of remote sensing data for a reconnoitre survey for groundwater is almost a routine now. Vertical electrical sounding and seismic refraction surveys in geophysics are used for recommendation of drilling points followed by electrical logging of the boreholes for exact lowering of strainers and subsequent groundwater development. Pumping test after the completion of the well leads to the determination of aquifer parameters and refining assessment of necessary input for design of wells (wells, tube wells and radial collector wells) and yield-drawdown relation. Collection of water samples and its chemical analysis are essential components to understand hydrogeochemistry of groundwater and contamination studies. Further, management of resource, artificial recharge and regulatory legislations are important from the viewpoint of sustained supply of water from aquifers.

Accordingly, Chap. 1 of the book provides introductory aspects of groundwater geology and geophysics followed by remote sensing application in Chap. 2. Chapter 3 extends a brief outline of the concepts, definitions and formulae for use in later chapters (Chap. 6) in determination of aquifer parameters and calculation of yield. Geophysical prospecting methods for groundwater survey are dealt with in Chap. 4, dealing with principles, interpretation and applications of the most useful and relevant techniques. Chapter 5 deals with geophysical well logging techniques and their applications in water wells including some case studies. Chapter 6 gives the procedure to conduct pumping test, interpretation of pumping test data for computation of aquifer parameters, yield and for design of radial collector well followed by an actual ease study. Groundwater quality and contamination aspects are discussed in Chap. 7; Chap. 8 deals with groundwater management, its sustainability and regulation.

Although this book is meant for students, in general, professionals involved in groundwater, engineering geology and environmental science will find it quite useful.

While attempting to incorporate varied topics on each of which books can be written, the present volume renders all aspects of groundwater investigations and management under one cover. In doing so, there may be errors of omission on the part of the author, and therefore, constructive comments and suggestion for improving the value and the utility of the work will be highly appreciated. I am thankful to co-authors S. Kunar, Member, CGWB, and Dr. S.K. Adhikari Scientist, CGWB, for contributing various case studies for different hydrogeological conditions along with present scenario of groundwater legislation and management in India. I am indebted to Prof. Amitabha Chakraborty, Prof. Shankar Kumar Nath and all other members of the staff of the Department of Geology and Geophysics for their interest and support needed for the work.

It is a pleasure to thank the Director of the Institute and Head of the Department of Geology and Geophysics, Indian Institute of Technology Kharagpur for their kind cooperation for the project work. The DST Project (Sanction No. 100/IFD/3374/98-99 dated 11.01.1999) under USERS scheme has been totally funded by the Department of Science and Technology (DST), Government of India, for which the author is extremely grateful.

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About the Authors

Prof. H.P. Patra graduated with Honours and Distinction in Physics from Bihar University in 1958 and completed Master of Technology degree in exploration geophysics in 1961 and Ph.D. degree in Geophysics from the Indian Institute of Technology Kharagpur in the year 1968. He had been directly engaged in teaching, research and field surveys in electrical and electromagnetic methods of prospecting applied to groundwater from 1961 to 1997. He is the author of several international books from Elsevier, Amsterdam, and Balkema, Amsterdam. These are (i) Direct Current Geo-electric Sounding: Principles and Interpretation, 1968; (ii) Geo-electric Sounding-2: Time–varying Geo-electric sounding, 1980; and (iii) Schlumberger Geo-electric Sounding in Ground Water: Principles, Interpretation and Application, 1999. Dr. Patra retired as Professor of Geophysics and as Head of the Department of Geology and Geophysics, IIT Kharagpur in June 1997.

Dr. Shyamal Kumar Adhikari completed Masters in exploration geophysics from IIT Kharagpur during 1985 and Ph.D. in 2001 from Indian School of Mines, Dhanbad, India. He is serving Central Ground Water Board (CGWB) as geophysicist for more than 28 years having colossal experience in the field of surface and borehole geophysical data acquisition, processing and interpretation by using latest state-of-the-art equipment and software in the field of groundwater geophysics in hard rock terrain, alluvial plain and coastal area. Apart from field investigation, Dr. Adhikari has published several scientific papers in national journals and volumes and presented in different workshops on various topics. He has contributed innumerable number of scientific reports on groundwater exploration in different terrains throughout his career.

Mr. Subrata Kunar graduated with Honours and distinction in Geology from Ranchi University in 1981 and completed Masters of Science in exploration geophysics from IIT Kharagpur during 1985, serving RITES as geophysicist for 30 years at different capacity including three years of service as Member in Central Ground Water Board (CGWB). Mr. Kunar is a life member of various societies and association like Association of Exploration Geophysics, Indian Society of Rock Mechanics and Tunnelling Technology, Indian Society of Engineering Geology, International Association of Hydrogeologist. He has a vast experience in the field of geophysical data acquisition, processing and interpretation with latest state-of-the-art equipment and software in the field of groundwater geophysics in hard rock terrain, alluvial plain and coastal aquifer system and application of geophysical techniques in engineering application. Mr. Kunar has contributed number of technical reports and presented scientific papers in national and international seminars.

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Chapter 1
Introduction

Abstract To have a reasonable equitable water distribution of groundwater, a planned approach for exploration, exploitation and management of water is required. General groundwater geology also must be well understood for exploration and exploitation in a particular area. The exploration is mainly done by geophysical investigation which is based on the physical properties of the earth formations. The electrical method of prospecting is most useful process for surface groundwater exploration. For subsurface, geophysical well-logging technique is very much useful because the data are closed to the borehole wall. For designing a well, the aquifer characteristics are required to be known with the help of pump tests. The water quality should be studied with different analysis before drinking. Though there is plenty of water in global scale, the shortage of water is observed in local scale. Hence, management planning of water in respect of demand and supply is very much important to meet the water requirement for present generation and future generation.

Keywords Groundwater · Exploration · Planned approach · Electrical method · Geophysical logging · Water quality · Management planning

1.1 Surface Water and Groundwater

At present (year 1999), the world's annual water requirement is more than 4500 km^3 (Wolff 1999). The total renewable water resource of the world is about 39,000 km^3 annually. Thus, there cannot be any water shortage on a global basis as the water is replenished through annual precipitation. The available resource is unevenly distributed, and therefore, sufficient water is not necessarily available in populated areas. Accordingly, water shortage does occur alarmingly depending on regional water balance, controlled largely by climate, altitude, soil composition and vegetation and mainly by precipitation. In order to have a reasonably equitable distribution, groundwater is used in conjunction with surface water. While surface water is easily available, groundwater needs a planned approach for exploration, exploitation and management for a sustained supply for proper utility.

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1.2 Groundwater Geology

Groundwater geology must be well understood for economic exploitation of subsurface water. Various aspects of groundwater have been treated in all textbooks on hydrology. The objective of this section is only to mention some useful factors needed for groundwater exploitation programmes. The programme comprises surface and subsurface investigations. Surface investigations are primarily used for establishing the geology of the area, giving distribution of geological formation on a map. The present approach is to prepare the map from satellite imagery data followed by essential ground checks. Once the geological map of the area is available, subsurface data regarding existence of sandy zones at different depths are collected from existing boreholes, if any. From the borehole samples, then, an idea can be made about porosity and permeability of the sands and their utility as an aquifer, in sedimentary areas. In hard rock areas, joints, fractures, fissures and cracks are to be located on the map after a study of lineation and fault traces. The background information obtained for groundwater geology is utilized in planning the prospecting programmes for groundwater.

1.3 Groundwater Geophysics

One has to depend on exploration geophysics for identification of different geological formations expected to be encountered in the subsurface. The subsurface lithology inferred through geophysics is controlled largely by the physical properties of the earth formations. The physical properties, e.g. density, conductivity and seismic wave velocity, of a water-saturated formation are dependent on distribution of grain size and quality of the water saturating the formation (e.g. sand or clay). In case of electrical conductivity or resistivity of a formation, electrolytic property of water plays an important role. The resistivity of the unit helps in the recognition of sand or clay from the likely formations.

This differentiation is possible through geophysical measurements from the surface (see, Chap. 4). Identification of formations can also be made through geophysical logging within the borehole (see, Chap. 5).

1.4 Groundwater Exploration

Of the various surface geophysical methods of prospecting, namely gravity-magnetic, seismic and electrical methods, only electrical method, based on the measurement of the electrical resistivity of subsurface formation, is most useful for exploring groundwater.

Electrical exploration for groundwater is based on the flow of direct current introduced into the earth and subsequent measurement of potential distribution on the surface. This gives an apparent resistivity, analysis of which gives resistivities of various layers leading to identification of the formations with depth. This is known as electrical resistivity method universally accepted as an ideal geophysical tool for groundwater exploration.

The theoretical aspects mainly of electrical resistivity method giving its principles, interpretation approaches and applications under varying geological situation are given, in detail, in Chap. 4.

1.5 Groundwater Development

Subsurface geophysical methods referred to as well-logging methods (Chap. 5) are essential tools in groundwater development. Surface geophysical method helps in locating the point suitable for drilling. Once the borehole is drilled, a suitable sensor is lowered to the bottom of the borehole and certain physical properties are recorded during upward uniform run of the sensor. The record of any characteristic physical property of the formations is known as geophysical log. Geophysical logs help in understanding the hydrology of the area clearly as the strata chart prepared from mixed-up drilling samples is not sufficiently reliable. While the logs are used for stratigraphic correlation from well to well, these may be used for the detection of bed boundaries, porous and permeable zones and saline water-bearing zones, having a strong bearing in groundwater supply and development. The thickness of porous and permeable zones and their lateral extent obtained from geophysical logs help in fixing spacing of wells and subsequent yield of wells.

1.6 Aquifer Parameters

The various important aquifer characteristics must be known for design of wells, tube wells and radical collector wells. These parameters are as follows: permeability (measure of hydraulic conductivity), transmissibility (transmissivity) and storage coefficient (storativity). In order to evaluate these parameters, pumping test is to be carried out after the completion of the tube well. Pumping test data are processed through different available methods (compatible to the geological conditions), and the values of transmissivity, hydraulic conductivity and storativity are estimated. Recovery test data also give transmissivity.

The values are utilized in the design of wells and in computation of yield from the wells. Aquifer parameters and their utility are outlined in Chap. 6.

1.7 Groundwater Quality and Contamination

1.7.1 Groundwater Quality

It is well known that the vast groundwater resource available on global basis is more than sufficient for providing good quality water to the world community. But for the want of even distribution, shortages do occur locally and seasonally, controlled largely by precipitation.

Besides, due to dissolved minerals present in the groundwater, it is sometimes brackish or saline and rich in iron content (more than 0.3 ppm). Such a water is of bad quality for drinking purposes.

For water to be suitable for drinking, a routine physical, chemical and biological analysis should be made. The water quality parameters which should be studied are as follows: pH, total dissolved salt (TDS), total hardness, turbidity; iron, arsenic, fluoride, calcium, magnesium, nickel, copper, lead and chloride; nitrate besides coliform bacteria. The parameters should be well within the prescribed international standards (see Todd 1995, pp. 277–282).

1.7.2 Groundwater Contamination

Our natural groundwater resources of mostly high quality are being contaminated gradually with time through domestic, agricultural and industrial pollutants releasing wastewater. Groundwater pollution is caused by human use of water and disposal of wastes into the ground. Without population and pollution control, the amount of per capita safe water available for use is gradually reducing with time. Although groundwater is replenishable, it is not inexhaustible.

Recently, arsenic contamination of groundwater has been detected around various parts of the world. World Health Organization (WHO) has compiled reports on cases of arsenic in drinking water in countries, e.g. Argentina, Bangladesh, China, Chile, Ghana, Hungary, India, Mexico, Thailand and USA. Arsenic is referred to as a toxic material and of environmental concern along with other three big metals, namely lead, mercury and cadmium. The presence of fluoride in groundwater is harmful due to its toxicity.

Attention should, therefore, be drawn to all such harmful contaminants in order to protect the environment.

1.8 Groundwater Management and Legislation

Statistics show the existence of sufficient amount of fresh groundwater resources on global scale. Depending on rainfall, climate, altitude, vegetation, etc., however, there is a large-scale shortage of water on regional and/or local scale. Without population and pollution control, the shortage will increase with time and some urgently needed intervention will be essential to safeguard the future of the mankind.

The difficulties can be overcome, at least partially, through a planned management of the available fresh groundwater resources.

Management strategies can be categorized into two, namely supply management and demand management. Supply management needs prospecting, exploitation and utilization of untapped groundwater resources as the uses of surface water sources are, by now, more or less in a saturated state of utility limit. Besides optimization of operations and maintenance of water supply plants, supply management plans reallocation of water resources among various user sectors.

Demand management, on the other hand, plans economic and efficient use aspects through special incentives and water-saving mechanisms. Regulatory measures through legislations for the protection of the environment include restrictions on quantity of water used, prohibition on specific uses, staggered supply and crop rotations. Regulations through legislation on groundwater extraction should be strictly enforced for proper development and management.

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Chapter 2
Remote Sensing in Groundwater Studies

Abstract Groundwater study in an area requires the idea of lithological units, structural disposition, geomorphic set-up, surface water condition, vegetation, etc. These can be well understood with the help of remote sensing (RS). It is the study of satellite images and aerial photographs. Satellite images are basically the electromagnetic (e-m) record of broad spectrum (ultraviolet, visible, infrared and microwave regions) by means of instrument such as scanners and cameras located on mobile platform such as satellite or spacecraft. The e-m radiation may come from an artificial source in the satellite or from the target itself if the target happens to be a source of e-m radiation. The radiation travels through the atmosphere being detected at the satellite recorder. The e-m spectrum in given bands can give information on the various targets on the earth. Vegetation, in general, appears green during daytime, because it reflects the green band of visible radiation preferentially, while absorbing other colour bands of the visible radiation. Before geophysical investigation, the RS data give the knowledge of the geological structures. Hence, the geophysicist can focus the survey area from a huge area which is not potential. The RS data are very accurate, fast and reliable as compared to the conventional data collection.

Keywords Remote sensing · Lithological unit · Geomorphic set-up · Vegetation · Satellite image · Aerial photography · Electromagnetic radiation · Colour band · Geological structure

2.1 General Considerations

Groundwater study of an area requires knowledge of the nature of lithological units occurring in the area, their structural disposition, geomorphic set-up, surface water conditions and the climate of the area. These can be studied through satellite images and aerial photographs, which provide detailed information about the large part of the surface of the earth in a very short time. Photograph interpretation studies help in the indication of groundwater potential through:

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(i) Identification of geological structures and the hydrophysical properties,
(ii) Water-bearing geological formations and water enrichment,
(iii) Areas of recharge,
(iv) Places of discharge,
(v) Nature of outlet of groundwater to the surface,
(vi) Depth and conditions for occurrence of groundwater,
(vii) Direction of movement and
(viii) Degree and nature of salinity.

Although remote sensing (RS) data do not directly detect deeper subsurface resources, it has been effectively used in groundwater exploration as RS data aid in drawing inferences on groundwater potentiality of the region indirectly.

The fresh water confined to channels of streams and rivers and stored in ponds, lakes and reservoirs is normally considered to form the surface water resources. These sources of surface water are directly detected by satellite RS data as water absorbs most of the radiation in the infrared region, which helps in the delineation of even smaller water bodies. Vegetation, which is easily detected through spectral reflectance, is indicative of the water saturation and moisture of the ground.

RS data provide only superficial and inadequate knowledge on the subsurface groundwater resources but help indirectly by giving certain ground information that aid in drawing inferences on groundwater potentiality of the area.

Primarily, the infiltration capacity of the soil determines the groundwater potentiality. The speed of infiltration is dependent upon mainly on porosity and permeability of the soil and the velocity of the surface run-off. Infiltration reduces to a great extent for steeply sloping ground surface as the velocity of surface run-off increases sharply. Also a vegetative cover gives a higher infiltration capacity compared to barren lands.

Several factors important in the storage of groundwater are:

(1) infiltration capacity,
(2) porosity and permeability of the soil,
(3) velocity of the surface run-off,
(4) vegetation (vegetative cover increases infiltration capacity) and
(5) thickness of the porous and permeable zone.

While making inferences on groundwater potentiality of an area from satellite RS data, the interpreter concentrates mainly on the geomorphic units, namely (a) fluvial, (b) denudational, (c) structural, (d) aeolian and (e) marine, briefly outlined as follows:

(a) These features (alluvial flood and deltaic plains; alluvial fans, river cut-offs and wadi, etc.) can be mapped easily from satellite imagery. As these features occupy the valley portion composed of local deposits of permeable material such as sand or clay, the groundwater prospects range from excellent to moderately good.

(b) Physical and chemical weathering through the action of wind, water and ice referred to as denudational processes, give rise to several landforms. The resistant rocks are left out without much damage, appearing as hills. On satellite imagery, these are seen as bare rock outcrops, normally devoid of any water as these are made up of compact crystalline rocks.
(c) Features of structural origin are structural hills and valleys, fractured plateau. Structural ridges are poor groundwater zones. When these features contain fractures and faults, they qualify as good groundwater potential zones. The lineaments and faults are observed as faint lines of straight or curved nature, which can be accurately mapped after ground check.
(d) Most of the features that form the desert topography fall into aeolian units. All except playa (dry lake) qualify as poor zones.
(e) Coastal plains, salt flats, mud flats, beach/sand bars and lagoons are the features formed due to marine processes which can be easily mapped from satellite imagery. Groundwater potential is limited due to the presence of saline zones.

Thus, the RS data followed by ground check give an idea of the probable groundwater potential zones. This should be detailed through surface and subsurface geophysical methods suitable for groundwater exploration. The scientific approach consists of three steps:

- RS-based investigations,
- Conventional hydrogeological investigations and
- Ground geophysical investigations.

RS records electromagnetic (e-m) radiation comprising a broad spectrum of wavelengths. This method, therefore, may be called an applied geophysical method in a broad sense and an e-m method in particular. The e-m radiation may come from an artificial source in the satellite or from the target itself if the target happens to be a source of e-m radiation. The radiation travels through the atmosphere being detected at the satellite recorder. The e-m spectrum in given bands can give information on the various targets on the earth.

With the advancement in technology, man is changing the face of the earth at a rapid phase. In order to channelize the development in proper direction with due consideration to environmental preservation, a planner needs to have an overall picture of the status of the region and its resources. Conventional methods of data collection are extremely time-consuming and are normally out of phase with the present-day conditions. In such circumstances, earth resource monitoring by space platforms is the only answer. The generation of accurate and reliable information at a cost-effective and short turnaround time coupled with a wide range of earth resource monitoring, prediction of crop yield, estimation of soil moisture conditions, in forestry applications such as wildlife habitat assessment and timber volume estimation.

In geological sciences, it is used in the study of morphology of the earth, and in lithological and structural mapping. Besides this, the technology is also used in locating sites suitable for major reservoirs and in targeting groundwater.

2.2 Remote Sensing

RS is the non-contact recording of information about the earth surface, from the ultraviolet, visible, infrared and microwave regions of the e-m spectrum, by means of instruments such as scanners and cameras, located on mobile platforms such as aircraft or spacecraft followed by the analysis of acquired information by means of photograph interpretation techniques, image interpretation and image processing (Sabins 1987).

The contact between the remote sensor and the target is through e-m energy (visible, thermal, infrared radiation), force fields (gravity, magnetic) or acoustic waves (sonar). Remote sensors measure the relative variation of these forms of energy that is either emanating from the body or being reflected from it for recognition and detailed studies.

For most of the atmospheric and earth surface observations, e-m energy is considered to be the supreme medium for two reasons. Primarily, this is the only form of energy that has the ability to propagate through free space and also a medium. Further, its property to interact with the media and the target in a variety of ways ensures the sensor to capture the subtle variations that exist in the nature of the earth features.

2.3 Remote Sensing Technique

Every part of the earth reflects the incident light depending on its optical characteristics. The information which characterizes objects is called "signatures". Different objects of the earth surface return different amounts of reflected/emitted energy in different wavelengths of the e-m spectrum (Fig. 2.1a) depending on the atmospheric windows (Fig. 2.1b), and this reflectance/emittance from each object depends on the wavelength of the radiation, the molecular structure of the object and its surface conditions. Vegetation, in general, appears green during daytime, because it reflects the green band of visible radiation preferentially, while absorbing other colour bands of the visible radiation.

Detection and measurement of these spectral signatures enable identification of surface objects both from airborne and spaceborne platforms. But often, similar spectral response from different surface objects creates spectral confusion leading to misinterpretation and misclassification. This can be avoided by systematic ground data verification. However, spectral variation in reflectance or emittance from objects is not the only characteristic of e-m radiation that helps in establishing their

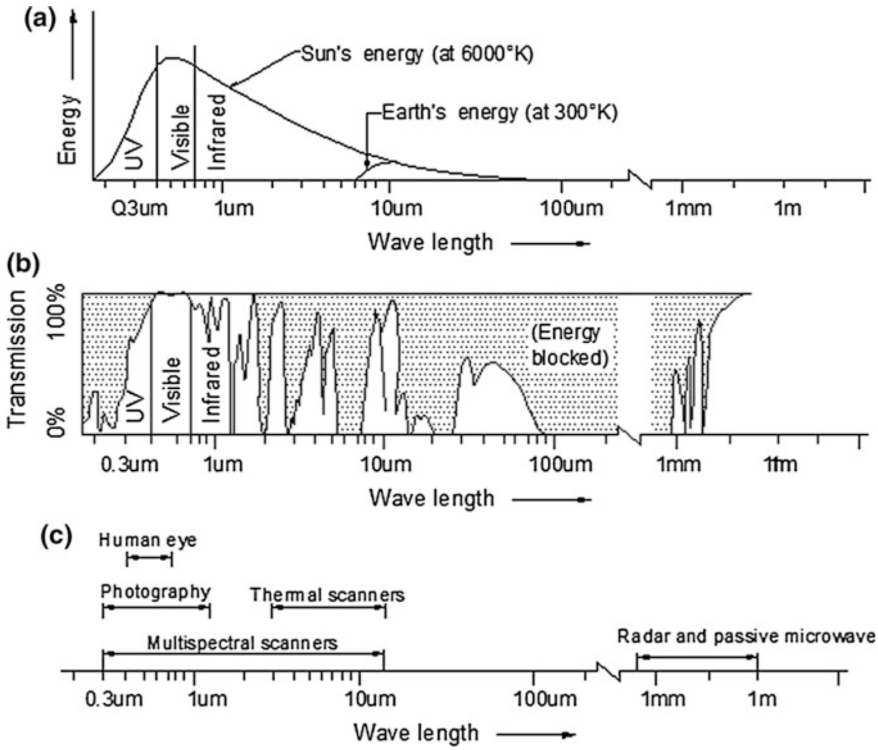

Fig. 2.1 Spectral characteristics of energy sources, atmospheric effects and sensing system (after Lillesand and Kiefer 1987). **a** Energy sources. **b** Atmospheric transmittance. **c** Common remote sensing system

signatures. Signatures, in fact, comprise of any set of observable characteristics which directly or indirectly lead to the identification of an object and its condition. The characteristics are spatial information, temporal (for example, seasonal) variation and polarization effect. The shape, size, texture, pattern, association, for example, are associated with special information.

Earth resource satellites collect information about earth's surface and transmit to the ground receiving stations. After carrying out initial corrections, two types of data products are generated for resource study. These are: (i) visual imagery hard copy and (ii) computer compatible tapes (CCTs). These data are processed and interpreted for the identification and classification of different objects of the earth.

Each satellite system is composed of a scanner with sensors. The sensors are made up of detectors. The scanner is the entire data acquisition system, such as the Landsat Thematic Mapper scanner or the SPOT panchromatic scanner (Lillesand and Kiefer 1987).

In a satellite system, the total width of the area on the ground covered by the scanner called the "swath width", or width of the total field of view (FOV). FOV differs from IFOV (instantaneous field of view); in that, the IFOV is a measure of the FOV of each detector. The FOV is a measure of the FOV of all the detectors combined together.

A sensor of a satellite is a device that gathers energy, converts it to a signal and presents it in a form suitable for obtaining information about the environment. A detector is the device in a sensor system that records e-m radiation. For example, in sensor system on the Landsat Thematic Mapper scanner there are 16 detectors for each wavelength band.

The common RS systems given in Fig. 2.1c have several characteristics:

(i) They have circular orbits that go from north to south and south to north;
(ii) They have Sun-synchronous orbits, meaning that they rotate around the Earth at the same rate as the Earth rotates on its axis, so data are always collected at the same local time of day over the same region;
(iii) They record e-m radiation in one or more bands; and
(iv) Their scanner produces nadir (the area on the ground directly beneath the scanner detectors) views.

2.4 Satellite Image

RS image is available in the form of hard copy paper prints visual imagery, in different scales, which are generated from the digital data collected by the sensors. In satellite, the sensor measures radiations reflected/emitted from the earth's surface. The altitude of the satellite and the size of the detector element define the spatial resolution or pixel (picture element) size. The value at each pixel on a satellite image represents the total amount of radiation reaching the sensor from the ground. Two-dimensional array of pixel values constitute a digital image of the scene. Each pixel value represents average radiance over a defined smaller area within a scene. The size of the pixel area affects the representation of the details within the scene. As the pixel area is reduced, more and more scene detail is preserved in the digital representation and this governs the spatial resolution.

The continuous radiance of the scene is, therefore, quantized into discrete grey levels in the digital image. The data are thus routinely recorded in digital form by space sensors, which are transmitted to the ground stations. These data are reprocessed by the computer to generate image for interpretation. The data can be displayed in suitable scales by appropriate computer processing.

2.4.1 Data

There are many data acquisition options available. These options range from photography to aerial sensors using film, to sophisticated satellite scanners.

A satellite system with detectors which produce digital data may be preferable for the reasons: (i) the digital data can be easily processed and analysed by a computer, (ii) the satellite is in orbit around the Earth, so the same area can be covered on a regular basis for change detection, (iii) once the satellite is launched, the cost of data acquisition is less than that for the aircraft data, (iv) satellites have stable geometry, meaning that there is less chance for distortion or skew in the final image. A wide variety of RS data are acquired from different types of satellites, viz. Landsat, SPOT, IRS-IB, IRS-1C, IRS-1D, NOAA, LISS-IV Pan merged data through Cartosat-2 and Resourcesat-2.

Landsat has a 15-m panchromatic sensor and a 30 m enhance. Thematic Mapper sensor is with 7 bands. SPOT has a 10-m panchromatic sensor and a 20-m multispectral sensor with 3 bands. IRS-IB has a 36-m multispectral sensor with 4 bands. LISS-IV sensor on-board satellite has the spatial resolution of 5.8 m as that of IRS 1D PAN, but it has enhanced spectral resolution. LISS-IV sensor consists of three spectral bands in the green, red and near-infrared regions of the e-m field. It can be tilted up to ±26° in the across-track direction, thereby providing a revisit period of 5 days and 70 km × 70 km stereo pairs. This opens a new field of microlevel applications. Remotely sensed raw data are not projected onto a plane. Therefore, rectification is necessary to project the data conforming to a map projection system before processing.

2.4.2 Resolution

Resolution is a broad term commonly used to describe the number of pixel we can display on a display device or the area on the ground that a pixel represents in an image file. Four distinct types of resolutions are associated with RS data discussed below.

Spectral resolution: Spectral resolution refers to the specific wavelength intervals in the e-m spectrum that a sensor can record (Simonett 1983). For example, Band 1 of Landsat Thematic Mapper sensor records energy between 0.45 and 0.53 μm in the visible part of the spectrum.

Spatial resolution: Spatial resolution is a measure of the smallest object that can be resolved by the sensor, or the area on the ground represented by each pixel (Simonett 1983). The finer the resolution, the lower, the number. For instance, a spatial resolution of 36 m is coarser than a spatial resolution of 20 m.

Radiometric resolution: Radiometric resolution refers to the dynamic range, or the numbers of possible data file values in each band. This is referred to by the number of bits the recorded energy is divided into. For instance, in 8-bit data, the values range from 0 to 255 for each pixel, but in 7-bit data, the values for each pixel range from only 0 to 128.

Temporal resolution: Temporal resolution refers to how often a sensor obtains imagery of a particular area. For example, the IRS-1B satellite can view the same area of the globe once every 22 days. Temporal resolution is an important factor to be considered when performing change detection studies.

2.5 Image Processing

The image processing is the manipulation of digital image data, including (but not limited to) rectification, enhancement and classification operations. The purpose of image processing is to generate thematic maps from satellite images. There is a large number of image processing softwares available from different vendors, namely ERDAS, IDRISI for both commercial and educational purposes either on personal or mainframe computers with array/vector processing capabilities (Fig. 2.2).

2.5.1 Image Interpretation

Image interpretation is a complex process of physical and psychological activities occurring in a sequence of time. The sequence begins with the detection and identification of objects and later by their measurements. Images are then considered in terms of information and final deductions to be confirmed by ground checks to avoid misclassification.

There are certain fundamental feature recognition elements seen on image that aid in visual interpretation of satellite imagery. Although there are differences of opinions on the number of such elements to be included, there is a general consensus in the following:

(i) *Tone or colour*: Different surface objects reflect/emit different amounts of radiant energy. These differences are recorded as tonal/colour or density variations on the imagery. In black and white images, objects appear in

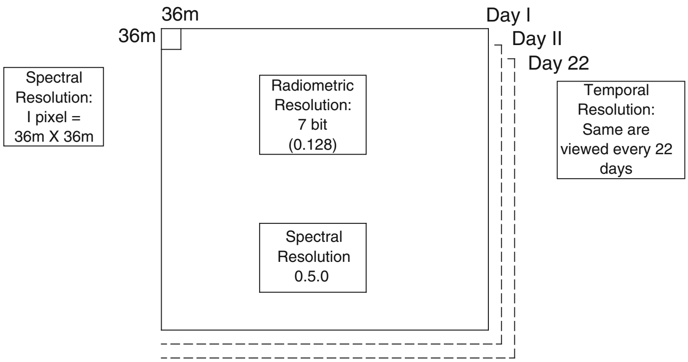

Fig. 2.2 Four types of resolution

different grey tones. These grey tones often fail to provide the interpreter a clear perception of objects, whereas true-colour or false-colour imagery increases interpretability by providing a subtle tonal contrast between them. Tonal contrast can be enhanced or reduced optically or by enhancement techniques on computers.

(ii) *Texture*: It is defined as a repetition of basic pattern. Texture in the image is due to tonal repetitions in a group of objects that are often too small to be discernible. It creates a visual impression of surface roughness or smoothness of objects and is a useful photo-element in image interpretation.

(iii) *Pattern*: It refers to the spatial arrangements of surface features which are characteristics of both natural and man-made objects. Similar features under similar environmental conditions reflect similar patterns of recurrence. More often, patterns also reflect association, e.g., intensity of drainage pattern shows its relation with rock types, soil texture, rainfall, run-off, etc.

(iv) *Size*: It refers to the spatial dimension of objects on ground. Size of an object is a function of scale of the image or photograph and is also measurable. There are different objects with varying sizes and shapes.

(v) *Shape*: It refers to physical form of an object and is also a function of scale of the image or photograph. Size and shape are interrelated. In the image, shape refers to plan or top view of the object as seen by the satellite. Shape can be irregular, regular and uniform.

(vi) *Shadow*: These are cast due to Sun's illumination angle, size and shape of the object or sensor viewing angle. The shape and profile of shadow help in identifying different surface objects, e.g. nature of hill slopes, apparent relief.

(vii) *Location*: The geographic site and location of the object often provide clues for identifying objects and understanding their genesis.

(viii) *Association*: It refers to situation of the object with respect to other neighbouring and surface features.

2.5.2 Image Enhancement

Improvement in the quality of an image in the context of a particular application is called image enhancement. Contrast stretching, band combination, data compression, edge enhancement and filtering, and colour display are some of the well-established techniques in image enhancement.

Contrast enhancement: In order to accommodate the tonal variations of a variety of environments spread over the earth, satellite sensors are designed to record a wide range of radiation intensity within every band width. Due to this, while scanning a particular scene, signals are recorded only within a small portion of this wider scale. This imagery when viewed in its raw state will exhibit a low contrast, often leading to difficulties in feature recognition. Therefore, to increase the

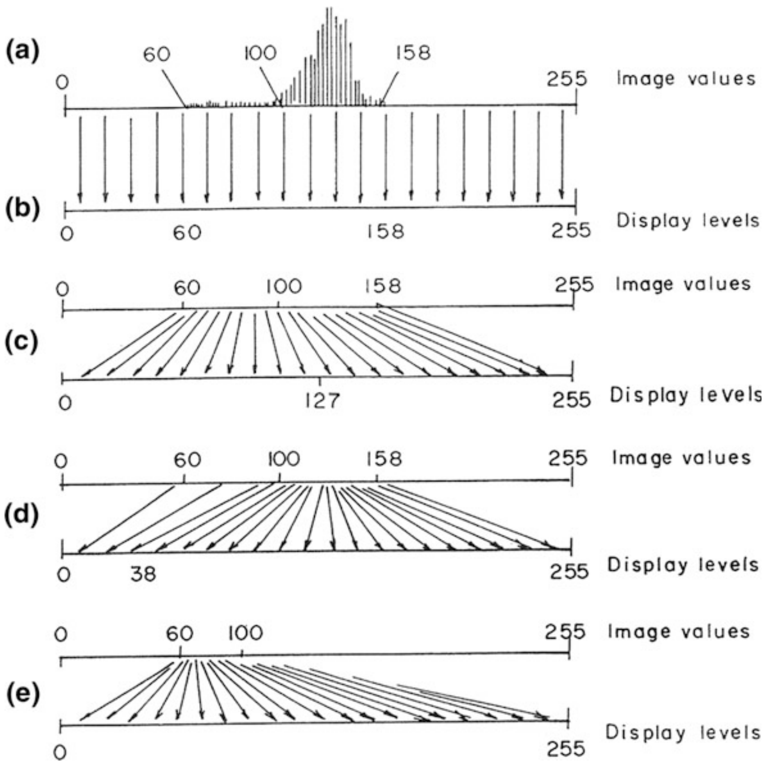

Fig. 2.3 Principle of contrast stretch enhancement. **a** Histogram. **b** No stretch. **c** Linear stretch. **d** Histogram stretch. **e** Spatial stretch

contrast, the recorded digital numbers are rescaled to a new longer scale following certain statistical criteria (Fig. 2.3). There are different methods of contrast enhancement, such as linear stretch, histogram equalization, binary stretch, logarithmic stretch, and Gaussian stretch.

Band combination: Band addition, subtraction and rationing are some of the common band combinations. Different bands of the same image is subtracted or rationed to suppress the details common to the two images and enhance details that are different. Band combination is also performed on geometrically registered multitemporal scenes to monitor the changes in the environment, such as the effect of floods, extension of forest fire, urban sprawl and in agriculture.

Principal component analysis (PCA): A major problem frequently encountered in the analysis of multispectral data is extensive interband correlation. High correlation indicates high degree of redundancy among the data, i.e., each band data convey essentially similar information. PCA is a technique designed to remove or reduce such redundancy in multidimensional data. The PCA compresses the whole of information contained in the original multiband data into fewer channels or components with zero correlation and are often more interpretable (Drury 1987).

PCA is the most widely used and popular technique among the digital enhancement methods (Radhakrishnan et al. 1992).

Edge enhancement and filtering: The edge enhancement is an operation which helps the analyst in achieving edge-highlighted image (Radhakrishnan et al. 1992). According to Jensen (1986), the edge enhancement operation delineates the edges and thereby makes the shapes and details comprising the image more conspicuous and perhaps easier to analyse. Edge enhancements are the techniques for enhancing sharp changes in the grey levels, such as lineaments, roads, canals, field boundaries and contacts of two land use classes. In geology, they are advantageous for enhancing joints, faults, lineaments and fractures. Edge enhancement is achieved by a process called "spatial filtering". Spatial filters emphasize or de-emphasize image data of various "spatial frequencies". Spatial frequencies refer to the roughness of the tonal variations occurring in an image. Image areas of high spatial frequency are tonally rough. That is, the grey levels in these areas change abruptly over a relatively small number of pixel (e.g. across roads, linear features). Smooth image areas are those of low spatial frequency, where grey levels vary only gradually over a relatively large number of pixel transformation of an image, where the transformation depends not only on the grey levels of the pixel concerned, but also on the grey levels of the neighbouring pixels. Spatial filtering is a context-dependent operation that alters the grey level of pixel according to its relationship with the grey level of a pixel in the immediate vicinity (Schowengerdt 1983).

Usually, different combinations of low-pass filtering and high-pass filtering are used in image processing by convolution using convolution windows. The window is moved over the input image processing by convolution using convolution windows. The window is moved over the input image from pixel to pixel, performing a discrete mathematical function transforming the original pixel values to new ones. The windows or filters may be rectangular or square. Each location in the box filter is given a certain weight. Many types and sizes of filters can be designed by changing the window size and varying the weights. The edges may be enhanced either by directional or non-directional edge enhancement techniques. Various edge-enhancing operators have been reported to detect linear patterns from images (Wang and Newkirk 1998; Holyer and Peckinpaugh 1989).

2.5.3 Image Classification and Generation of Thematic Maps

Multispectral classification is the process of sorting pixels into a finite number of individual classes, or categories of data, based on their data file values. If a pixel satisfies a certain set of criteria, the pixel is assigned to the class that corresponds to the criterion.

The classification process breaks down into two parts—training and classifying. First, the computer system must be trained to recognize patterns in the data.

Training is the process of defining the criteria by which these patterns are recognized (Hord 1982). The result of training is a set of signatures, which are statistical criteria for a set of proposed classes. Training can be performed with either a supervised or an unsupervised method. Pixels of an image area are then sorted into classes based on the signatures, by the use of a classification decision rule. The decision rule is a mathematical algorithm that uses particular statistics such as maximum likelihood and Bayesian methods to sort the pixels.

Supervised classification: This type of classification is more closely controlled by the user. In this process, user selects the pixels that represent the pattern with the help of other sources, such as aerial photographs, ground truth data or maps. Knowledge of the data, and of the classes desired, is required before classification. By identifying patterns, user can train the computer system to identify pixel with similar characteristics. If the classification is accurate, each resulting class represents an area of interest within the data that corresponds to the pattern user originally identified.

Unsupervised classification: This type of classification is more computer-automated. It allows the user to specify some parameters which the computer uses to uncover statistical pattern that are inherent in the data. These patterns do not necessarily correspond to directly meaningful characteristics of the scene, such as contiguous, easily recognized areas of a particular soil type or land use. They are simple groups of pixels with similar spectral characteristics. In some cases, it may be more important to identify groups of pixels with similar spectral characteristics than it is to sort pixel into recognizable categories. Unsupervised classification is dependent upon the data itself for the definition of classes. The method is usually used when less is known about the data before classification. It is the responsibility of the user, after classification, to attach meanings to resulting classes to generate thematic maps. Unsupervised classification is only useful if the classes can be appropriately interpreted.

2.5.4 Case Study

The study area is Midnapur District, West Bengal (location map in Fig. 2.4, reproduced from Nath et al.2000) covers 631 km^2. It is a typical soft rock area having hydrogeological conditions favourable for shallow groundwater reserve. For the groundwater investigations, thematic maps of surficial geology and drainage pattern are prepared from IRS-1B LISS-II data. The data have spatial and radiometric resolutions of 36 m and 7 bits, respectively. In the first step, raw image data are projected onto a plane using Everest projection method and taken into Universal Transverse Mercator (UTM) coordinate system for further processing.

Enhancement of the image is accomplished by using PCA on bands 1, 2 and 3 for the generation of geological map of the area. PCA 1, 2 and 3 are assigned the colours red, green and blue, respectively, for generating a false-colour composite (FCC) of the image. Three distinct features are identified in the enhanced image

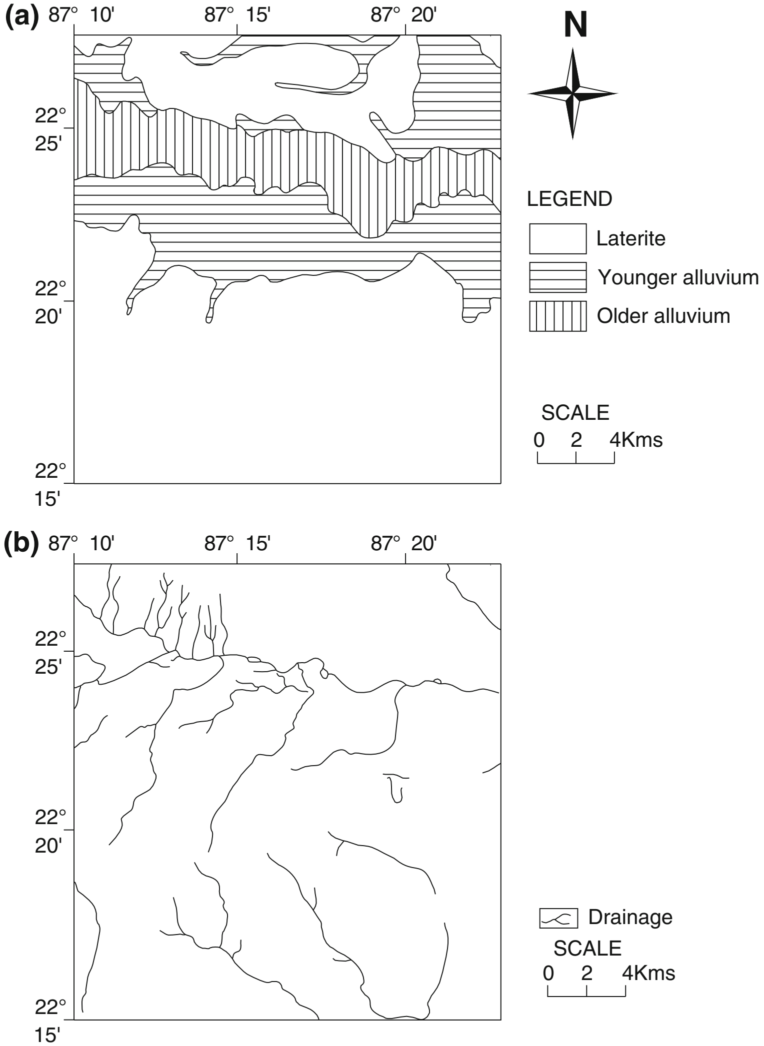

Fig. 2.4 Thematic map of **a** geology and **b** drainage pattern generated from IRS-IB LISS-II data

from their tones and textures. From ground check-up, these features are found to be laterite, older alluvium and newer alluvium. The spectral signature of these features are used to classify (supervised) the image and generate the thematic map of the geology of the area, as shown in Fig. 2.4a.

For the preparation of thematic map of drainage pattern of the study area, a standard FCC (using bands 1, 2 and 3) is generated. The water bodies are identified by their blue tone and fine texture. A GIS package is used to digitize the rivers, streams and channels from the image. The evolved thematic map of the drainage of the study area is presented in Fig. 2.4b.

2.6 Applications

2.6.1 Surface Water Harvesting

The fresh water that is confined to channels of streams and rivers and accumulated in ponds and lakes are normally considered as surface water resources. The infiltration capacity of the earth surface, coupled with evapotranspiration of the region, controls the volume of water in a channel. Further, the channel size and its gradient also control the water holding capacity. In order to harvest this resource, barrages or dams are constructed across the rivers and artificial lakes or reservoirs are formed from where the water supply is regulated through a network of canals.

Several criteria are taken into consideration while selecting suitable sites for dam construction. The first and most important factor in dam designing depends on normal aerial coverage and lower evaporation loss. Further, they are beneficial as the area of submergence is nominal and also the cost of dam construction works out to be far cheaper. The nature of the valley bottom material and the catchment area is another important criteria. Impervious and consolidated basement crystalline rocks are supposed to be excellent valley bottom material as the loss of water due to percolation is minimized. Further, catchment area having good vegetative cover and soils resistant to erosive forces are considered good as the rate of siltation of the reservoir will be low and also the loss of water due to infiltration will be less.

The ability of recording the earth-related information in narrow wavelength bands coupled with synoptic coverage makes the satellite data, a potential tool in the hands of the interpreter in deriving the required information for locating hydel projects. A careful observation of the satellite imagery helps in determining the width of the valley, size of the upstream catchment and in evaluating the total area of submergence and loss of vegetative and forest cover due to submergence, etc. Further, by coupling the satellite data with other field inputs it is possible to extract information regarding the nature of valley floor material, lineaments criss-crossing the area, erodability of the catchment material, area occupied by the artificial reservoir and finally, in estimating the total area to be irrigated by the hydel project.

2.6.2 Groundwater Exploration

Although remotely sensed data often provide only a superficial and inadequate knowledge on the subsurface resources, it is time and again used, quite effectively, in the exploration of groundwater. This is because, the satellite imageries help in acquiring certain ground information that aid in drawing inferences on groundwater potential of a region. This section examines the basic requirements of groundwater accumulation and the hydrogeomorphological features that aid in the exploration for groundwater resources using satellite RS data.

The water to be stored beneath the surface of the earth as groundwater requires an intricate balance between many factors. Primarily, the infiltration capacity of the soil determines the groundwater potential. The speed of infiltration is dependent upon, mainly, the porosity and permeability of the soil and the velocity of the surface run-off. If the surface run-off is extremely high due to steeply sloping nature of the ground then, even if the soil is porous and permeable, the soil infiltration capacity is reduced to a great extent. Another point to be noted here is the part played by vegetation. It has been found that the surfaces covered with abundant vegetative cover have better infiltration capacity than barren lands. The thickness of the permeable layer is another very important factor that determines the storage of groundwater.

While making inferences about the groundwater potential of an area using the satellite data, an interpreter concentrates mainly on the geomorphic units that he can observe on the imagery. Based on the nature of origin, the geomorphic units can be grouped into five main classes, namely (i) fluvial, (ii) denudational, (iii) structural, (iv) aeolian and (v) marine.

2.6.2.1 Geomorphic Units of Fluvial Origin

Alluvial plains, flood plains, alluvial fans, deltaic plains, river cut-offs, bajada, wadi (dry river bed) are some of the geomorphic features that have come into existence due to fluvial process. All these features can be mapped easily from the satellite imagery. All these features occupy the valley portion and are composed of loose deposits of permeable material like sand or clay. The groundwater prospects range from excellent to moderately good.

2.6.2.2 Geomorphic Units of Denudational Origin

The surface of the earth is constantly being acted upon by different kinds of exogenetic forces, such as wind, water and ice. These forces tend to bring about both physical and chemical weathering of the bed rocks and also transport and deposit the weathered debris in certain locations on the earth. The complete phenomenon is referred to as denudational process, and this gives rise to many characteristic landforms.

The earth's crust is made up of several kinds of material and when the exogenetic process operates in a region certain resistant rocks are left out without much damage. These rocks will be appearing as hills of bare rock dotting a plain land. They are called denudational hills and inselbergs. They can be observed in satellite imagery as bare rock outcrops and they are normally devoid of any water, as they are totally made up of compact crystalline rock.

The gently inclined surfaces that are formed in front of major slopes during the process of erosion are the pediments. They form the zone of recession due to valley formation. Sometimes by the process of valley formation and widening, a few adjoining pediments will merge to give rise to a wider plain—the pediplain. Usually, they are found to be either poor or at the most moderately good as far as their groundwater prospects are concerned.

Under humid tropical conditions, the crystalline rocks are subjected to intense chemical weathering, giving rise to lateritic uplands. Although the laterites are soft, permeable and porous, their location at the ridge tops prevents them from holding sufficient water resources, against the gravitation force, to be considered as good groundwater prospecting zones. On the standard FCC, they appear as bright light brown spots or lines.

The eroded material that has been deposited in the valleys gives rise to piedmont and talus cones. Piedmonts are the alluvial fans that are found at the foot of the hills or mountain chains.

Normally, they are composed of fine silts and clay and are considered to be very good zones of groundwater accumulation. These are readily visible in standard FCC as triangular zones of high reflectance at the foot of hills. Talus cones are heaps of cobble and boulder, found at the foot of hills. They are the result of glacial action, and due to the absence of finer sediments, they are not suitable for holding any moisture or groundwater.

2.6.2.3 Geomorphic Units of Structural Origin

Due to the tectonic readjustments that are taking place within the crust of the earth, many features are formed. The most important features of this category are structural hills and valleys, fractured plateau, mesa and butte. Mesa and butte are the resistant rock outcrops of volcanic origin, consolidated in nature and do not qualify as rich groundwater potential zones. The structural ridges are also considered to be poor groundwater zones. On the contrary, if these features contain sets of fractures or faults then they qualify as good sources of groundwater, this is because the numerous fractures and faults act as conduits for groundwater movement. While faulting, due to the abrasion of the opposite blocks a zone of breccia is formed and this zone is considered to be extremely rich in groundwater.

In a standard FCC, the joints and structural hills and valleys can be readily mapped. The lineaments and faults are also observed on the imagery as faint lines of straight or curved nature. Sometimes, they are also located by the abrupt tonal contrast in the imagery. In cases where the lineaments are not readily visible, then image enhancement techniques like edge enhancement, using high-pass filters, have yielded good results. In fact it is easy to map the lineaments of fairly large dimensions from the digitally enhanced satellite imagery rather than by following the conventional geophysical methods. Once the lineaments are traced from the satellite imagery, then the conventional methods are adopted to fix their location with accuracy on the ground.

2.6.2.4 Geomorphic Units of Aeolian Origin

Most of the features that form the desert topography fall into this category. All except the playa (dry lake) qualify as zones of very low potentiality for groundwater prospecting.

2.6.2.5 Geomorphic Units of Marine Origin

Coastal plains, salt flats, mud flats, beach/sand bars and lagoons are the features formed due to marine processes. Most of the features can be mapped easily from the satellite imageries using their characteristic spectral signatures and spatial associations. Except a few broad coastal plains, all the other units are rich in saline water and, therefore, are not of much use, as far as their resource potential is considered.

2.6.3 Monitoring of Freshwater Submarine Springs

Gardino and Tonelli (1983) used RS to detect freshwater submarine springs in the coastal areas of Italy, Sicily and Sardinia. About seven hundred such springs have been studied along a coastline of 1500 km.

Isotherm maps were prepared for all the coastal inflows. Ground checks were carried out to distinguish spring flows from pollution seepage discharges. Isotherm maps have also been used to compute the likely yield on the basis of thermal balance between water from the spring and the sea. Aerial thermal surveys have been found to be quite useful in locating rapidly and cheaply the regional carbonate aquifers discharging reasonably good amount of water into the sea.

2.6.4 Water Table Depths for Aquifers in Deserts

The possibility of estimating shallow groundwater table depths through remotely sensed thermal infrared data was studied by Menenti (1983).

In arid zones, both surface and groundwater reservoirs lose water through evaporation. This aspect of the problem, particularly the evaporation rate, was analysed cheaply in the Fezzan region of Libya (Menenti 1983). Evaporation loss through the playas (dry lakes) was estimated by combining ground experiments with remotely sensed data. An infrared line scraping (IRLS) airborne survey with adequate agri-meteorological support led to the assessment of shallow water table depth and evaporation rate in the deserts.

2.6.5 Lineaments from IRS LiSS H Satellite Data

Prasad and Sivaraj (2000) used IRS LiSS-II satellite data and aerial photographs to locate structurally controlled weaker zones, i.e., lineaments suitable for groundwater accumulation in the Nileshwar river basin areas of the state of Kerala (India).

2.6.5.1 Geology of the Area

Nileshwar river flows over a length of 46 km and joins the Laccadive Sea through Karingotte river. This river drains an area of 190 km^2 and is bounded within latitudes 12° 13′ and 12° 23′N and longitudes 75° 05′ and 75° 17′E. The basin is covered by hard rocks with only fringes of alluvium along the coast. Basin areas are characterized by charnockites of Precambrian age, laterites of Pliestocene age and the alluvium (Prasad and Sivaraj 2000). The hydrogeomorphological map of Nileshwar basin is reproduced in Fig. 2.5.

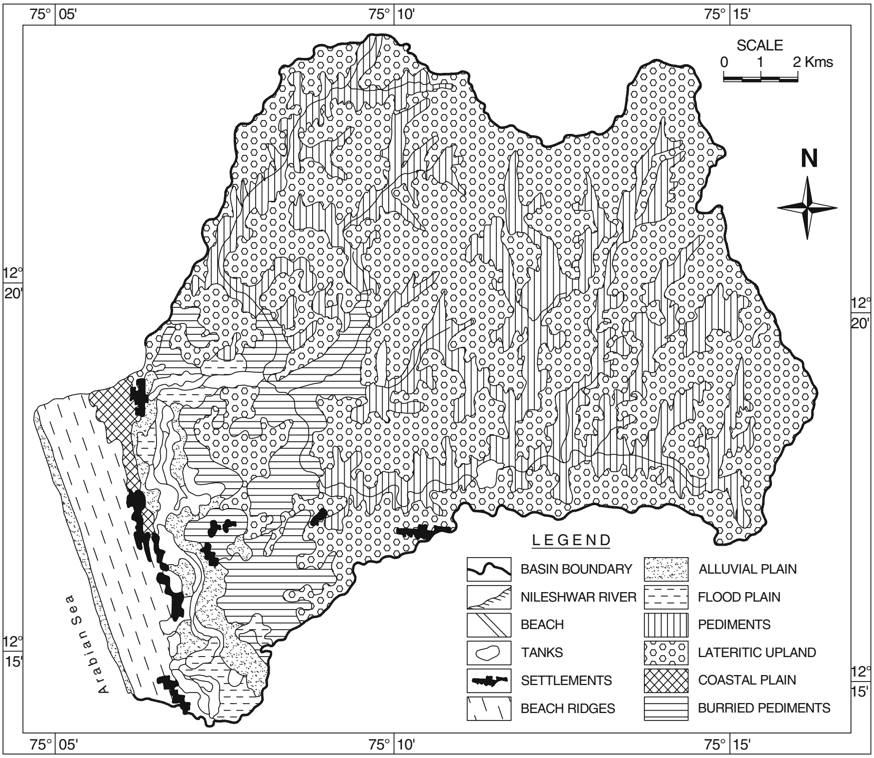

Fig. 2.5 Hydrogeomorphological map of Nileshwar basin (after Prasad and Sivaraj 2000)

2.6.5.2 Lineaments

The lineaments obtained from aerial photographs and IRS LISS satellite data are the surface manifestations of the linear feature like faults joints and fractures. The nature of two sets lineaments with general trend along NW-SE and NE-SW are shown in Fig. 2.6.

2.6.5.3 Observation

The wells existing near the lineaments are found to have a perennial shallow groundwater source. Groundwater potentiality of high order is indicated where lineament runs along/across the alluvial zones with several lineaments intersecting each other. However, it has been suggested that further field investigations involving drilling and yield test be carried out for detailing and confirmation (Prasad and Sivaraj 2000).

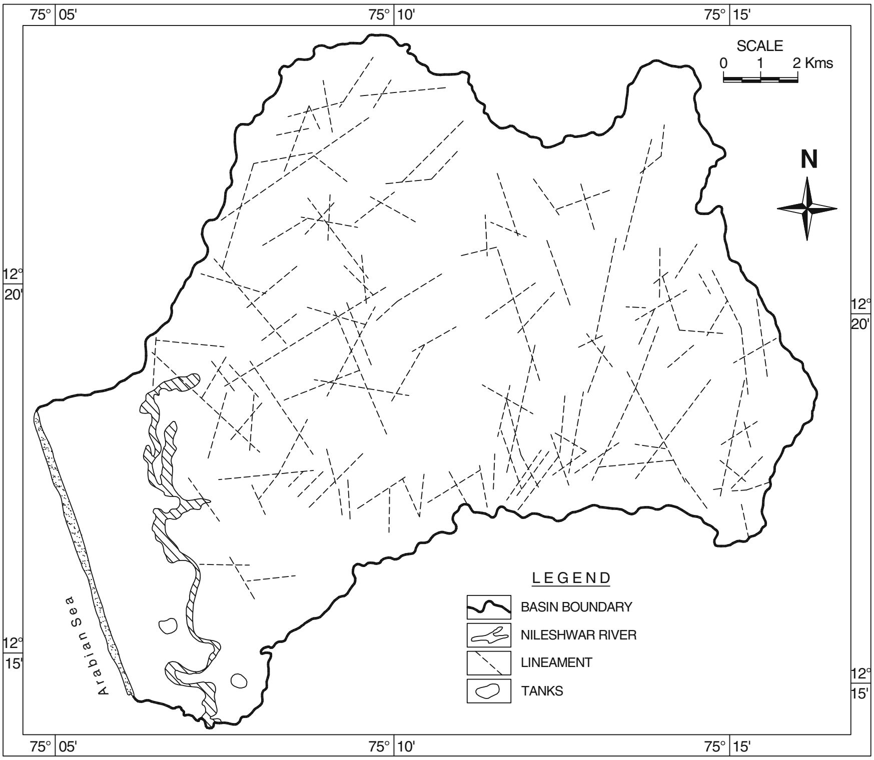

Fig. 2.6 Lineament map of Nileshwar basin (after Prasad and Sivaraj 2000)

2.7 Other Geological Applications

The availability of spaceborne data gave an opportunity to several geologists to apply it in regional-scale mapping of structural features, thereby leading to the discovery of several hitherto unknown lineaments, faults and folds in areas considered to be reasonably well mapped. When this information was correlated with known mineral deposits of the area, a clear relation between the lineaments and the zone of mineralization and groundwater accumulation could be established. This experiment convinced the geological community, beyond doubt, the efficiency of the spaceborne data in providing the information that is so vital in updating the existing mineralogical maps. After the initial enthusiasm, geologists slowly started exploring the potential of space derived data in tackling other geological problems.

But, geological mapping with spaceborne data is not as easy as forest or land use mapping as most of the geological features of interest are not readily visible on the initial imagery and requires the application of a series of interactive image enhancement techniques.

2.7.1 Geomorphology

Geomorphology is one of the principal subdisciplines of geology and deals with the study of the surface configuration of the earth. Here, the landforms are described, classified and an attempt is made to explain the origin and development of the present-day landforms and their relationship to tectonics.

Earlier, the geomorphologist had heavily depended on air photographs for acquiring the information on earth feature, but now with the availability of the various kinds of satellite imageries such as visible, near-infrared, thermal infrared and radar imageries at regular intervals the geomorphologist is better equipped for mapping and monitoring the various changes that are taking place with regard to the size and shape of the landforms, slope of the terrain, river courses and the drainage networks. All these data have provided an insight into the geomorphologist in understanding of the processes that are shaping the earth and also in predicting the future trend of the changes.

2.7.2 Geological Mapping

Geological mapping comprises of recording information on the extent and distribution of different rock types and their structural deformation, through satellite imageries and subsequent ground checks.

2.7.2.1 Lithological Mapping

The diversity in the spectral reflectance properties of the various geological materials serves as basis for lithological discrimination using satellite data. For example, most of the acidic or felsic rocks (rocks composed of light minerals) show reflectance values between 25 and 50 % in the wavelength region of 0.5–1.1 m and in the same region most of the mafic rocks (rocks composed of heavy minerals) have reflectance <25 %. However, in practice it is not very easy to discriminate rock types, due to the soil and vegetation cover. Recently, it has been found that the thermal infrared imagery is best suited for the discrimination of consolidated rock outcrops from the surrounding as their radiation emissions are much higher than the unconsolidated soil. Further, the differences in the spatial domain such as spread of the outcrop, drainage pattern of the region, drainage density and associated vegetation also help in inferring the nature of the rock type.

In case of sedimentary terrain, the discontinuities existing between beds of differing characters can be distinguished, again by their differing spectral signature such as variation in colour, texture, tone and the nature of vegetation, by mapping the ridge and furrow system of semi-parallel nature formed due to the differential erosion of the beds in a sedimentary basin the nature and orientation of the beds can be deciphered. Drainage patterns, such as trellis, rectangular, parallel, also furnish information on the attitude of beds and lineaments.

2.7.2.2 Structural Mapping

Structural study involves the mapping of linear features representing major faults or joints (lineaments), detection of unconformities, mapping of bedding planes and folds of regional extent. Satellite imageries provide the most useful single tool for initiating a regional analysis of large-scale tectonism and structural deformation as they provide synoptic views of large areas at a constant low-azimuth Sun angle, thereby creating an apparent relief and accentuating minor variation in the morphology.

Lineaments, by definition, are two-dimensional geomorphological features, presumably reflecting the subsurface tectonic phenomena, of mappable dimension possessing rectilinear or lightly curvilinear characteristics. They are considered to be weak tracts representing, zones of mineral enrichment or groundwater potential zones. In an imagery, they are recognized by abrupt changes in the tonal contrast from the adjacent features or as lines of pixel with distinctive tones. However, due to certain limitations in the sensor resolution they may not be readily recognizable and in such instances the data have to be further enhanced by applying high-pass digital filter. As discussed earlier, this technique involves the transformation of the raw image to display the quantum of changes that are existing between the adjacent pixels of the imagery rather than their absolute digital values, thereby enhancing the zones of maximum variation—the lineaments.

2.8 Geographic Information System (GIS)

Geographic information system (GIS) is a tool to efficiently capture, store, update, manipulate, analyse and display all forms of geographically referenced data. It stores data about the world as a collection of thematic layers, a pictorial representation of which is given in Fig. 2.7, to be linked together in spatial domain using geographic reference system. This simple but extremely powerful and versatile concept has proven invaluable in solving many real-world problems from tracking delivery vehicles, to recording details of planning applications and managing natural resources. The use of GIS in groundwater investigations is growing tremendously. Nowadays, it is used for groundwater potential (Chi and Lee 1994; Krishnamurthy et al. 1996) and vulnerability assessment (Rundquist et al. 1991; Laurent et al. 1998), groundwater modelling (Chieh et al. 1993; Watkins et al. 1996) and management (Hendrix and Buckley 1989). In regional scale, it requires to handle large volume of georeferenced (spatial) and attribute (aspatial) data. Using GIS, one can play around with the data and generate themes as required for specific applications.

GIS is an organized collection of computer hardware, software, geographic data and personnel designed to turn the geographic data into information to meet the users' needs. For example, if the hydrogeological properties of aquifers, their locations and lateral extent of an area are given as input, GIS can manipulate these data into information such as the groundwater potential zones, vulnerability to pollution. GIS is the only system that can produce this type of spatial information not possible by any other means.

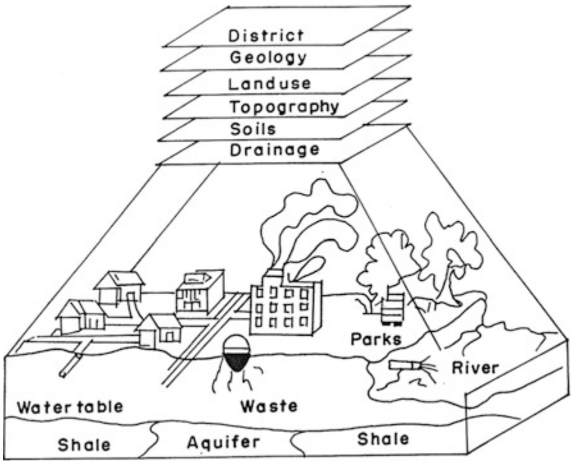

Fig. 2.7 The real-world geographics represented as a number of layers or them

2.8.1 Basic Components of GIS

From the structural point of view, GIS is very similar to conventional database management system (DBMS), except for the fact that the database of GIS is more sophisticated and has the capability to associate and manipulate enormous volume of spatially referenced interrelated data (Fig. 2.8).

GIS stores spatial and aspatial data into two different databases. The geocoded spatial data defines an object that has an orientation and relationship with other objects in two- or three-dimensional space. It is also known as topological data, stored in topological database. The data that described the objects are known as attribute data stored in a relational database. GIS links the two databases by maintaining one-to-one relationship between records of object location in the topological database and records of the object attribute in relational database by using end-user defined common identification index or code.

GIS uses three types of data to represent a map or any georeferenced data, namely point type, line type and area type or polygon type. It can work with both vector and raster geographic models. The vector model is generally used for describing discrete features, while the raster model is used for continuous features.

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

A GIS approach comprises three distinct phases: (I) data acquisition, (2) data processing and (3) data analysis. The data acquisition phase includes establishing control of the data quality, which consists of positional accuracy, and reliability of observation. There are several ways of digitizing map data for its incorporation in a GIS. The data can be directly digitized from the map using a digitizing table or it can be digitized by tracing the outline of required classes on a transparent overlay in image processing software. The latter approach is common for hydrogeological mapping. In the present study, image processing software ERDAS is used for the processing of satellite imagery. The maps are prepared by tracing the outline of the classes of the enhanced image in GIS software Arcinfo by activating the live-link facility between ERDAS and Arcinfo. The slope is calculated from the elevation

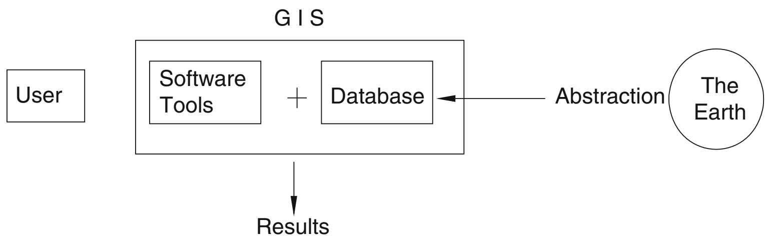

Fig. 2.8 Components of a geographic information system

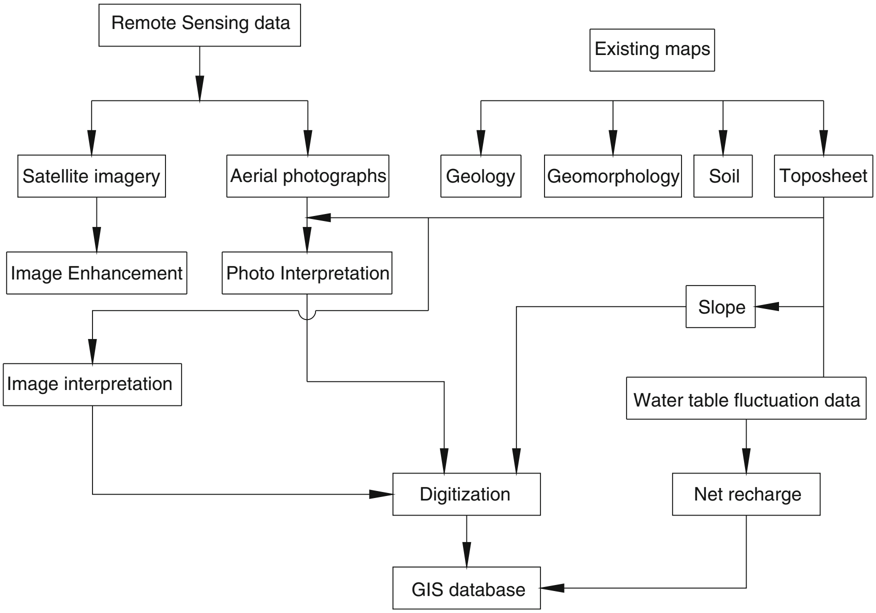

Fig. 2.9 Preparation of thematic maps

contour given in the topographic sheet of Survey of India. The mapping of slope classes is done by classifying the slope values into different ranges and digitizing the polygons of each class using digitizing table. The net recharge of the area is calculated from the water table fluctuation data. The procedure followed to prepare different thematic maps for the development of a GIS database is shown by the flowchart of Fig. 2.9.

2.9 Application of GIS in Groundwater

Groundwater exploration in any terrain is largely controlled by the prevalence and orientation of primary and secondary porosity. The exploration involves delineation and mapping of different lithological and morphological units and identifying quantitative parameters of the drainage network, soil characteristics and slope of the terrain. These parameters play major roles in evaluating hydrogeological parameters, which in turn enable in understanding the groundwater situation in an area. Studying all these parameters in an integrated way facilitates effective groundwater exploration and exploitation. In many developing countries, readily available RS data may comprise a majority of the existing information over local and regional scale. Establishing relationships between features identified in RS data, borehole records, surface geophysical data and other hydrogeological phenomena, is critical in any strategy aimed at maximizing water development efficiencies. These strategies are developed using a GIS as the unifying element for all collected data. Many studies have been attempted to integrate groundwater controlling parameters, such as geology, landform, soil characteristics, topographic features and quantitative morphometric characteristics. (Ross and Tara 1993; Krishnamurthy et al. 1996; Laurent et al. 1998). The topological data structure of GIS allows the hydrologist to increase the degree of spatial units into the distributed models. Spatial modelling with GIS can be used to extract relevant information, such as slope, watershed limits, and flow path. We will now deal with specific applications of GIS in the present context.

2.9.1 Groundwater in a Soft Rock Area Through GIS: A Case Study

The occurrence and movement of groundwater are controlled mainly by porosity and permeability of the surface and underlying lithology. The same lithology forming different geomorphic units will have variable porosity and permeability thereby causing changes in the potential of groundwater, this is also true for same geomorphic unit with variable lithology. The surface hydrological features such as topography, drainage density, water bodies, play important role in groundwater replenishment. High relief and steep slopes impart higher run-off, while the topographic depressions help in an increased infiltration. An area of high drainage density also increases surface run-off compared to a low drainage density area. Surface water bodies such as river, ponds can act as recharge zones enhancing the groundwater potential in the vicinity. Hence, identification and quantization of these features are important in generating groundwater potential model of a particular area. GIS can be effectively used for this purpose to combine different hydrogeological themes objectively and analyse those systematically for demarcating the potential zone. In the present study, an empirical model is developed within the logical condition of GIS for the qualitative assessment of groundwater potential in a soft rock area. It is tested in Midnapur District, West Bengal, India. The results are benchmarked by correlating with the available borehole and pumping test data.

2.9.1.1 Methodology

The GIS used hydrogeological settings of an area as the basic mapping units. Seven themes were evaluated, viz. (i) lithology (*L*), (ii) geomorphology (*G*), (iii) soil (*S*), (iv) net recharge (*R*), (v) drainage density (*D*), (vi) slope (*E*) and (vii) surface water body (*W*). Each theme was assigned a value from 1 to 7 ranges on the basis of its direct control of the groundwater occurrence. Each feature of an individual theme was next ranked in the 1–10 scale in the ascending order of hydrogeological significance. The Groundwater Potential Index (GWPI) for an integrated layer was calculated using GIS as follows:

$$\mathrm{GWPI} = (L_w L_r + G_w G_r + S_w S_r + R_w R_r + D_w D_r + E_w E_r + W_w W_r) / \sum w \quad (2.1)$$

where w represents the weight of a theme and r the rank of a feature in the theme.

GWPI is a dimensionless quantity that helps in indexing the probable groundwater potential zones in an area.

2.9.1.2 Study Area

The test site in Midnapur District, West Bengal, India (87° 10′E, 22° 15′N to 87° 22′ 30″E, 22° 27′ 30″N), covering an area of 631 km^2 falls under Gangetic West Bengal region (Fig. 2.4) with an average annual rainfall of 152 cm and temperature of 31 °C. This forms a typical soft rock area having hydrogeological conditions favourable for shallow groundwater reserve. This was, therefore, best suited for testing the proposed GIS integration tool (Shahid et al. 2000).

2.9.1.3 Preparation of Thematic Maps

All the thematic maps were prepared in 1:50,000 scale with a spatial resolution of 0.1 km^2 using GIS package Arcinfo. Depending on the relative importance in groundwater exploration, the themes were assigned specific weights. As used by Krishnamurthy et al. (1996), geomorphology was assigned the highest weight of 7 while surface water body the least value of 1. Thematic map preparations and ranking of various features are highlighted below.

Lithology: The lithological map of the area was prepared from the standard false-colour composite (FCC) of Indian Remote Sensing (IRS-IB) Linear Image Scanner System (LISS-II) data (Fig. 2.10a). Three types of lithounits were observed in the satellite sensor image, viz. (i) *laterite* as light bluish tone with coarse texture, (ii) *older alluvium* as dark bluish tone with fine texture and (iii) *newer alluvium* as white and red tone with medium texture. Lithounits were ranked on the basis of their groundwater yield capacity.

Geomorphology: The geomorphological map of the area was prepared from the hybrid FCC of PCA of Band 1, 2 and 3 as shown in Fig. 2.10b. The following seven geomorphological units were identified in the area:

(i) *older deltaic formation* by reddish brown tone and fine texture,
(ii) *older filled valley cuts* by reddish brown tone and coarse texture in the lateritic formation,
(iii) *younger deltaic formation* by bluish tone and medium to coarse texture,

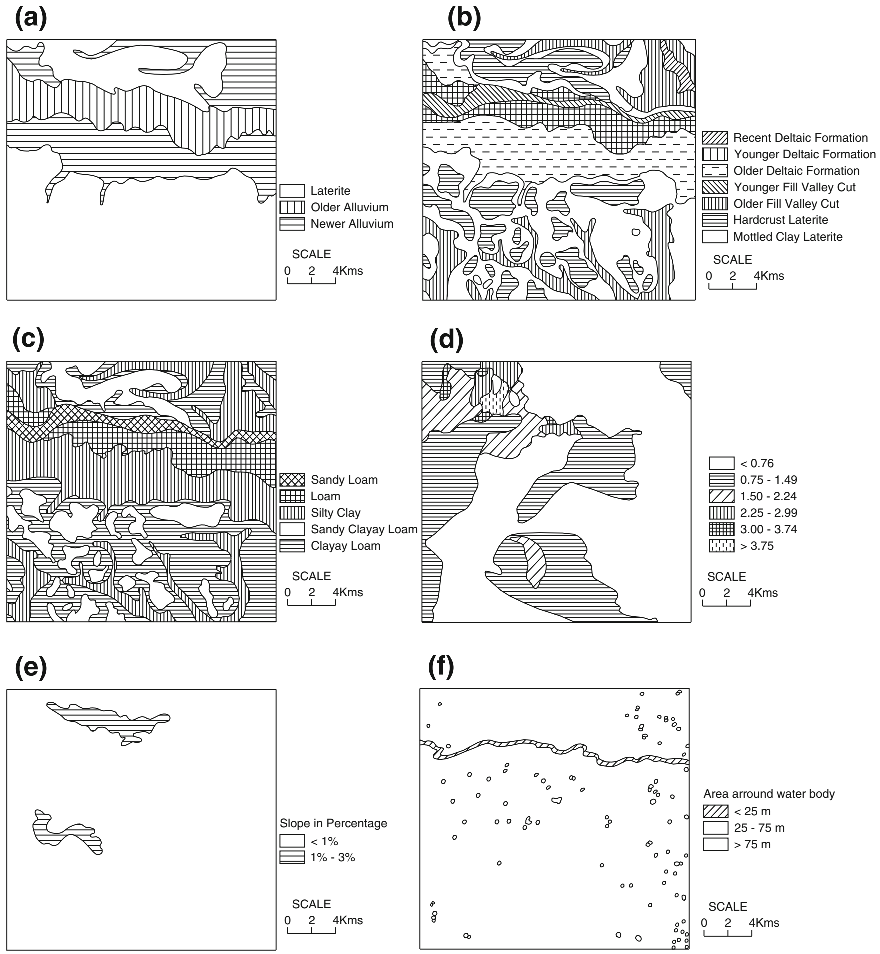

Fig. 2.10 Thematic map of **a** lithounit, **b** geomorphology, **c** soil, **d** drainage density, **e** slope, **f** surface water body of the area

(iv) *younger filled valley cuts* by bluish tone and medium to coarse texture in older deltaic formation,
(v) *recent deltaic formation* by light yellow tone and fine texture,
(vi) *hard crust of laterites* by reddish brown tone and coarse texture and
(vii) *mottled clay of laterites* by reddish brown tone and fine to medium texture.

Depending on the hydrogeological significance, the geomorphic features were ranked.

Soil: The soil map of the area as shown in Fig. 2.10c was prepared using RS data, aerial photograph and field investigation. The area is covered by five soil types, viz. (i) *sandy loam,* (ii) *loam,* (iii) *silty clay,* (iv) *sandy clayey loam* and

Table 2.1 Assigned weightage for the layers

Sl. no.	Theme	Attribute	Rel. weightage
1	Hydrogeomorphology	Valley fill	120
		BPP-D	90
		BPP-M	60
		BPP-S/PP	30
2.	Overburden thickness	>25 m	140
		15–25 m	105
		05–15 m	70
		<5 m	35
3.	Lineament	NW-SE orientation	20
		NE-SW orientation	10
4	Slope	0–1 %	10
		1–3 %	5

Abbreviation—*BPP-D* Buried Pediplain-Deep, *BPP-M* Buried Pediplain-Medium, *BPP-S* Buried Pediplain-Shallow and *PP* Pediplain

(v) *clayey loam*. Soil ranking as indicated in Table 2.1 was done on the basis of its infiltration capability.

Net recharge: The net recharge can be calculated from the annual water table fluctuation data in an area. A net recharge of 25 cm and above was ranked 10 following DRASTIC ratings of Aller et al. (1987). The present area was found to be in this class.

Drainage Density: Using standard FCC, drainage map of the area was prepared for developing the thematic map of the drainage density as presented in Fig. 2.10d. The features of drainage density were ranked in the 1–10 by Krishnamurthy et al. (1966).

Slope: The elevation contours in the topographic sheet No. 73(N/7) of Survey of India helped us in generating the slope thematic map (Fig. 2.10e), each feature of which was ranked following the DRASTIC ratings.

Surface water body: Surface water body thematic map (Fig. 2.10f) was generated from standard FCC. Although there is no yardstick as to what extent the surface water bodies can recharge in the immediate vicinity, we had chosen two buffer zones with radii 25 and 75 m and ranked them as 6 and 3, respectively, in our present analysis. Using the above thematic maps, the GIS integration was performed.

2.9.1.4 Integration and Modelling

The rank of each thematic map was scaled by the weight of that theme. All the thematic maps were then registered with one another through ground control points and integrated step by step using the normalized aggregation method in GIS for

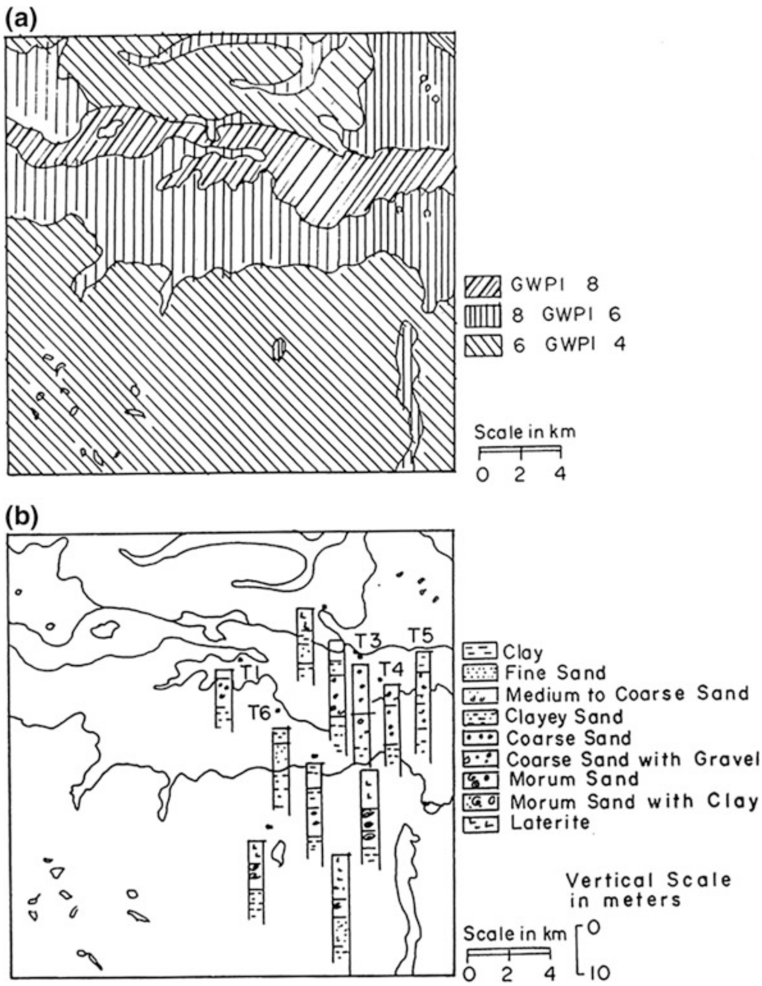

Fig. 2.11 **a** Thematic map of GWPI model depicting groundwater potential, and **b** locations of boreholes and pumping wells in the study area with available lithosection

computing GWPI of each feature. The evolved thematic map of groundwater potential of the area is displayed in Fig. 2.11a.

2.9.1.5 Field Verification

The accuracy of the estimates from the GIS model was determined with the existing borehole and pumping test data. The locations of boreholes along with the litho-section and pumping test sites (T1-T6) are shown on the GWPI map given in Fig. 2.11b. Lithology sections obtained from the boreholes clearly show that approximately 10-m-thick shallow aquifer of coarse sand is present in the area where GWPI is greater than or equal to 8. Approximately 8-m-thick shallow sandy aquifer is occupying in the zone where GWPI is in between 6 and 8. A thin fine sand and morum sand layer can be detected in the zone where GWPI is less than 6.

2.9.1.6 Concluding Remarks

A model is, therefore, developed to *assess* the groundwater potential of a soft rock area by integrating seven hydrogeological themes through GIS. The field verification of this model undoubtedly establishes the efficacy of the GIS integration tool in demarcating the potential groundwater reserve in soft rock terrain. Hence, this method can be used routinely in the groundwater exploration in favourable geological conditions.

2.10 Integration of Multigeodata for Hard Rock Area: A Case Study

One of the important aims of GIS application is to integrate the information and its analysis, which will provide useful information about spatial and non-spatial data. Arcinfo is the most complete desktop GIS. It can edit and analyse the data in order to make better decisions in faster way. Arcinfo is the de facto standard for GIS. It has the functionality of ArcEditor and ArcView and adds advanced spatial analysis, extensive data manipulation and high-end cartography tools. It can create and manage personal geodatabases, multiuser geodatabases, and feature data sets. Also it can perform advanced GIS data analysis and modelling.

The multigeodata technique will provide through various spatial data of the same area in same geographic coordinate using command like “union” an integrated layer of the described area containing all useful information. “union” method in GIS is a topological overlay of two polygon coverages which preserves features that fall within the spatial extent of either input data sets, i.e. all features from both coverages are retained. The integration of different data layers involves a process called overlay. At its simplest, this could be a visual operation, but analytical operations require one or more data layers to be joined physically. The integration of multigeodata technique has been used in the Govind Sagar dam environs of Lalitpur District to have an integrated groundwater potential map. Total four themes, i.e. hydrogeomorphology, lineament, overburden thickness and slope in the area of Lalitpur District, have been integrated using “union” command. Each theme has different categories of attributes, and they have been assigned relative weightage as per their importance. The relative weightages are the assigned values in places of attributes of a theme in order to higher groundwater potential is having higher relative weightage values and less potential is having less values. The assigned relative weightages for different themes are shown in Table 2.1. To cite an example, the maximum weight assigned for the valley fill (which is more potential) is 120, whereas the lower weight of value 30 is assigned to BPP-S (which is less potential) in hydrogeomorphology theme. On the other hand, in overburden thickness layer, a maximum weight of 140 is assigned for thickness is having >25 m. and a minimum weight of 35 for thickness is having <5 m.

There have been number of polygons created in the composite map after integration and the weightage values of each polygon have been summed up. Sum of the weightages of these polygons have been reclassified into four distinct classes according to their groundwater potentiality.

2.10.1 Classification

Depending on the attributes of four GIS coverages and the general properties pertaining to the groundwater criteria, decision rule has been prepared. The probable groundwater potential zones have been classified from all the polygons in the composite coverage. Then, the polygons have been reclassified according to the weightage. Sum weightage 200–290 has been considered for "Class-4", which is "excellent" groundwater potential zone, sum weightage 140–200 has been considered for "Class-3", which is "good" groundwater potential zone, sum weightage 110–140 has been considered for "Class-2", which is "moderate" groundwater potential zone and sum weightage up to 110 has been considered for "Class-1", which is "poor" groundwater potential zone. Figure 2.12 shows that the probable groundwater potential zones constitute four classes. These classes can respond to certain specified management practices for the purposes of optimization of the available resources.

The methodology and results clearly show the usage of GIS in exploration of groundwater. The technique also envisages the usefulness of RS information in groundwater exploration. The integrated results of more number of coverages can yield more accurate information about the groundwater in that area. Also the same technique can add the proper management of land utilization.

2.10.2 Depth to Bed Rock Contour

Although some information can be obtained regarding the availability of groundwater from geoelectric depth slicing up to a certain depth, the topography of hard rock below 15 m depth is not obtainable and, hence, there is a need for depth contour map. It can give at a glance the variation of resistant substratum with depth in addition to the thickness of weathered and fractured/jointed rock at the subsurface.

In general, the study area shows that depth of overburden increases from north to south. The thickness of the overburden (Fig. 2.13) varies in between 5 and 25 m in

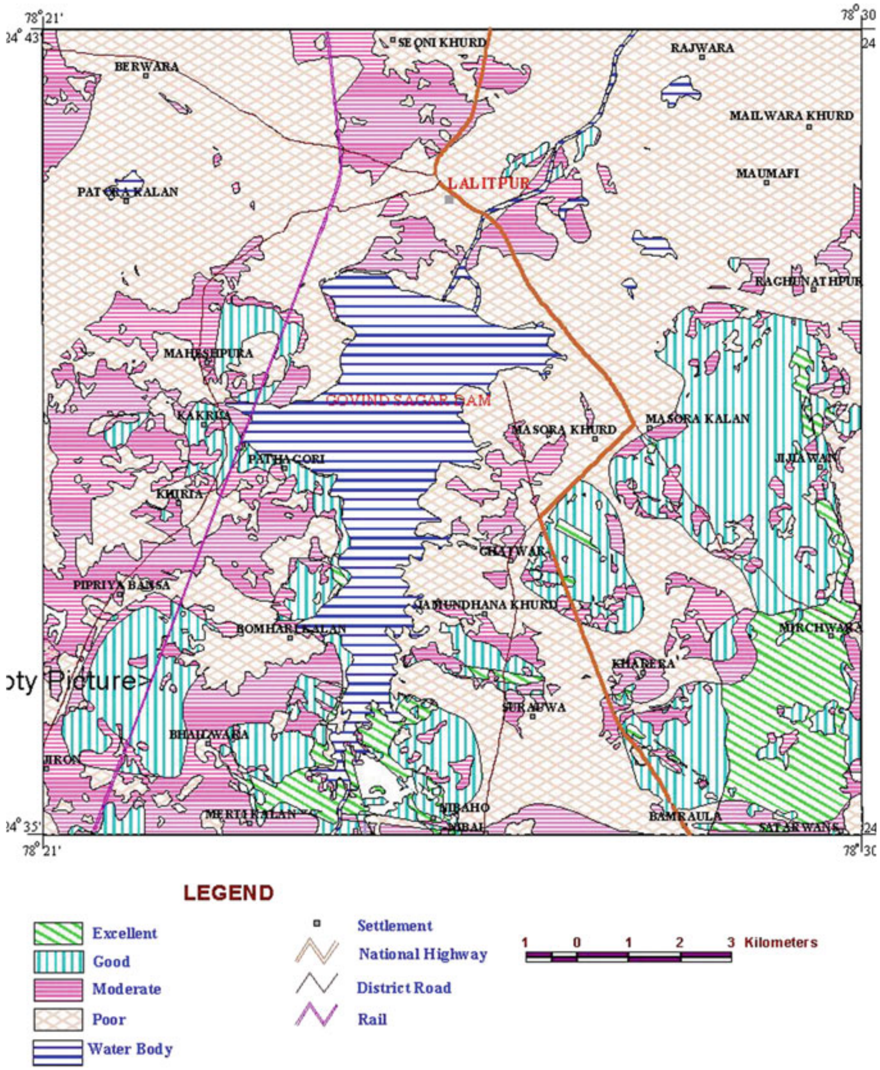

Fig. 2.12 Integrated map showing groundwater potential zones Govind Sagar dam environs, District Lalitpur

the study area except the SE part, where the overburden exists up to 40 m. This part of the area is having moderate to good thickness of aquifer, which is the only indicative of the presence of exploitable groundwater through tube well in the area. Further, it is evident also from the boreholes drilled on the basis of geophysical recommendations. The reported well discharges in this part vary from 30 lpm (litre/minute) to 600 lpm.

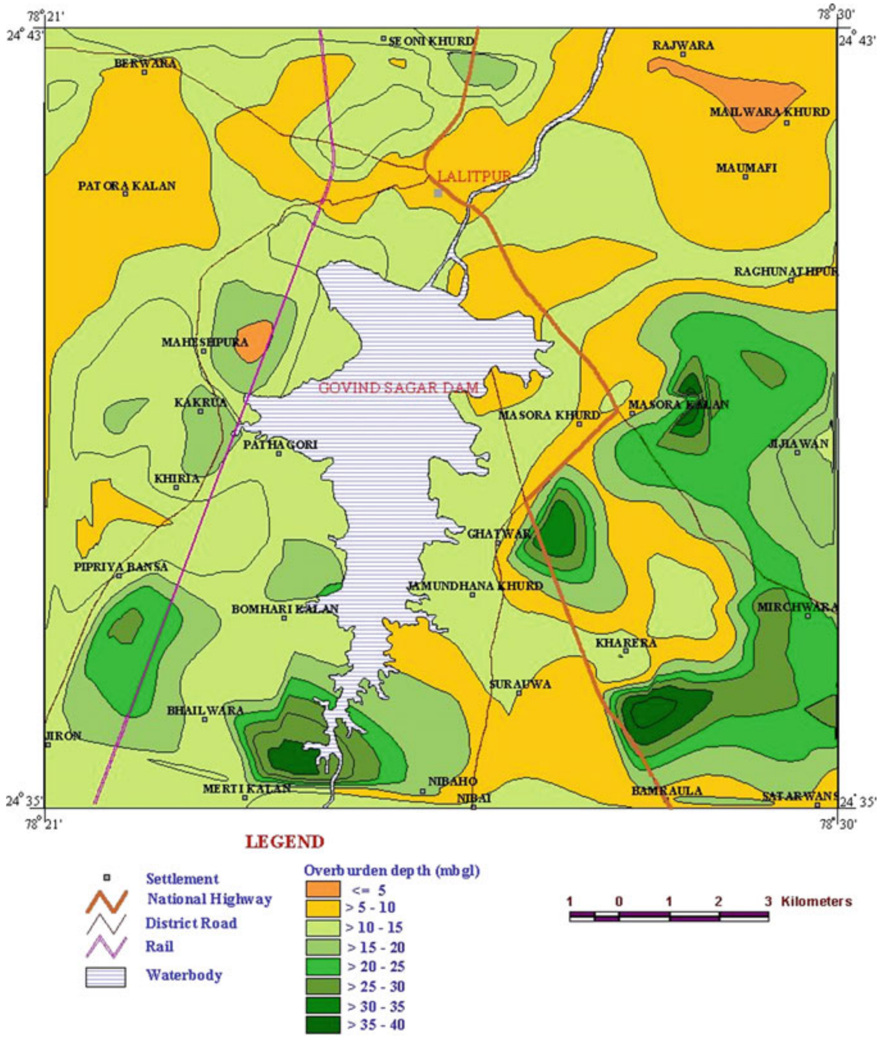

Fig. 2.13 Depth to basement contour map of Goving Sagar dam environs District Lalitpur

2.10.3 Dar Zarrouk Parameters

The product of the two parameters, longitudinal unit conductance (*S*), the ratio of thickness and resistivity (unit is mho), and transverse unit resistance (*T*) (unit is ohm-m^2), are termed as Dar Zarrouk parameters. Sum of such parameters for a sequence of layers within a particular depth or total depth column of overburden gives a qualitative picture of the area regarding groundwater potentiality within that depth column. It is an established fact that a combination of high *T* and low *S* shows potential aquifer in hard rock area, where the general quality of groundwater is more or less uniform (Mallet 1947; Chandra and Athavale 1977). Variation of S reflects the basement topography if the overburden resistivity is not varying rapidly. In order to identify the potential aquifer at the Govind Sagar dam environs, the contours for *T* and *S* were drawn from geoelectrical data with the help of Arcinfo Tin GIS. From the careful examination of the *T* and *S* contour maps (Figs. 2.14 and 2.15), it has been observed that the area enclosed by *T* contours >400 and <2000 Ωm^2 and the same area enclosed by *S* contours >0.20 and <1.3 mho hold

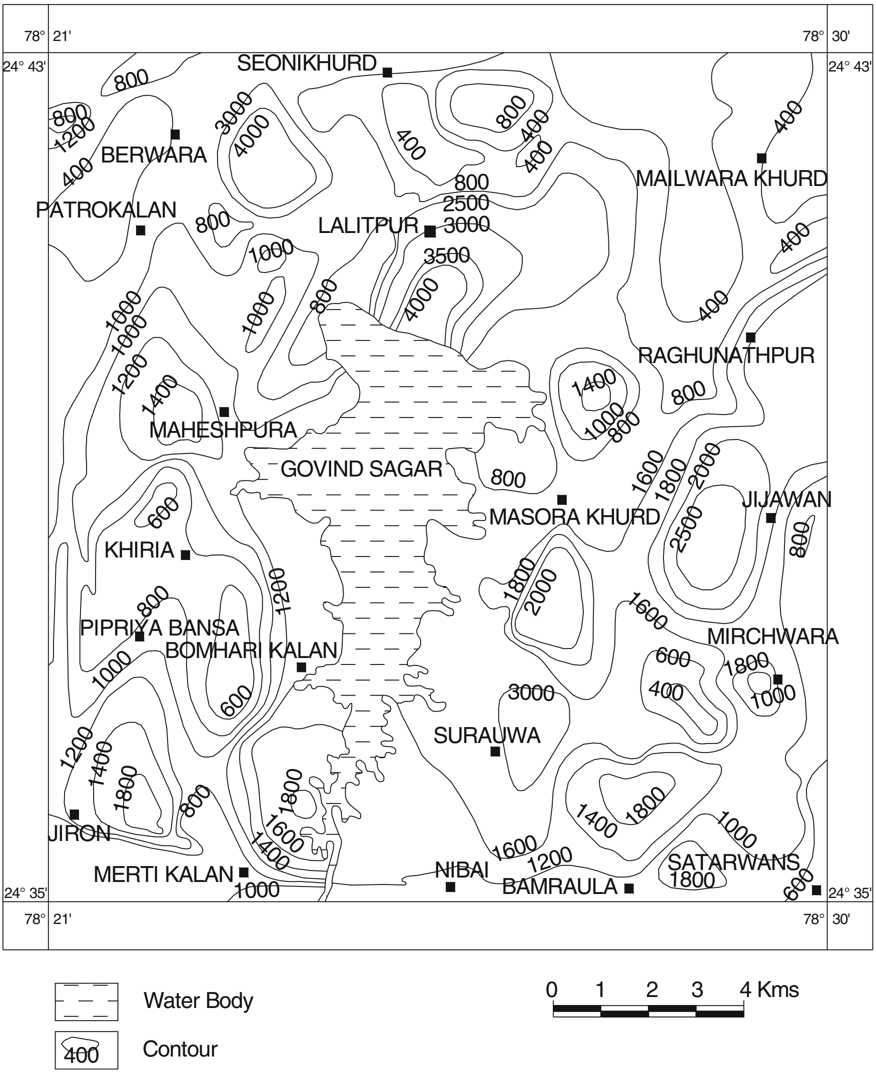

Fig. 2.14 Transverse resistance contour map

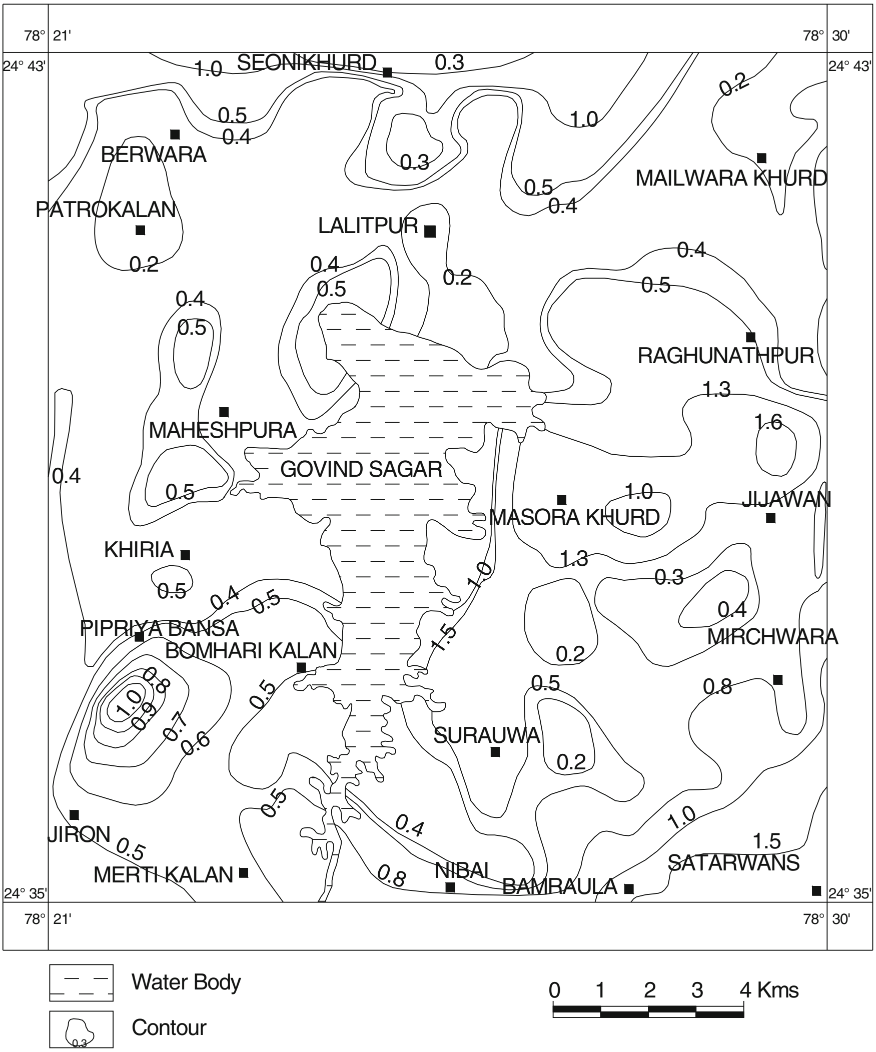

Fig. 2.15 Longitudinal conductance contour map

potential groundwater-bearing zones. It is demonstrated from the above contour values at the Govind Sagar dam environs that (i) SW part, i.e. near village Pipriya Bansa, (ii) near village Bhailwara and Merthi kalan, (iii) SE part, i.e. near village Mirchwara, Satarwans and Bamraula, are the favourable areas for groundwater exploitation.

2.10.4 Vadose Zone Contour

Vadose zone characteristics give the idea of rock formation within the zone of aeration. From the water table contour map (preferably premonsoon), the thickness of overburden above the zone of saturation can be determined and, hence, the transverse resistance of vadose zone (T_V) can be calculated. This particular parameter (T_V) can give the quantitative and qualitative picture of the area regarding relative groundwater recharge. Keeping in view as a part of research study, the areas which are related to recharge in Govind Sagar dam environs are

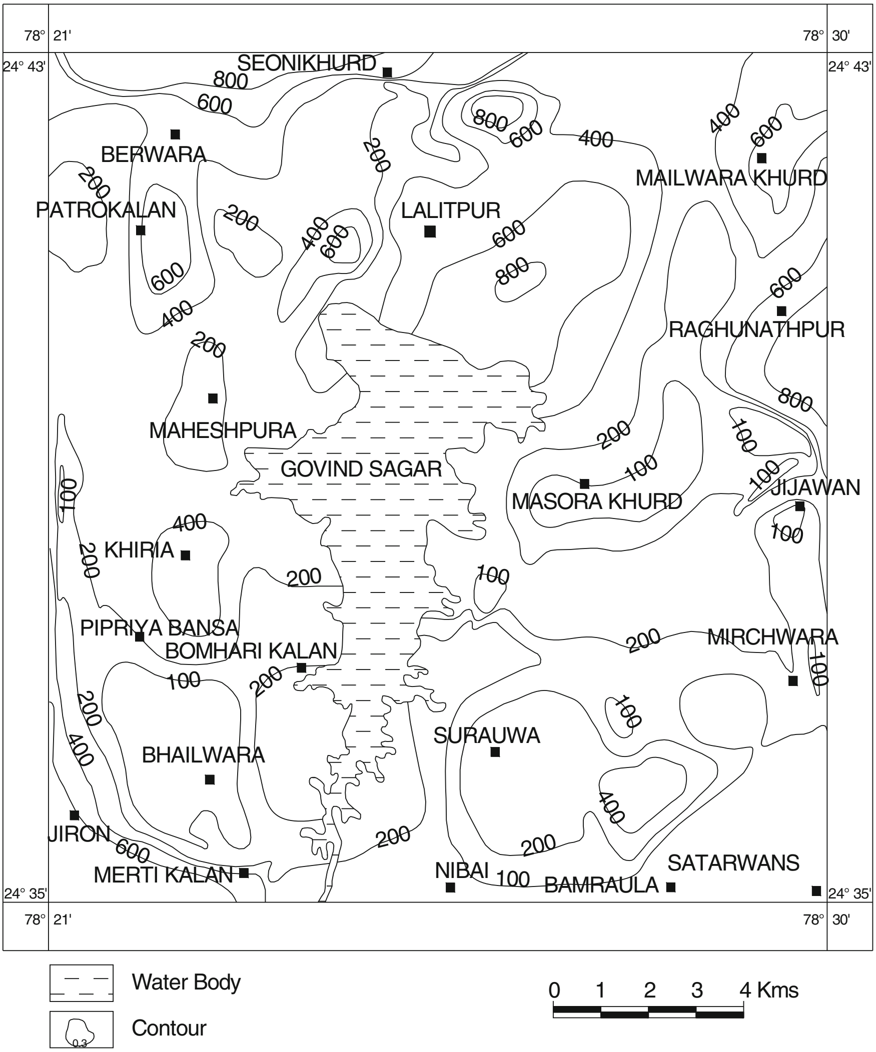

Fig. 2.16 Transverse resistance contour map of vadose zone

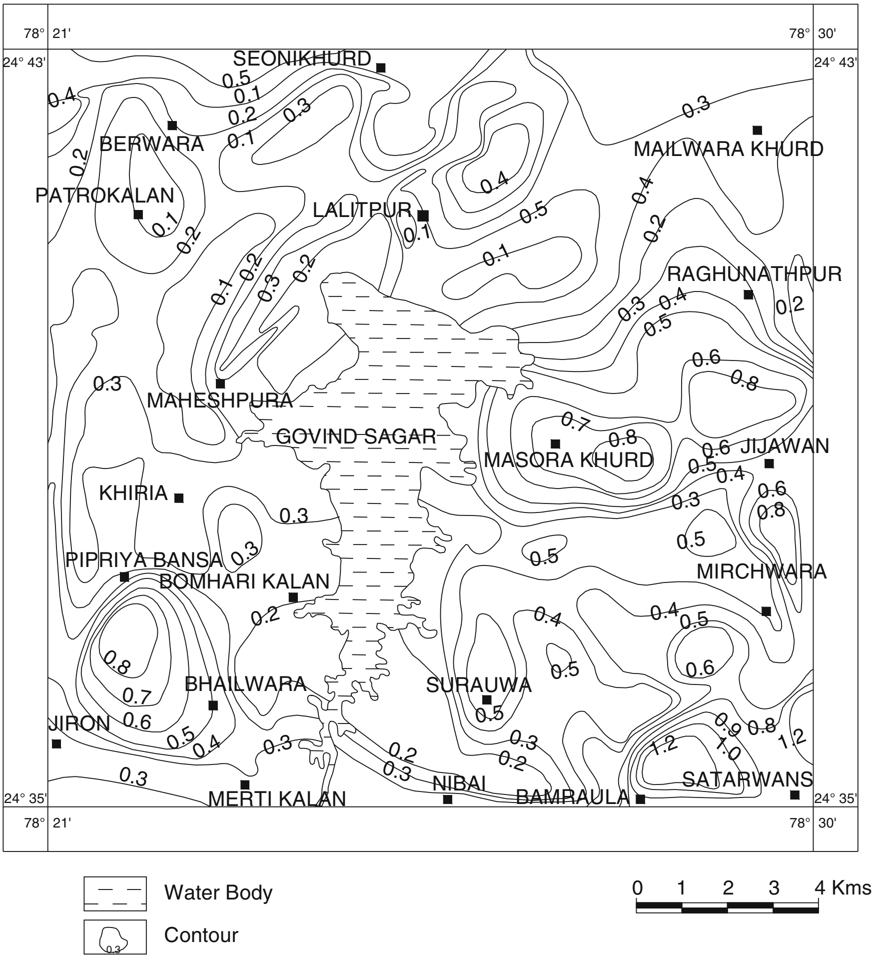

Fig. 2.17 Longitudinal conductance contour map of vadose zone

required to be known. The same can be achieved through T_V and S_V contour. The same parameters are derived from the water level and resistivity data. Later, T_V and S_V values were contoured in Arcinfo GIS. The proper examination of both the contour maps (Figs. 2.16 and Fig. 2.17) along with water-level variation reveals that area enclosed by S_V contour between 0.1 and 0.4 mho and the same area enclosed by T_V contour between 200 and 500 Ωm^2 are identified as recharge area for groundwater. The same area can be suitable to also for artificial recharge. The identified areas which could be considered for natural/artificial recharge are as follows:

(i) Western side of village Merthi kalan,
(ii) Between village Bomharikalan and Bhailwara,

(iii) Between village Mirchwara to Ghatwar,
(iv) SE part of village Bamraula,
(v) Western and SW part of village Patora kalan and
(vi) Western part of Mailwara khurd.

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Chapter 3
Groundwater Geology and Geological Prospecting

Abstract To explore groundwater in area, the groundwater geology must be well understood by the process of remote sensing, geological mapping, and hydrogeological investigation, and finally, geophysical method is used to delineate subsurface aquifer dispositions horizontally and vertically in a particular geological structure and to assess aquifer property, water quality, etc. Hydrogeological cycle is the process of precipitation, run-off, groundwater flow, evaporation and transpiration. Thus, groundwater is a part of the cycle in the upper lithosphere. It is observed from different studies that sedimentary rocks are most prospective from groundwater point of view compared to igneous and metamorphic formation. Limestone cavities serve as reservoirs for water storage. This is carbonate aquifers. Basaltic lava flows have sometimes been found to be serving as good aquifer. The types of aquifers (confined and unconfined), water table, aquitard, aquiclude, aquifuge, etc., should be well understood for groundwater geology. To determine the aquifer parameters, pumping test should be carried out and storage coefficient and transmissivity are calculated from time–drawdown curve. Hence, it is understood that from geological background, geophysical investigation is done, and on the basis of idea of aquifers, drilling is done. After drilling with the help of geophysical logging, the actual depths of aquifers are known and strainers are fitted. Finally after pump tests, the aquifer characteristics are known and thereby water wells are prepared.

Keywords Geological map · Hydrogeological investigation · Hydrogeological cycle · Aquiclude · Aquifuge · Aquitard · Precipitation · Run-off · Lithosphere · Confined · Aquifer · Limestone cavity · Water table · Water well

3.1 Introduction

Groundwater geology must be understood well before geological prospecting methods can be used scientifically in the exploitation of groundwater. Several textbooks are available (Todd 1995; Karanth 1995; Domenico and Schwartz 1990,

H.P. Patra et al., *Groundwater Prospecting and Management*,
Springer Hydrogeology, DOI 10.1007/978-981-10-1148-1_3

for example) giving geological and hydrogeological processes, in detail. Prospecting for groundwater should sequentially consist of the following steps:

(i) Remote sensing (Chap. 2) comprising use of satellite images for hydrogeomorphic mapping of the terrain, lineament mapping and shallow groundwater potential zone mapping;
(ii) Geological methods for lithological and structural mapping and for fracture trace analysis;
(iii) Hydrogeological investigations are used for lithological classification with respect to hydrologic properties, hydraulic continuity in relation to geologic structures and location of springs;
(iv) Surface geophysical methods (Chap. 4) are used to delineate the subsurface distribution of formations. Subsurface well-logging techniques (Chap. 5) are used for detecting aquifer thickness, aquifer property and water quality.

The purpose of this chapter was not to detail the above methods but to outline the terms relevant to groundwater prospecting point of view. Readers are advised to consult the text books mentioned earlier and many other available books on the subject, if necessary.

3.2 Hydrologic Cycle

The circulation of water from the ocean to the atmosphere, the atmosphere to the lithosphere and the lithosphere to the oceans, through complex and independent processes including precipitation, run-off (surface + subsurface, i.e. percolation), groundwater flow, evaporation and transpiration, is called the hydrologic cycle (Told 1995).

Thus, groundwater is a part of the cycle in the upper lithosphere. Another well-known cycle called basin hydrologic cycle refers to the flow of groundwater in a basin. Domenico and Schwartz (1990) have devoted a full chapter on "groundwater, in the basin hydrologic cycle".

3.3 Groundwater in Different Types of Rocks

3.3.1 Sedimentary Rocks

Sedimentary areas are observed to be most prospective from groundwater point of view compared to igneous and metamorphic formations. A study of aerial photographs and satellite imageries along with topographic maps gives the pattern of run-off in the area. Geological and hydrogeological mapping together with lithological data from experimental and existing borehole gives rise to information regarding underground formations and leads to the aquifer zones and their variations. Normally, sedimentary aquifers yield a large amount of water through a perennial recharge.

3.3.2 Igneous and Metamorphic Rocks

These rocks are relatively less permeable and serve as poor aquifers. The base of the top weathered portion retains some water at the zone of saturation. However, in such hard rocks, water may be stored in the fractured and shear zones. Special maps are prepared from satellite imagery and ground truths, showing location of the faults, dykes, veins and shear zone contacts. Such features lead to the probable sites for the accumulation of groundwater for domestic purposes in sufficient quantity.

3.3.3 Carbonate Rocks

Carbonate aquifers are mainly of limestone, which varies widely in density and porosity depending on its history of deposition and consolidation. The secondary porosity becomes significant due to the formation of solution cavities. These cavities serve as the voids for water storage.

3.3.4 Volcanic Rocks

Volcanic rock can form permeable aquifers. Basaltic lava flows have sometimes been found to be serving as good aquifer (Told 1995).

3.4 Types of Aquifers

The water-bearing geologic formations or strata which yield significant quantity of water for economic extraction from wells are called aquifers.

Aquifer may be classed as unconfined or confined, depending on the presence or absence of a water table, while a leaky aquifer represents a combination of the two types (Told 1995). Besides unconfined and confined aquifers, definitions of aquiclude, aquifuge and aquitard are given by Raghunath (1987) as follows:

Aquiclude: A geologic formation which can only store water but cannot transmit significant amounts, e.g. clay lenses and shale, is called aquiclude.

Aquifuge: Aquifuge is a geologic formation with no interconnected pores and hence can neither absorb nor transmit water, e.g., basalt and granite.

Aquitard: A geologic formation of a rather impervious nature which transmits water at a slow rate compared to an aquifer but insufficient to supply individual wells, e.g., clay lenses interbedded with sand, is known as aquitard.

Confined aquifers are also known as artesian or pressure aquifers. Perched water body is a special case of unconfined aquifer separated from the main groundwater by impermeable layer, which yields temporary or small quantities of water if tapped.

3.5 Basic Equation on Determination of Aquifer Parameters

Continuous pumping test, recovery test and step-drawdown test are carried out in the pumping well with recording of drawdown in the pumping and observation wells. These data help in the field determination of aquifer parameters, namely transmissibility (transmissivity) and storage coefficient (storativity). These aquifer characteristics are used to evaluate the behaviour of groundwater levels in wells with pumpage. Theoretical solutions are available for groundwater movement under different aquifer conditions which are presented in convenient forms for practical applications in the field.

3.5.1 Steady-State Flow Conditions in an Unconfined Aquifer

An equation for steady radial flow to a well utilizes Theim's equilibrium condition where two points on the logarithmic-drawdown curve are known, as given by Told (1995 P 119, Eq. 4.23). The equation is used to compute transmissibility (T'). Such steady-state conditions are not always valid, and Theis method given below is preferred.

3.5.2 Unsteady Conditions in Confined and Unconfined Aquifers

This non-equilibrium equation describes the drawdown in a well fed by confined aquifer. Drawdown increases with time after pumping is started. The pump test data (time–drawdown curve) give the values of storage coefficient (S') and transmissivity (T'). The equations for T' and S' are given in Chap. 6 (Sect. 6.3.2).

3.5.3 Cooper–Jacob Method of Determination of T' and S'

This is a simplified version of Theis method also known as straight-line method. Cooper–Jacob straight-line method is briefly outlined in Chap. 6 (Sect. 6.3.1).

3.6 Water Wells

After a detailed investigation comprising remote sensing, vertical electrical sounding and seismic refraction surveys, the suitable points (prospective from groundwater point of view) for drilling boreholes are recommended. From deep drilling point of view, boreholes are normally sunk below a depth of 100 m, sometimes up to 250–300 m depending upon the depths to sandy horizons of sufficient thickness. As soon as the borehole is completed after logging of the borehole for exactly locating the aquifer zone and with placement of casing and filters suitably packed with gravels, the well is developed usually with compressed air.

Yield test is carried out after the well is developed. This helps in getting an idea of the quantity of expected water supply. The "static water level" (SWL) is first recorded, and then, the well is pumped at a maximum possible rate until drawdown ceases and stabilization is reached. The yield is given by the discharge for the recorded fixed drawdown. The discharge–drawdown ratio gives an estimate of the specific capacity of the well.

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Chapter 4
Geophysical Prospecting for Groundwater

Abstract Geophysical methods are based on the measurement of physical properties of subsurface lithosphere units. The gravity and magnetic methods are based on the measurement of density and susceptibility contrast, respectively. In ground water exploration, these surveys are required generally to determine bedrock depth contours in different aquifer-bearing structures such as faults, folds, veins, and dykes. Seismic method is based on the measurement of velocity contrast and used mainly to locate the overburden thickness. Within the overburden, the particular velocity range determines the groundwater-bearing zones. Electrical and electromagnetic methods are based on the measurement of electrical resistivity or conductivity of subsurface minerals and rocks. Electrical method is very popular in groundwater prospecting. Here, current and potential differences are measured between two points (probes) when the ground is energized by another two current electrodes. Here, the ratio of voltage and current multiplied by geoelectric constant provides the apparent resistivity. Interpretation with curve-matching techniques provides the true resistivities and respective thicknesses. Different range of resistivities indicate different rock types or minerals. Thus, the sand with water contents is determined. The electromagnetic method is based on the principle where primary wave is sent through the transmitter to the ground, and depending on the intensity of signals, it encounters the depth. The secondary wave generated inside the ground is received by the receiver with time. From these secondary waves, the apparent resistivities are calculated. Presence of groundwater then understood with resistivity range.

Keywords Geophysical method · Electrical method · Gravity method · Magnetic method · Resistivity · Seismic method · Electromagnetic method · Primary wave · Secondary wave

4.1 General Considerations

Surface and subsurface methods, briefly outlined in the next section, are based on the measurement of the physical properties of subsurface lithostratigraphic units or fluids within. Selection of suitable geophysical prospecting methods is determined

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for specific problems by the appropriate physical properties of the hydrological units or the contrast in physical properties such as electrical resistivity (or conductivity) and magnetic susceptibility. The choice is critical for the effective use of a method for particular problems. Based on the physical properties of rocks and minerals, the development of various geophysical methods has taken place; these are listed in the following section.

4.2 Geophysical Methods

Geophysical methods of prospecting available for the detection of subsurface anomaly causing bodies may be classified into two groups:

I. Surface methods
   A. Gravity and magnetic
   B. Seismic
   C. Electrical and electromagnetic
   D. Radioactive
II. Subsurface methods (well logging)

Brief description of the methods indicating generalized application is given below.

IA. (i) Gravity method

Gravity method, based on the measurement of density contrast between the anomaly causing body and the surrounding rocks, may be used for exploration of minerals, groundwater, oil and gas. In mineral exploration, gravity method is useful particularly for heavy minerals such as barite and chromite. In groundwater location, gravity survey helps in mapping key beds bearing stratigraphic or structural relation to the water-bearing bed, in delineating thick sedimentary basins where porous and permeable water-bearing beds may occur and in locating ancient river valleys buried at larger depths.

IA. (ii) Magnetic method

Magnetic method, based on the measurement of susceptibility contrast between the anomaly causing body and the rock around, is used for exploration of all magnetic minerals and minerals associated with magnetite or magnetic materials. In groundwater prospecting, magnetic method may be used for the determination of magnetic basement depth and thickness of overburden and sediments. This also helps in locating veins, faults, dykes and other structural features suitable for groundwater percolation and storage.

IB. Seismic methods

These methods are based on the measurement of seismic wave velocity contrast obtained from available time–distance curves. Seismic refraction method is normally not used for mineral exploration but may be used for locating aquifers having a velocity contrast depending on its water saturation. Shallow salt domes as possible place for occurrence of oil and gas may be detected by refraction seismic. Seismic reflection method, on the other hand, is meant for deeper investigations especially for oil- and gas-related structures. The seismic reflection is not generally used for shallow mineral and groundwater prospecting work.

IC. Electrical and electromagnetic methods

Electrical and electromagnetic methods, based on the measurement of the electrical resistivity or conductivity of the subsurface minerals and rocks, are most useful for prospecting of mineral and groundwater.

A list of some such methods are given as follows:

(i) Self-potential (SP) method
(ii) Resistivity methods
(iii) Inductive e-m method
(iv) Telluric method
(v) Magneto-telluric (MT) method
(vi) Induced polarization (IP) method
(vii) Changed body (mise-a-la-masse) method
(viii) VLF method
(ix) Ground penetrating radar (GPR) method

A brief outline of each of the above methods is given below:

(i) Surface self-potential studies measure the naturally existing potential at the ground due to shallow subsurface conductors having difference in pH concentration within the fluid at the top and the bottom. In groundwater prospecting, SP measurements can be made to study the direction of groundwater flow.
(ii) One of the most widely used methods of geoelectric prospecting is the resistivity method detailed later in Sect. 4.3. Resistivity studies may be broadly classified into resistivity sounding and profiling depending on the field procedure. Resistivity sounding where position of the electrodes are changed with respect to a fixed central point (known as sounding point) is particularly useful for locating horizontal discontinuities. In profiling, on the other hand, all the electrodes are shifted simultaneously along with the centre of the spread on a predetermined line and are used for vertical discontinuities. The well-known electrode configurations for both sounding and profiling are Schlumberger, Wenner and dipole arrangements. Electrical soundings are used for groundwater as well as oil prospecting. Electrical

profiling is useful in exploration of conducting minerals and groundwater in hard rocks.

(iii) Inductive methods of prospecting make use of alternating current, which induces eddy currents on the subsurface conductors giving rise to a secondary electromagnetic response. The underground conductors (minerals or water-saturated zones) give rise to an anomaly leading to the delineation of the target. Depending on the nature of the type of artificial sources, three important inductive methods are line source, loop and dipole methods. These electromagnetic (e-m) methods are quite useful in shallow mineral or groundwater exploration particularly when the surface rock is highly resistive and resistivity method fails to work due to a high-contact resistance.

(iv) Telluric method of prospecting makes use of the electric field due to naturally flowing earth currents caused by activities in the ionosphere to investigate depths beyond the one normally penetrated by direct current resistivity method. The natural source telluric method may, therefore, be used for mapping basement structures below thick sedimentary column indirectly helping in the location of likely groundwater-bearing zones within the sediments.

(v) Magnetotelluric (MT) method of prospecting makes use of the electromagnetic fields due to natural telluric currents within the earth and helps in the investigation of deeper subsurface structures of the order of a few kilometers or more. MT method is, however, not used in groundwater prospecting.

(vi) Induced polarization (IP) method is based on over-voltage effects. IP method measures the decay voltage (in time domain or frequency domain) produced due to polarization of the electrode interfaces at the subsurface after the current flow being stopped. IP measurements can be made to differentiate between clays and sands on the basis of their chargeabilities.

(vii) Charged body (mise-a-la-masse) method is used to find the extent of an ore body and the direction of groundwater flow and fractures in hard rocks.

(viii) Very low frequency (VLF) e-m method makes use of the field due to electromagnetic waves transmitted (5–50 kHz) from existing radio broadcasting stations used for navigational purposes. The depth of investigation is limited and only shallow subsurface conductors and conducting water-saturated zones may be detected.

(ix) Ground penetrating radar (GPR) method uses very high-frequency e-m energy in the range of 50–1000 MHz generated by artificial sources. The method is applicable in shallow groundwater investigation and in archaeological and engineering geological studies particularly within highly resistive rocks.

ID. Radioactive methods

Radioactive methods of prospecting are based on the measurement of the spontaneously disintegrated alpha, beta and gamma rays by various radioactive materials and detection of sources of such disintegration by means of field version of the instruments, namely G-M and Scintillation counters.

Radioactive methods may help in locating tectonic zones as probable groundwater source within hard rocks and detailing of aquifer within borehole. Radon emission technique is also used to detect such weaker zones.

II*. *Subsurface well-logging methods

Any characteristic information regarding the formation met within a well and record in terms of depth is known as "well log". Such logs help in evaluating porosity, permeability, water saturation and hydrocarbon saturation of the formation and are useful in the development stage for groundwater, oil and gas. In mineral exploration, well-logging methods are used either for detailing ore deposits or for locating ore deposits missed narrowly by drilling. A detailed account of well-logging tools relevant for groundwater wells is given in Chap. 5. Different important logs used in subsurface geophysical exploration are enlisted here.

(i) Self-potential (SP) log
(ii) Resistivity logs: (a) conventional, (b) induction and (c) microlog
(iii) Laterolog and microlaterolog
(iv) Radiation logs: (a) natural gamma, (b) neutron and (c) density
(v) Sonic log
(vi) Calliper and microcaliper logs
(vii) Temperature log

SP log gives a record of the naturally occurring potential with depth and is utilized for distinguishing "porous and permeable" beds (sands) against shale and clay.

Conventional logs comprising mainly short normal, long normal, short lateral and long lateral are used to compute true resistivity of the formation. Induction log gives the value of the true resistivity of the formation in case of empty holes or holes with highly resistive mud. Microlog gives the resistivity of the flushed zone leading to porosity determination. Laterolog and microlaterolog with the focusing arrangement help to find formation resistivity when saline mud is used for drilling, particularly in oil exploration.

Gamma ray log measures the natural radioactivity of the formation and is used to identify shales and clays against sand particularly when SP log fails to do so. Neutron log records the response due to neutron-capture gamma rays which depends on the hydrogen content of the formation. Gamma-gamma ray or density log measures the intensity of scattered gamma rays which is dependent on the density of the formation.

Sonic log records the time required for a sound wave to travel through unit length of the formation from which the sonic velocity is noted and porosity is calculated.

Caliper and microcaliper logs measure the effective diameter of the borehole, giving the indication of casing, if any. Temperature log records the variation of temperature with depth which helps in the interpretation of log data.

Out of the several surface and subsurface geophysical prospecting techniques noted earlier, the following methods or combinations thereof are found to be most suitable from groundwater exploration and development point of view.

(1) Surface geophysical methods:
   (i) Electrical resistivity method
   (ii) Seismic refraction method
(2) Subsurface geophysical methods
   (i) SP logging
   (ii) Point resistance logging
   (iii) Conventional resistivity logging (normal and lateral)
   (iv) Natural gamma ray method and radioactive tracer techniques
   (v) Calliper logging (drilling time log is used as a substitute)
   (vi) Temperature logging (temperature with depth gradient is used as substitute when temperature logs are not recorded)

The choice of geophysical methods in soft and hard rock areas is given in Sect. 4.2.1. While surface geophysical methods suitable for groundwater survey are detailed later in this chapter, the subsurface methods are outlined in the next chapter (Chap. 5).

4.2.1 *Choice of Geophysical Methods*

The problem of the use of geophysical methods in the assessment of groundwater may be classified into two categories:

(1) Soft rock area problem
(2) Hard rock area problem

4.2.1.1 Soft Rock Areas

The application of geophysical methods in soft rock areas for groundwater is well established. The cheapest and the best approach is vertical electrical sounding with resistivity profiling, if necessary. Normally, Schlumberger resistivity sounding is carried out, as a routine matter (Patra and Nath 1999) after probable water-saturated zones are roughly located through remote sensing data.

A step-wise detailing in soft rock areas will be as follows:

(i) Schlumberger vertical electrical sounding and seismic refraction studies at prospective sites.
(ii) Recommendation of the borehole points.
(iii) Electrical logging of the borehole after drilling for detailing of the water well.
(iv) Planned utilization of available groundwater after water-quality analysis, for a sustained yield throughout the year and over the years.

4.2.1.2 Hard Rock Areas

Fractured rock hydrogeology has been of marginal interest for groundwater so far. Of late, the hydrogeologists have discovered that the favourite sand and gravel aquifer is not really very homogeneous or isotropic at all. The aquifer tends to display differential flow pathways and macro-pore systems, showing a suspicious resemblance to a fractured rock system in many ways. Recently, the importance of hard rock for water supply has increased in the third world. In shield areas in temperate regions, hard rocks have been important for rural water supply. Over large parts of the earth surface fissured hard rocks crop out or lie, close to surface under a thin cover of weathered, alluvial or glacial deposits.

Hard rock areas comprise igneous and metamorphic rock of Precambrian shield, thrusted Precambrian rocks. In India, hard crystalline rocks cover large part of the country. With the emergence of importance of groundwater in hard rocks, its proper exploration, development and management will become a thrust area problem beyond 2000 AD. The step-wise plans given for the soft rock areas have been found to be quite suitable for hard rock areas also. However, the following geophysical methods will be ideal for groundwater assessment in such areas.

4.2.2 Surface Geophysical Methods for Fractured Aquifers

Several conventional geophysical methods such as gravity (also microgravity), magnetic, seismic and radioactive methods (Henkel 1993) may be used in hard rock area survey following remote sensing for delineating the overall targets. Detailing may be done using these conventional geophysical methods.

Considering the cheapest methods needed for the expected free supply of drinking water, electromagnetic methods may be used for locating conducting saturated zones within hard rocks. As mentioned earlier, the conventional electrical resistivity sounding and profiling are used under favourable circumstances.

The combination of electrical, electromagnetic and seismic refraction methods used for groundwater exploration in detail in the areas where mapping of faults and fractured zones have been located by means of remote sensing will be as follows:

(1) Resistivity profiling,
(2) Horizontal loop electromagnetic (HLEM) profiling at least at two frequencies,
(3) Very low-frequency (VLF) method.

HLEM method is comparatively costlier (as an artificial source is required). VLF is the cheapest electromagnetic method for groundwater survey. The electric currents measured in VLF method originate from radio waves called VLF signals. These electromagnetic waves are sent out from transmitters distributed throughout the world and used for navigational purposes. Here, a VLF receiver is needed requiring only existing sources producing primary signals. Thus, a combination of resistivity and VLF profiles will be sufficient to delineate fractured saturated zones in hard rock areas and will form the foundation for drinking water supply in the near future. Cavities filled with water in limestone countries can be easily detected by seismic refraction method. Ground penetrating radar (GPR) method is now being increasingly used for shallower engineering and archaeological problems in hard rock areas and sometimes for water-saturated zones.

4.3 Electrical Resistivity Methods

Geoelectricity is a member of a group of sciences known as the geophysical sciences. It deals with the electrical state of the earth and includes discussions on the electrical properties of rocks and minerals under different geological environments, as well as their influences upon various geophysical phenomena. Geoelectric exploration (or, more simply, electrical exploration) is a major branch of exploration geophysics. It uses the principles of geoelectricity for geological mapping of concealed structures, for the exploration and prospecting of ores, minerals and oil, and in the solution of many hydrogeological and engineering geological problems.

It was earlier believed that geoelectric methods were suitable only for shallow exploration, i.e. for mining and engineering geological problems. Today, however, modern developments and refined techniques of interpretation using high-speed computers have increased the depth of investigation to the order of 8–10 km with higher precision.

Geoelectric exploration consists of exceedingly diverse principles and techniques and utilizes both stationary and variable currents produced by either artificial process or natural processes. One of the most widely used methods of geoelectric exploration is known as the resistivity method. In this, a current (a direct or very low-frequency alternating current) is measured between two points (probes) suitably placed with respect to the current electrodes. The potential difference for unit current sent through the ground is a measure of the electrical resistance of the ground between the probes. The measured resistance is a function of the geometrical configuration of the electrodes and the electrical parameters of the ground. Broadly speaking, we can distinguish two types of resistivity measurements. In the first, known as the geoelectric profiling or mapping, the electrodes and probes are shifted without changing their relative positions. This gives us an idea of the surface variation of resistance values within a certain depth. In the second method, known as geoelectric sounding, the positions of the electrodes are changed with respect to a fixed point (known as the sounding point). In this way, the measured resistance values at the surface reflect the vertical distribution of resistivity values in a geological section.

The two types of electrode configuration, which are most frequently used in resistivity sounding, are called Wenner and Schlumberger arrays. While the Wenner configuration is used in shallow exploration programmes, the Schlumberger configuration is almost exclusively used both for shallow and deeper investigations. As far as groundwater exploration is concerned, Schlumberger electrode arrangement is invariably used throughout the world.

Resistivity profiling with a fixed depth of investigation is mainly used in locating lateral variation and thus is useful in mineral exploration. However, it may also be used in deciphering secondary porosity zones in hard rocks and buried channels in soft rock areas. Electrical resistivity sounding with a varied depth of penetration is useful in delineating extensive aquifers constituting a horizontally stratified earth.

In this chapter, an outline of the theoretical approach of vertical electrical sounding (VES) governed by Laplace's equation will be presented followed by the computation of apparent resistivity master curves. These curves will be used for the interpretation of field data followed by computer-aided estimation of layer parameters. The layer parameters are subsequently used to prepare geoelectric and lithological sections leading to the recommendation of suitable drilling points.

When a water-bearing zone is covered by highly resistive rock with a large contact resistance (igneous, metamorphic rocks and limestones, laterites, for example), direct current method fails as no current can penetrate. Here, electromagnetic method of prospecting (both natural and "artificial time-varying current") is useful along with seismic refraction. Broadly speaking, we can adopt two types of field measurements with electromagnetic prospecting as in direct current methods. In the first, known as electromagnetic (e-m) profiling or mapping, the lateral variation in conductivity is studied. The second approach, known as EM depth sounding, studies the variation of conductivity with depth. Unlike DC resistivity sounding, EM depth sounding may be carried out either by a change of frequency in primary source current or by a change of transmitter–receiver separation. However, frequency control is used more commonly than variation of source–receiver offset (Patra and Mallick 1980).

Economic aquifers in hard rock areas (15–50 m depths) usually occur in fractured zones accompanying faults. Such zones can be identified on aerial photographs and satellite imageries, but their precise location on the ground is virtually impossible by visual means. Because of small size of the aquifers, a location error of 5 m can make the difference between a productive well and dry hole. Resistivity profiling has been traditionally used to locate fractured zones. This task can be performed faster, cheaper and more accurately by very low-frequency (VLF) and EM methods. VLF is normally supplemented by artificial source horizontal loop electromagnetic (HLEM) method. Although studies demonstrate that EM surveys can provide data of quality at least equivalent to resistivity profiling at a lower cost, EM has a limited use because of a need of higher initial investment. Under the circumstances, seismic refraction prospecting is preferred.

Before we deal with the current flow in a homogeneous medium, it is essential to enlist the factors controlling the electrical properties of rocks. Current conduction in a rock may be electrolytic and electronic types. The resistivity of rocks and minerals varies between 10^{-6} and 10^{+14} Ω m (a range of 10^{20}). While electronic conductivity is mainly encountered in minerals, in groundwater studies, electrolytic conductivity

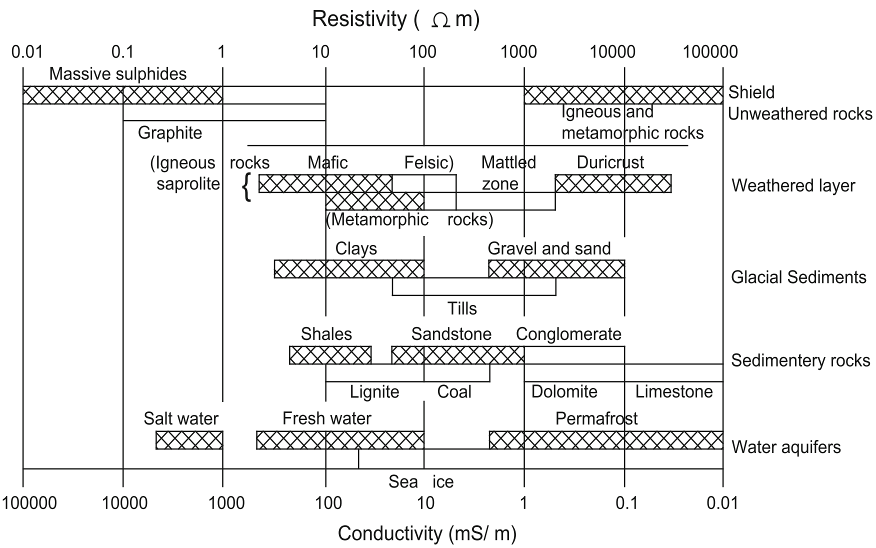


Fig. 4.1 Variation of resistivity in different rock types and water

Table 4.1 Electrical resistivity for different rock types

Rocks and sediments	Resistivities (Ω m)
Limestone	$>10^{1Z}$
Qiartz	$>10^{1U}$
Granite	$5000–10^6$
Sandstones	35–4000
Moraine	8–4000
Limestone	120–400
Clays	1–120
Basalt	$10–1.3 \times 10^7$ (dry)
Schists	$20–10^4$
Gneiss	$6.8 \times 10^4–3 \times 10^6$
Alluvium and sands	10–800
Surface water	15–100
Saline water, 3 %	0.15
Saline water, 20 %	0.05

is most important. Here, the conductivity is largely controlled by porosity, water content and water quality. For clay, however, we get both electronic and electrolytic conductivities. Clay has, therefore, a very low resistivity. Typical ranges of values of electrical resistivities are shown in Fig. 4.1 and Table 4.1.

4.4 Current Flow in a Homogeneous Earth

The flow of current in a medium is based on the “principle of conservation of charge” and is expressed by the following relation.

$$\mathrm{div}\bar{J} = -\frac{\partial \rho'}{\partial t} \tag{4.1}$$

where J is the current density (A/m^2) and ρ' is the charge density (C/m^3). This relation (4.1) is also known as the “equation of continuity”. For stationary current, Eq. (4.1) reduces to:

$$\mathrm{div}\,\bar{J} = 0 \tag{4.2}$$

If ρ is the resistivity (Ω m) of the medium, then the current density J is related to the electric field intensity E (V/m) by means of Ohm’s law, which is given as:

$$\bar{J} = \frac{I}{\rho}\bar{E} = -\frac{I}{\rho}\mathrm{grad}V \tag{4.3}$$

where V is the electric potential (volts). For an isotropic medium, ρ is a scalar function of the point of observation, and J is in the same direction as E. In anisotropic medium, however, J has a directive property and, in general, is not in the direction of E. This calls for modified Ohm’s law in an anisotropic medium where conductivity forms a symmetric tensor having six components. The current flow in an anisotropic medium and other aspects are outside the scope of this book.

For an isotropic medium, we got from relations (4.2) and (4.3)

$$\mathrm{div}\left[\frac{I}{\rho}\mathrm{grad}V\right] = 0 \tag{4.4}$$

or

$$\mathrm{grad}\left(\frac{I}{\rho}\right)\cdot\mathrm{grad}V + \frac{I}{\rho}\mathrm{divgrad}V = 0 \tag{4.5}$$

This is the fundamental equation of electrical prospecting with direct current. If the medium is homogeneous, ρ is independent of the coordinate axes and hence:

$$\nabla^2 V = 0 \tag{4.6}$$

This is Laplace’s equation derived from Maxwell’s equations. Thus, the electric potential distribution for direct current flow in a homogeneous isotropic medium satisfies the Laplace’s equation.

As a prerequisite to the evaluation of potential distribution in a layered earth, we must first calculate the normal potential at the surface due to a point source of current I. We find out the potential at any point (P) in an infinite homogeneous medium of resistivity ρ. Laplace's equation (4.6) in spherical polar coordinates with symmetry with respect to θ and Ø reduces to:

$$\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\frac{\mathrm{d}V}{\mathrm{d}r}\right) = 0 \tag{4.7}$$

On integration, we get:

$$V = C_1 + \frac{C_2}{r} \tag{4.8}$$

As the potential is taken to be zero at a large distance from the source, the integration constant $C_1 = 0$. It is clear that the equipotential surfaces are spherical, and the electric field lines as well as the current lines are radial. The current density at a distance r may be written as:

$$J = -\frac{1}{\rho}\frac{\partial V}{\partial r} = \frac{1}{\rho}\ C/r^2 \tag{4.9}$$

Thus, the total current flowing out of a spherical surface of radius r is

$$4\pi r^2 J = (4\pi/\rho)\ C_2 \tag{4.10}$$

Since this is equal to I, the total current introduced at P, the constant C_2 is given by:

$$C_2 = I\rho/4\pi$$

For a semi-infinite medium, i.e. when the current is introduced into a homogeneous ground, the total current flowing out of a hemispherical surface of radius r is given by the relation, $2\pi r^2 J = (2\pi/\rho)\,C_2$, and the constant C_2 is equal to $(I\rho/2\pi)$.

Thus, the potential at any point due to a current source at the surface of a homogeneous earth is given as:

$$V = \frac{I\rho}{2\pi}\frac{1}{r} \tag{4.11}$$

In practice, the current is introduced into the ground by means of two electrodes, i.e. a source and a sink, and the potential at any point due to this "bipolar" arrangement is given as:

$$V = \frac{I\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \tag{4.12}$$

where r_1 and r_2 are the distances of the point P from the source and the sink, respectively.

4.5 Resistivity Measurement

Consider that a direct current of strength I is introduced into a homogeneous and isotropic earth by means of two point electrodes A and B (Fig. 4.2). The potential difference between the two points M and N on the surface is given by—using Eq. (4.12).

$$V = \frac{I\rho}{2\pi}\left[\left(\frac{1}{\mathrm{AM}} - \frac{1}{\mathrm{BM}}\right) - \left(\frac{1}{\mathrm{AN}} - \frac{1}{\mathrm{BN}}\right)\right] \tag{4.13}$$

where, ρ is the resistivity of the ground. Thus, the resistivity of the homogeneous earth can be determined from the measurements on the surface.

Various electrode arrangements for A, B, M, and N have been suggested for the purpose. The ones more commonly used for resistivity sounding are: (1) symmetrical arrangement and (2) dipole arrangement. In the symmetrical arrangement, the points, A, M, N, and B are taken on a straight line such that the points M and N are symmetrically placed on the centre O of the "spread" AB (Fig. 4.3). Here:

$$\Delta V = \frac{I\rho}{2\pi}\left(\frac{4}{L-\ell} - \frac{4}{L+\ell}\right) \tag{4.14}$$

which gives:

$$\rho = \frac{\pi}{4}\frac{(L^2-\ell^2)}{\ell}\frac{\Delta V}{I} \tag{4.15}$$

In the "Wenner arrangement", L is taken equal to $3l$ (is conventionally denoted by "a" in the Wenner configuration and is known as spacing or separation of the electrodes), and the resistivity is given by:

$$\rho = 2\pi a\frac{\Delta V}{I} \tag{4.16}$$

If $L \geq 5\,\ell$, we can put $(L^2 - \ell^2)$ in Eq. (4.15) equal to L^2 with an error less than 4 %. This is known as the "Schlumberger arrangement" (Fig. 4.3). In this case, the resistivity is given by:

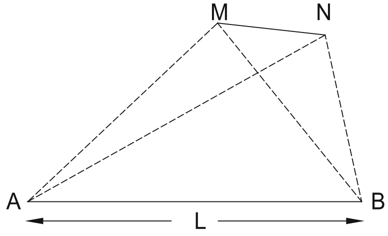


Fig. 4.2 Point electrodes over a homogenous and isotropic earth. A, B = point source and sink; M, N = observation points on the surface of the earth

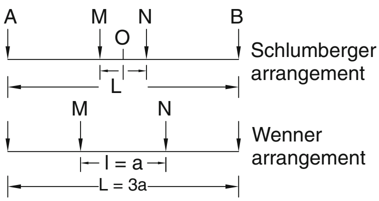


Fig. 4.3 Symmetrical electrode arrangements. *Top* Schlumberger arrangement, *bottom* Wenner arrangement

$$\rho = \frac{\pi L^2}{4}\frac{\Delta V}{\ell}\frac{1}{I} = \frac{\pi L^2}{4}\frac{E}{I} \tag{4.17}$$

where $E = \Delta V/\ell$ is (approximately) the electric intensity at the central point O. Hence, this arrangement is sometimes known as the "gradient arrangement" and Wenner's arrangement as a "potential arrangement".

The general dipole arrangement is shown in Fig. 4.4, where r is usually taken to be much larger than AB. The potential at O due to AB is given by:

$$\begin{aligned} V &= \frac{I\rho}{2\pi}\left(\frac{1}{\mathrm{AO}} - \frac{1}{\mathrm{BO}}\right) \\ &= \frac{I\rho}{2\pi r}\left[\left\{1 + (L/2r)^2 - (L/r)\cos\theta\right\}^{-1/2} - \left\{1 + (L/2r)^2 + (L/r)\cos\theta\right\}^{-1/2}\right] \end{aligned} \tag{4.18}$$

which can be expressed in a series and the potential may be written as:

$$V = \frac{I\rho L\cos\theta}{2\pi r^2}\left[1 + (L/2r)^2\frac{1}{2}\left(5\cos^2\theta - 3\right) + \text{higher order terms}\right] \tag{4.19}$$

If $r \gg L$, the expression (4.19) may approximately be written as:

$$V \approx \frac{I\rho L\cos\theta}{2\pi r^2} \tag{4.20}$$

If r is greater than $3L$, the error of neglecting the higher order terms is less than 3 %. Thus, the potential is equal to that of a dipole of moment $\frac{I\rho L}{2\pi}$. Hence, the electric field can be written as:

$$\begin{aligned} E_r &= -\frac{\partial V}{\partial r} = \frac{I\rho L\cos\theta}{\pi r^3} && \text{(radial)} \\ E_\theta &= -\frac{I}{r}\frac{\partial V}{\partial\theta} = \frac{I\rho L\sin\theta}{2\pi r^3} && \text{(azimuthal)} \\ E_x &= -\frac{\partial V}{\partial x} = \frac{I\rho L}{2\pi}\frac{3\cos^2\theta - 1}{r^3} && \text{(parallel)} \\ E_y &= -\frac{\partial V}{\partial y} = \frac{3}{2}\frac{I\rho L}{\pi}\frac{\sin\theta\cos r^2\theta}{r^3} && \text{(perpendicular)} \end{aligned} \tag{4.21}$$

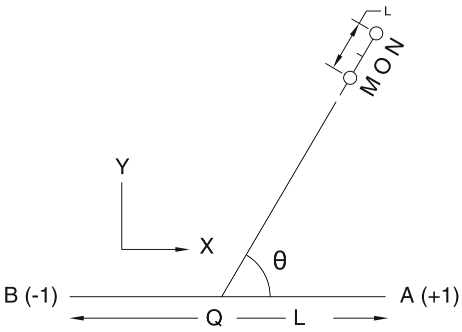


Fig. 4.4 General arrangement for dipole electrical sounding. AB = current dipole; MN = measuring dipole; Q, O = mid-points of current and measuring dipoles

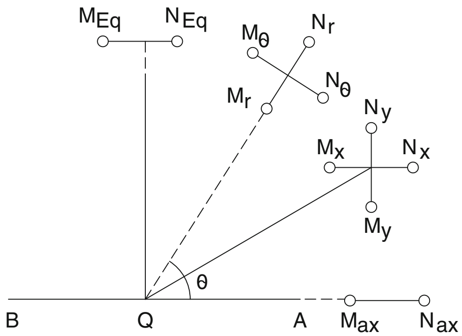


Fig. 4.5 Various arrangements for dipole sounding. M_{ax} N_{ax} = axial; M_x N_x = Parallel; M_y N_y = perpendicular; M_r N_r = radial; M_Θ N_Θ = azimuthal; M_{Eq} N_{Eq} = equatorial

The electric field can be measured by means of two electrodes, M and N, as shown in Fig. 4.5 for different orientations. If the distance ℓ is small, then we can write: $E = \frac{\Delta V}{\ell}$. Thus, from the relation 4.21, the resistivity of the ground can be determined.

When $\theta = 90°$, we gel the electric field for the "equatorial arrangement", given by:

$$E_{\text{eq}} = \frac{I\rho L}{2\pi \text{r}^3} \tag{4.22}$$

and when $\theta = 0°$, we get the electric field for the "axial arrangement", given by:

$$E_{\text{ax}} = \frac{I\rho L}{\pi r^3} \tag{4.23}$$

Of the various dipole arrangements, the last two, i.e. the equatorial and the axial arrangements, are commonly used for dipole sounding.

The dipole method is now used extensively for deep electrical soundings (i.e. for depths more than 1 km).

4.5.1 Resistivity and Apparent Resistivity

Resistivity of a material is the resistance offered between the opposite faces of a unit cube. Using the formulas given so far, we can find out the resistivity of a semi-infinite homogeneous earth by means of any of the electrode arrangements discussed earlier. For an inhomogeneous medium, we define a quantity $\bar{\rho}$ known as the apparent resistivity. The apparent resistivity of a geologic formation is equal to the true resistivity of a fictitious homogeneous and isotropic medium in which, for a given electrode arrangement and current strength I, the measured potential difference ΔV is equal to that for the given inhomogeneous medium. The apparent resistivity depends upon the geometry and resistivities of the elements constituting the given geologic medium. Thus, $\bar{\rho} = \overline{K}(\Delta V/I)$, where $\overline{K}$ is the geometrical coefficient having the dimension of length (m). For the different arrangements discussed in the section on current (low in a homogeneous earth), the values of $\overline{K}$ will be as given below:

(1) Symmetrical:

$$\begin{aligned} &\overline{K}_{\mathrm{w}} = 6.28a && \text{(Wenner)} \\ &\overline{K}_{\mathrm{s}} = 0.785\frac{(L+\ell)(L-\ell)}{\ell} && \text{(Schlumberger)} \end{aligned} \tag{4.24}$$

(2) Dipole:

$$\left.\begin{array}{ll} \text{Radial:} & \overline{K}_r = \frac{\pi r^3}{L\ell \cos\theta} \\ \text{Azimuthal:} & \overline{K}_\theta = \frac{2\pi r^3}{L\ell \sin\theta} \\ \text{Parallel:} & \overline{K}_x = \frac{2\pi r^3}{L\ell}\frac{1}{3\cos^2\theta - 1} \\ \text{Perpendicular:} & \overline{K}_y = \frac{2\pi r^3}{3L\ell}\frac{1}{\sin\theta\cos\theta} \\ \text{Equatorial:} & \overline{K}_{\mathrm{eq}} = \frac{2\pi r^3}{L\ell} \\ \text{Axial:} & \overline{K}_{\mathrm{ax}} = \frac{\pi r^3}{L\ell} \end{array}\right\} \qquad 4.25$$

4.5.2 Anisotropy in Rocks

The anisotropy in a geological body may be due to several reasons. It is a well-known fact that in stratified rocks the strike offers a particularly favourable path for the flow of electric currents. The reason may be that a large number of mineral crystals possess a flat or elongated shape (mica, kaolin, etc.). At the time of their deposition, they naturally take an orientation parallel to the sedimentation. The weathered surface soil, owing to vegetable matter, growth and decay of minerals in the soil, etc., also manifests an anisotropic character. In electrical exploration, the usual practice is to characterize the electrical property of a stratified rock by two parameters, namely the longitudinal resistivity ρ_s (parallel to the plane of stratification) and the transverse resistivity ρ_t (normal to the stratification). Thus, any anisotropy in the plane of stratification is usually neglected, being very small in most practical cases.

The anisotropy characterizes finely stratified rocks, which appear homogeneous to the eye, and, in fact, in numerous cases this corresponds to a real homogeneity in composition. This type of anisotropy is microscopic and may be called "microanisotropy". In electrical prospecting, it is necessary to consider a second kind of anisotropy, which may be called "macro-anisotropy". In practice, it is sometimes difficult to draw the boundary between the micro- and the macro-anisotropy.

We may call a medium macro-anisotropic so long as the layers can be distinguished—for example, by electrical logging in a borehole. The concept of macro-anisotropy will be explained in brief in the next few paragraphs.

Macro-anisotropy results from the repetitive alternation of two different isotropic lithologic facies. When the individual layers become infinitely thin and infinitely repetitive, we obviously reach the domain of microanisotropy. The study of this parameter is of primary importance to the geophysicist, because the distribution of the electric field, due to two current electrodes at the surface of the ground, will be governed by the resistivity and thickness of the underlying layers in addition to the distance between the current electrodes. This effective resistivity and effective thickness are controlled by anisotropy.

In electrical prospecting, the two parameters of importance are resistivity parallel to stratification (ρ_s) and resistivity normal to stratification (ρ_t); the physical significance of these has already been explained. Consequently, it is found that by adopting the concept of (ρ_s) and (ρ_t) for a group of layers, we are concerned with an anisotropy phenomenon, and the layers may be considered to behave as a single anisotropic layer of pseudo- or equivalent anisotropy λ. This anisotropic fictitious layer may be taken to be equivalent to another, single isotropic layer of pseudo-resistivity ρ_e and pseudo-thickness h_e. This forms the basis of the analytic-graphical auxiliary point method (Ebert chart method) of interpretation, which will be dealt with in detail later in this chapter.

Anisotropy plays an important role in the interpretation of layer parameters as an error is introduced in ignoring it. Surface measurements do not differentiate an isotropic bed of thickness h and resistivity ρ from anisotropic bed of thickness h/λ and resistivity ρ_m. λ being always greater than unity, this means that depth derived from isotropic concept is more than the true depth when there exists an anisotropy but is neglected. Geological control and well-logging data help in correct interpretation of such cases.

4.6 Current Flow in a Horizontally Stratified Earth

In electrical prospecting, it is often necessary to determine the depth and the electrical resistivity of horizontal or nearly horizontal layers. In order to solve this problem, we should calculate the potential and the electric field, due to a point source of current, at any point on the surface of a stratified earth.

Let us choose a cylindrical system of coordinates, with the origin at the point source A, and the Z-axis vertically downward normal to the surface (Fig. 4.6). Let ρ_1, ρ_2,..., ρ_n be the resistivities, and h_1, h_2, ..., h_n be the thicknesses of n layers from the top. Also let H_1, H_2, ..., H_n denote the depth of the bottom of each layer. We shall assume that the lowermost layer extends to infinity, i.e. $h_n = \infty$, $H_n = \infty$.

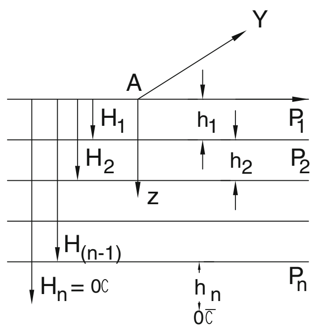
Under the conditions stated above (Fig. 4.6), the solution for potential expressions over a layered earth model has been given in Bhattacharya and Patra (1968), Koefoed (1979) and Patra and Nath (1999) in detail leading to apparent resistivity relations over a multilayer earth. These relations are used to compute master curves theoretically with the help of computers.

The complications in computation increase with the increase in number of layers. With the use of computers, it has been possible to plot sets of theoretical master curves to be used for interpretation and such sets of two-, three- and four-layer master curves are available in the published form (Mooney and Wetzel 1956; Compagnie Generate de Geophysique 1963; Orellana and Mooney 1966).

It may be mentioned here that various simplified approaches to the computation of theoretical curves have been suggested from time to time. Flathe (1955) introduced his method of calculating sounding curves with an ordinary desk calculator, but this is suitable only for cases approximated by perfectly conducting and perfectly insulating substratum. Van Dam (1965) has introduced a simple method for the calculation of sufficiently exact sounding curves with hand calculators.

A procedure to compute apparent resistivity curves for layered earth structure for the Schlumberger, Wenner and dipole configurations has been given by Mooney et al. (1966), where use is made of large digital computers. In this method, the formulation is relatively simple, and a single programme can handle any number of layers; in addition, a single set of stored coefficients can be used repeatedly by

Fig. 4.6 A multilayer earth



different electrode spacing and for different electrode arrangements. The technique is claimed to be relatively simpler and more accurate compared to those described by the Compagnie Generale de Geophysique (1955, 1963) and Flathe (1955). However, the method suggested by Van Dam (1967) is somewhat similar to the one described by Mooney et al. (1966) and this method is meant for use with digital calculators.

Existing methods (CGG 1963; Flathe 1955; Mooney et al. 1966) based on evaluation of Kernel function require that layer thicknesses be multiples of some common thickness for a rapid convergence of the series to be computed. Calculation of apparent resistivity curves with known layer parameters using inverse filter coefficients (Ghosh 1971b), on the other hand, is without such restriction and is straightforward. Patra and Nath (1999) dealt with the forward problem of computation of apparent resistivity using inverse filter coefficients', universally applicable and are available in Appendix 4.1 of the book by Patra and Nath (1999) and Appendix 2.1 in Nath et al. (2000).

4.7 Schlumberger Apparent Resistivity-Type Curves

4.7.1 Two-Layer Curves

Two sets of theoretical two-layer master curves are available for (ρ_2/ρ_1) greater than unity, ascending type (Set I) and for (ρ_2/ρ_1) less than unity descending type (Set II).

The values of ρ_2/ρ_1 for which curves have been plotted are as follows:

$$\text{Set I}: \ \rho_2/\rho_1 = 11/9,\ 3/2,\ 13/7,\ 2,\ 7/3,\ 3,\ 4,\ 5,\ 17/3,\ 7,\ 9,\ 19,\ 39,\ 99,\ \infty$$
$$\text{Set II}: \ \rho_2/\rho_1 = 9/11, 2/3,\ 7/13, 1/2, 3/7, 1/3,\ 1/4,\ 1/5, 3/17,\ 1/7,\ 1/9,\ 1/19,\ 1/39,\ 1/99, 0.$$

These sets of two-layer theoretical master curves have been reproduced in Fig. 4.9 plotted on a double-logarithm graph sheet with a modulus of 62.5 mm (Bhattacharya and Patra 1968; Patra and Nath 1999) and can be used for construction and interpretation of multilayer curves.

4.7.2 Three-Layer Curves

The whole set of three-layer sounding curves can be divided into four groups, depending on the relative values of ρ_2, ρ_1 and ρ_3:

(1) Minimum type: when $\rho_1 > \rho_2 < \rho_3$. This is also referred to as H-type (associated with the name of Hummel) and bowl type.

(2) Double ascending type: when $\rho_1 < \rho_2 < \rho_3$. This is also known as A-type (corresponding to the term anisotropy).
(3) Maximum type: when $\rho_1 < \rho_2 > \rho_3$. This is known as K-type or is sometimes referred to as DA-type (meaning displaced or modified anisotropy) and bell type.
(4) Double descending type: when $\rho_1 > \rho_2 > \rho_3$. This is known as Q-type and is sometimes referred to as DH-type (meaning displaced Hummel or modified Hummel).

A diagrammatical representation of all these type curves is given in Fig. 4.7 for the three-layer cases. The following theoretical three-layer master curves for Schlumberger configuration are available in the published form: (1) The Compagnie General de Geophysique (1955, 1963) contains 48 sets of curves, each set containing 10 curves giving a total of 480 separate curves available for interpretation. (2) Orellana and Mooney (1966) presented master tables and curves representing 76 three-layer sets (25 each of H- and K-type and 13 each of Q- and A-type) with a total of 912. (3) EAEG publication of standard set of three-layer curves has been an attractive addition with 2260 cases (prepared by Rijkswaterstaat 1969). The parameters of the curves are noted on the different sets of the album of curves.

4.7.3 Four-Layer Curves

From a combination of the curves of the types H, A, K and Q (Fig. 4.7), it is easily seen that there can be only eight types of four-layer curves, shown in Fig. 4.8. These may be designated as HA, HK, AA, AK; KH, KQ; and QH, QQ. Theoretically plotted master curves for four-layer cases are available as “Paletka” in Anonymous (1963). The album of four-layer theoretical master curves contains 122 sets, covering all the eight types (Fig. 4.9).

The values of the parameters are given below:

$$\rho_2/\rho_1 = 1/39,\ 1/19,\ 1/9, 3/17, 1/4, 3/7,\ 2/3,\ 3/2,\ 7/3,\ 17/3,\ 3,\ 4,\ 9\,\text{and}\,39,$$
$$\rho_3/\rho_1 = 1/39,\ 1/19,\ 1/9, 3/17, 1/4, 3/7,\ 2/3,\ 3/2,\ 7/3,\ 17/3,\ 3,\ 4, 9\,\text{and}\,39,$$
$$h_2/h_1 = 1/2,\ 1, 2, 3, 5, 24,$$
$$h_3/h_1 = 1/2, 1, 2, 3, 10, 12,\text{and}\,72.$$

The four-layer curves published by Orellana and Mooney (1966) consist of a total of 480 cases distributed in 30 sets.

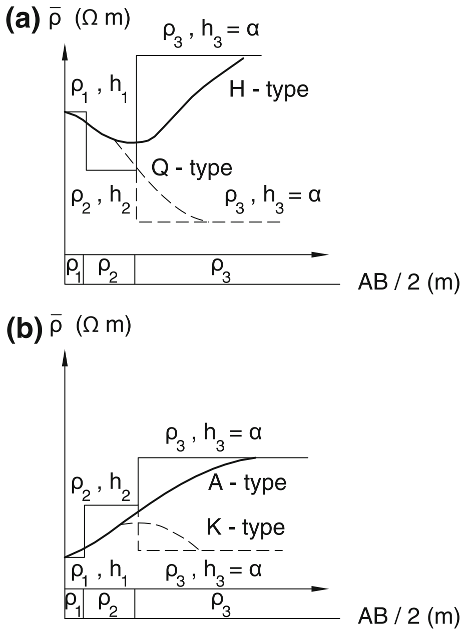


Fig. 4.7 Three-layer-type curves. **a** H-type ($\rho_1 > \rho_2 < \rho_3$) and Q-type ($\rho_1 > \rho_2 > \rho_3$). **b** A-type ($\rho_1 > \rho_2 < \rho_3$) and K-type ($\rho_1 < \rho_2 > \rho_3$)

4.7.4 Asymptotic Values of Schlumberger Curves

The apparent resistivity (ρ) for a two-layer earth may be written, for Schlumberger arrangement (Bhattacharya and Patra 1968; Eq. 2.55; Patra and Nath 1999, Eq. 2.59) as

$$\frac{\bar{\rho}}{\rho_1} = 1 + 2\sum_{n=1}^{\infty} \frac{K_{12}^n (\mathrm{AB}/2\mathrm{h}_1)^3}{\left[(\mathrm{AB}/2\mathrm{h}_1)^2 + (2\mathrm{n})^2\right]^{3/2}} \tag{4.26}$$

where

$K_{12} =$ $(\rho_2 - \rho_1)/(\rho_2 + \rho_1)$

AB = electrode separation

h_1 = thickness of the first layer

Several limiting cases, which can be derived from Eq. (4.26), are:

(a) When $\rho_2 = \rho_1$, $\bar{\rho} = \rho_1$, the apparent resistivity is equal to the true resistivity of the semi-infinite medium.

(b) When AB/2 $\rightarrow$ 0, $\bar{\rho} = \rho_1$, i.e. for a two-layer earth, the apparent resistivity is equal to the true resistivity of the first layer for small values of electrode separation.

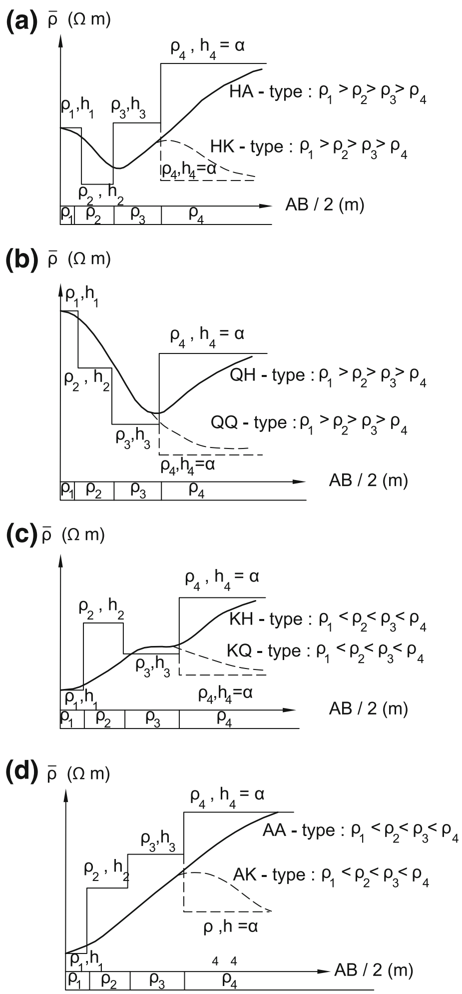


Fig. 4.8 Nature of four-layer-type curves. **a** HA- and HK-type; **b** QH- and QQ-type; **c** KH- and KQ-type; **d** AA- and AK-type

(c) When AB/2 → ∞, $\bar{\rho} = \rho_2$, i.e. the apparent resistivity is equal to the true resistivity of the second layer for large values of electrode separation.

We can write Eq. (4.26) in the form:

$$\bar{\rho} = \rho_1 f(\mathrm{AB}/2h_1) \tag{4.27}$$

assuming that K_{12}, i.e. ρ_2/ρ_1, remains constant.

If we plot, $\bar{\rho}$ against AB/2h_1 from Eq. (4.27) on an arithmetic scale, we get different curves for different values of ρ_1—even for a fixed value of h_1—and similarly for each value of h_1 with ρ_1 fixed.

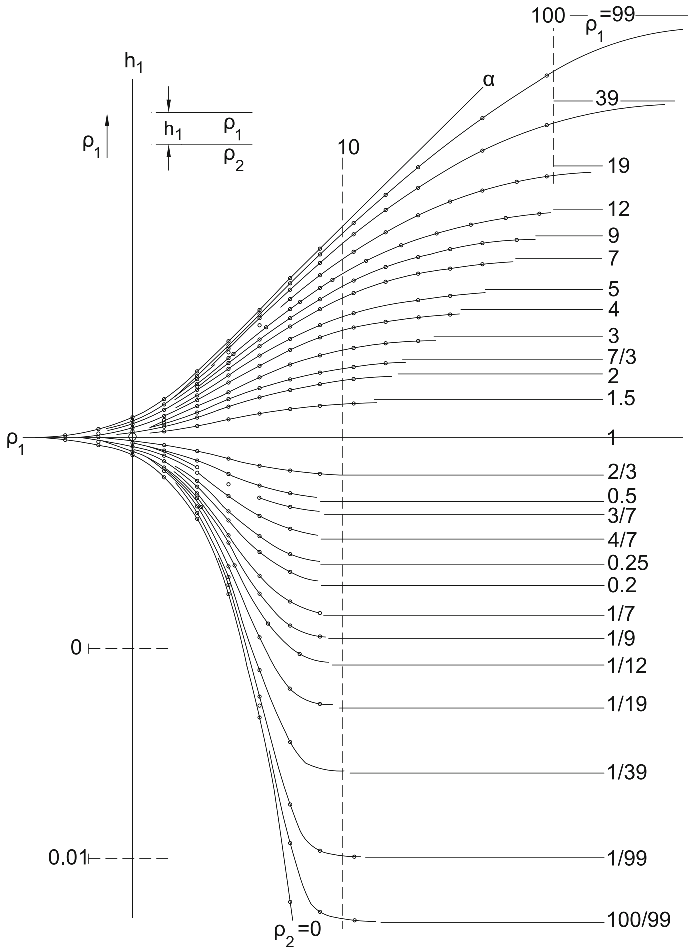


Fig. 4.9 Two-layer ascending- and descending-type master curves

Using logarithmic scale for Eq. (4.27), the influence *of* ρ_1 and h_1 on the form of the curve may be removed as we get:

$$\log\,\bar{\rho} - \log\,\rho_1 = F(\log\,\text{AB}/2 - \log h_1) \tag{4.28}$$

or,

$$\log(\bar{\rho}/\rho_1) = F(\log\,\text{AB}/2\,h_1) \tag{4.29}$$

Equation 4.29 shows that a plotting of $\bar{\rho}$ (ordinate) and AB/2 (abscissa) on a double-logarithmic scale will give curves of exactly the same form for any value of

ρ_1 and h_1 as long as ρ_2/ρ_1 remains constant. The effect, then of ρ_1 is to shift the curve upward or downward parallel to the ordinate, and that of h_1 is to the left or right, parallel to the abscissa.

Thus, the form of the Schlumberger curves, plotted on a double-logarithmic scale, is independent of the resistivity and thickness of the first layer in a two-layer section if ρ_2/ρ_1 is constant. This is found to be valid for a multilayer geoelectric section also.

From field measurements, we get apparent resistivity as a function of the electrode separation, i.e. $\bar{\rho} = f(\text{AB}/2)$.

Using logarithm scale for this relation, we get:

$$\log \bar{\rho} = F(\log \text{AB}/2) \tag{4.30}$$

Equations 4.28 and 4.30 are of the form: $y - b = f(x - a)$, and $y = f(x)$

These equations are similar to each other, except that the first curve is shifted parallel to the coordinates with respect to the second curve plotted on logarithm scale. This shows that the interpretation of the field curves by matching is made possible through the use of the logarithmic scale. Thus, for each value of ρ_1 and h_1, we need not have different curves as form of the curve remains unchanged in log scale, a single master curve may be used for any value of ρ_1 and h_1 provided ρ_2/ρ_1 remains the same.

In Fig. 4.10, the two-layer field curve ($\bar{\rho}$ versus AB/2) is shown for h_1 = 5 m and ρ_1 = 4 Ω m and ρ_2/ρ_1 = 7. The two-layer theoretical master curve ($\bar{\rho}/\rho_1$ vs. AB/2 h_1) for ρ_2/ρ_1 = 7 (the same as the field curve) is shown in the same diagram. These two curves can be matched easily by shifting the field curve over the theoretical curve, keeping the axes parallel. Actually, the theoretical curve can be matched with any field curve for any value of ρ_1 and h_1, provided ρ_2/ρ_1 is the same as that of the theoretical curve.

The method adopted for finding ρ_1 and h_1 has been indicated in Fig. 4.11. The procedure is to plot the field curve on a transparent double-logarithmic graph sheet which has a modulus the same as that for the theoretical master curves (a modulus of 62.5 mm), and then to superpose the transparent graph sheet on the master curve,

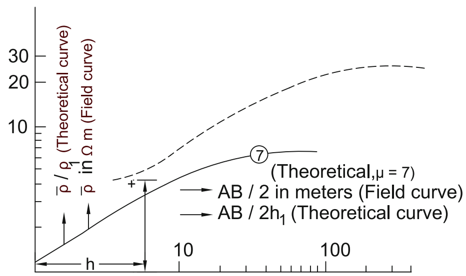


Fig. 4.10 Relation between theoretical and field curves. Field curve of the same form as the theoretical one but shifted with respect to it and parallel to the coordinate axes

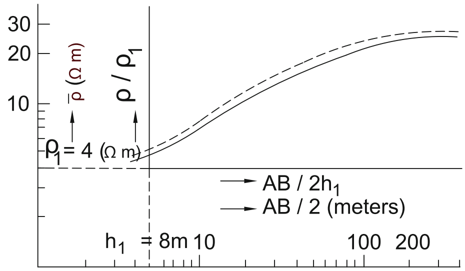


Fig. 4.11 A two-layer field curve superimposed over a two-layer master curve. Origin of the master curve as read over the field curve gives the thickness and resistivity of the upper layer

the transparent graph sheet is moved parallel to the coordinates until a match is obtained. Figure 4.11 represents the matched condition, and the point on the transparent double-logarithmic sheet coinciding with the origin of the master curve ($\bar{\rho}/\rho_1 = 1$, AB/2h_1 = 1) gives, along the abscissa, log (AB/2) = log h_1 i.e., h_1 = AB/2(m), and along the ordinate it gives log $\bar{\rho}$ = log ρ_1 = $\bar{\rho}$ (Ω m).

Thus, the use of the logarithm scale opens up the possibility of determining ρ_1 and h_1 from the theoretical and field curves.

Besides, as large variation in resistivity and larger spacings are to be accommodated, log scale is the only logical choice. Further, log scale suppresses effect of high resistivity and thin layers at larger depths but enhances low resistivity and thin layers at smaller depths which is, obviously, advantageous.

It is easily seen that on a double-logarithm scale, the conditions of limiting values are still satisfied and the asymptotic nature is retained, and therefore, double-logarithmic scale is most useful.

Let us now find the asymptotic values of the apparent resistivity when the second layer is of infinite resistivity (basement). It is obvious that at sufficiently large distances from the sources, the current lines will be all parallel to the surface and the equipotential surfaces will be cylindrical, having the vertical through the source as the axis. Let us consider an equipotential surface at a large distance r; then the current, I, is given by $I = 2\,\pi r h_1$. J,. where $J = I/2\,\pi r h_1$. Therefore, $E = \rho_1$ I/2 $\pi r h_1$.

Hence, the apparent resistivity for Schlumberger configuration is given by:

$$\bar{\rho} = 2\pi r^2 (E/I) = (\rho_1/h_l) r$$

Now taking the logarithm, we get:

$$\log\,\bar{\rho} = \log\,r + \log(\rho_1/h_l) = \log\,r - \log(h_l/\rho_1) \qquad (4.31)$$

This is the equation of a straight line inclined at an angle of 45° to the abscissa, cutting it at a distance (h_l/ρ_1) from the origin. It can be shown that for an n-layer earth (n-th layer of infinite resistivity) the same asymptotic relation holds good, provided ρ_1 is changed to ρ_s—longitudinal resistivity of ($n - 1$) layers and h_1 is changed to H—the total thickness of ($n - 1$) layers.

4.8 Principle of Reduction

Consider a prism of unit cross section, with thickness h and resistivity ρ. Then, the resistance (T) normal to the face of the prism and the conductance (S) parallel to the face of the prism are given by:

$$T = h\rho \tag{4.32}$$

and

$$S = h/\rho \tag{4.33}$$

Wherefrom we get:

$$h = \sqrt{ST} \text{ and } \rho = \sqrt{T/S} \tag{4.34}$$

Thus, each value of S and T determines a section with definite values of h and ρ given by Eq. (4.34). Now, from Eq. (4.32), we can write:

$$\log\ \rho = -\log\ h + \log\ T \tag{4.35}$$

This equation defines a straight line inclined at an angle of 135° to the h-axis and cutting it at a distance T from the origin, if ρ is plotted against h on a double-logarithm scale.

Similarly, from relation 4.33 we get:

$$\log\ \rho = \log\ h - \log\ S \tag{4.36}$$

which defines a straight line—also see Eq. 4.31—inclined at an angle of 45° with the abscissa (h-axis) and meeting it at a distance S from the origin.

The point of intersection of the two straight lines defined by Eqs. 4.35 and 4.36 then uniquely defines the resistivity and thickness for a particular combination of T and S.

Consider now that the prism consists of n parallel homogeneous and isotropic layers of resistivities ρ_1, ρ_2, … ρ_n and thicknesses h_1, h_2, …, h_n, respectively (Fig. 4.12). When the current is flowing normal to the base, the total resistance of the prism is given as:

$$T = T_1 + T_2 + \cdots + T_n = \sum_{i=1}^{n} T_{\mathrm{i}} = \rho_1 h_1 + \rho_2 h_2 + \cdots + \rho_n h_n = \sum_{i=1}^{n} \rho_i h_i \tag{4.37}$$

When the current is flowing parallel to the base, the total conductance is given as:

$$S = S_1 + S_2 + \cdots + S_n = \sum_{i=1}^{n} S_i = h_1/\rho_1 + h_2/\rho_2 + \cdots + h_n/\rho_n = \sum_{i=1}^{n} h_i/\rho_i \tag{4.38}$$

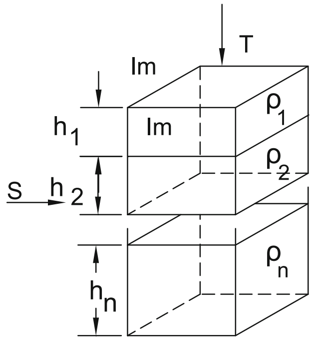


Fig. 4.12 An n-layer prism of unit cross section

The parameters T and S defined as transverse resistance and longitudinal conductance, respectively, play a very important role in the interpretation of sounding data. It may be mentioned that Maillet (1947) used the notations R and C for these parameters and called them "Dar Zarrouk Variable" and "Dar Zarrouk Function", respectively. Zohdy (1973, 1974) has utilized Dar Zarrouk curves for the interpretation of Schlumberger curves through a computer programme, which automatically calculates layer parameters from digitized apparent resistivity curves.

For the particular case of a two-layer prism, we get:

$$T = T_1 + T_2 = \rho_1 h_1 + \rho_2 h_2 \tag{4.39}$$

and

$$S = S_1 + S_2 = h_1/\rho_1 + h_2/\rho_2 \tag{4.40}$$

If ρ_s and ρ_t are, respectively, the longitudinal and transverse resistivities of the block, then:

$$\rho_t(h_1 + h_2) = \rho_1 h_1 + \rho_2 h_2 \tag{4.41}$$

and

$$(h_1 + h_2)/\rho_s = h_1/\rho_1 + h_2/\rho_2 \tag{4.42}$$

Thus, the coefficient of anisotropy λ and the mean resistivity ρ_m are, respectively, given by:

$$\lambda = \sqrt{\rho_t/\rho_s} = \frac{1}{h_1 + h_2}\left[(h_1\rho_1 + h_2\rho_2)\left(\frac{h_1}{\rho_1} + \frac{h_2}{\rho_2}\right)\right]^{\frac{1}{2}} \tag{4.43}$$

and

$$\rho_m = \left[\frac{(h_1\rho_1 + h_2\rho_2)}{h_1/\rho_1 + h_2/\rho_2}\right]^{\frac{1}{2}} \tag{4.44}$$

We shall now assume that the anisotropic prism may be replaced by a homogeneous and isotropic prism of thickness h_e and resistivity ρ_e, which may be called, respectively, the effective thickness and the effective resistivity of the block.

Then,

$$h_e \rho_e = T = h_1\rho_1 + h_2\rho_2 \tag{4.45}$$

and

$$h_e/\rho_e = S = h_1/\rho_1 + h_2/\rho_2 \tag{4.46}$$

from which we get:

$$h_e = \left[(h_1\rho_1 + h_2\rho_2)\left(\frac{h_1}{\rho_1} + \frac{h_2}{\rho_2}\right)\right]^{\frac{1}{2}} = \lambda(h_1 + h_2) = \lambda H \tag{4.47}$$

and

$$\rho_e = \left[\frac{(h_1\rho_1 + h_2\rho_2)}{h_1/\rho_1 + h_2/\rho_2}\right]^{\frac{1}{2}} = \rho_m = \lambda\rho_s \tag{4.48}$$

Thus, it is possible to transform an isolated two-layer block (each homogeneous and isotropic) into a single homogeneous and isotropic medium. A complete isolation of this kind is possible in the case of A-type curves, where the third layer is highly resistive and the second layer is more resistive than the first. Here, the effective thickness of the reduced layer is equal to λ times the total thickness and the effective resistivity is equal to the mean resistivity of the mediums. Since λ is always greater than unity, the effective thickness of the composite layer is greater than the total thickness of the two layers.

4.9 Schlumberger Curve Matching with Ebert Charts

The theoretical derivations (Bhattacharya and Patra 1968; Patra and Nath 1999), given earlier, form the basis of "auxiliary point method" of interpretation of Schlumberger sounding and azimuthal dipole sounding with the help of album of standard two-layer theoretical curves and Ebert charts (Figs. 4.13 and 4.14). The results of such interpretation, referred to as preliminary interpretation, may give us a fairly accurate representation of layer parameters under favourable circumstances with suitable geological control. However, this being a grapho-analytical approach has its intrinsic drawbacks and, therefore, may not reliably obtain the correct geoelectric parameters with a prescribed degree of exactitude and precision

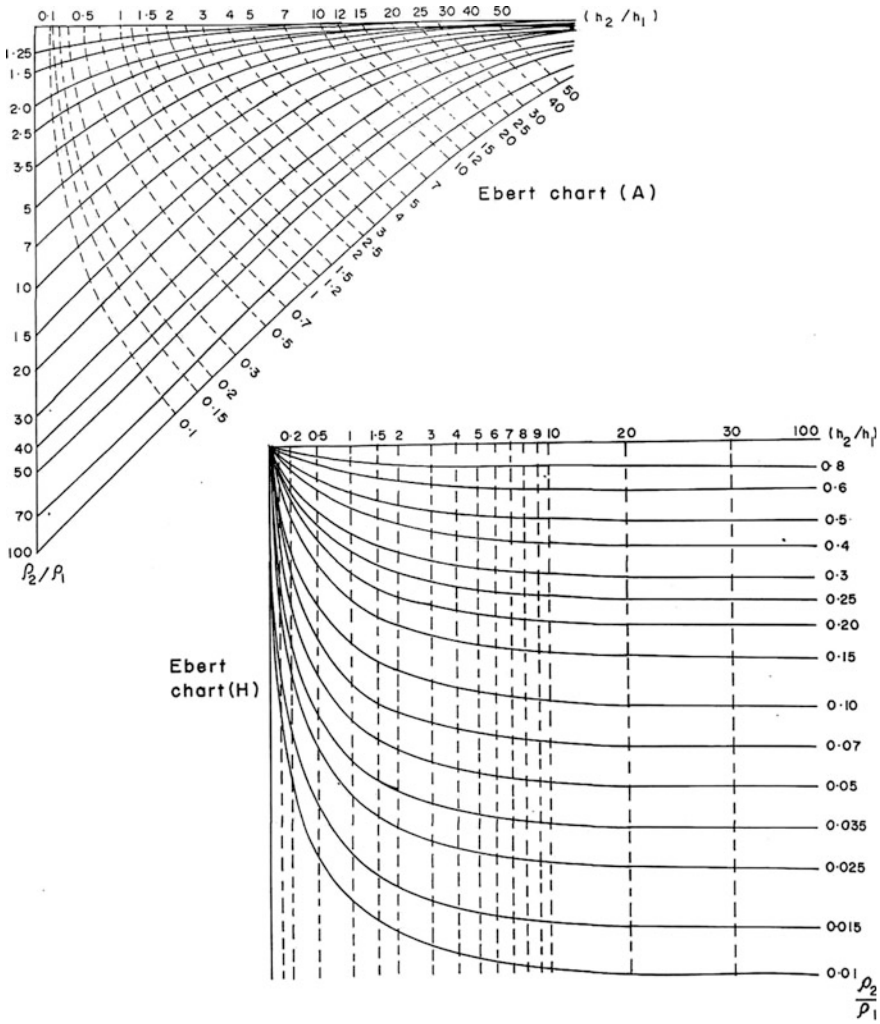


Fig. 4.13 Ebert charts (*A* and *H*)

necessary for accurate assessment of the data. In order to check the validity of the results of preliminary interpretation, these are fed to computer and synthetic sounding curves obtained. A comparison is made between the two curves and final interpretation achieved through trial and error, if necessary.

The curve-matching techniques for interpretation of Schlumberger VES curves using two-layer master curves (Fig. 4.9) and Ebert charts (Figs. 4.13 and 4.14) are given as follows.

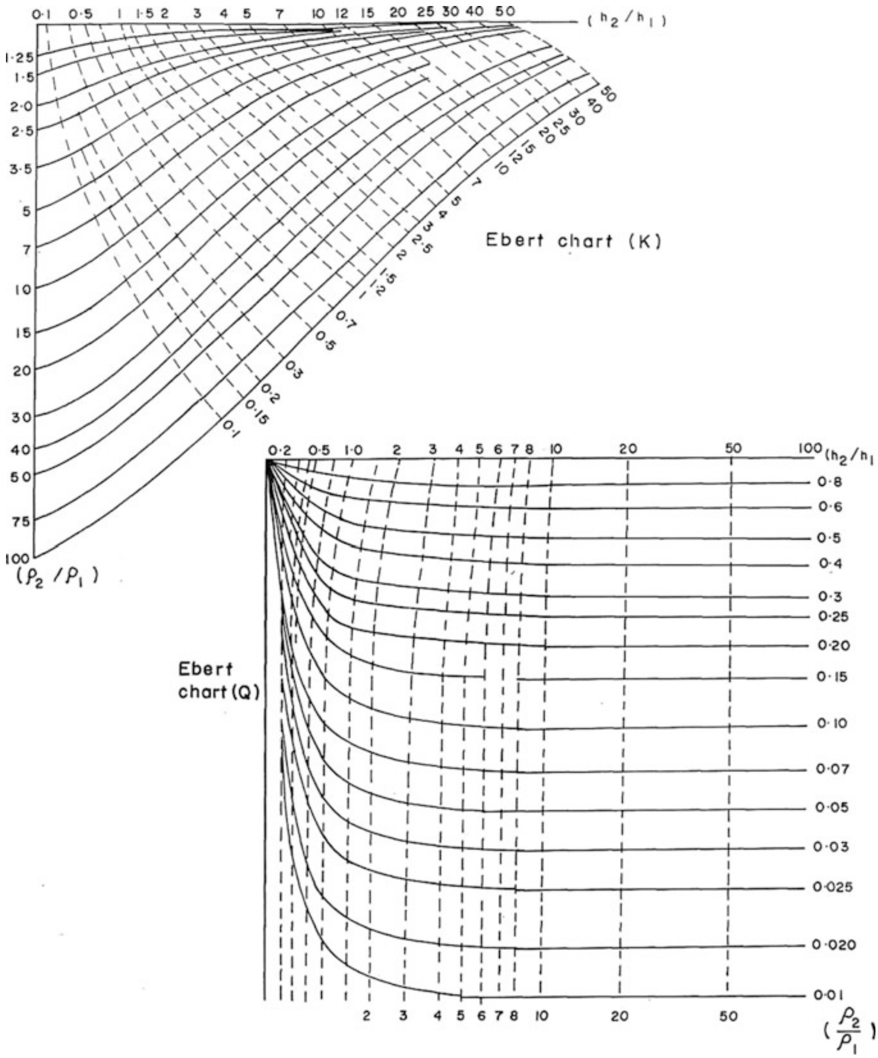


Fig. 4.14 Ebert charts (*K* and *Q*)

4.9.1 Ebert Chart Method

(a) Each of the branches of an apparent resistivity curve is approximated by a two-layer one.
(b) The coordinates of the cross of this two-layer curve are considered to represent the thickness and the resistivity of a fictitious layer that replaces the sequence of shallower layers.
(c) To get the parameter for the fictitious layer, sets of graphs are used. The coordinates on these graphs are the ratio of the thickness of the replacing layer

to that of the first layer and the ratio of the resistivity of the replacing layer to that of the first layer. The parameters are thickness ratio and resistivity ratio plotted on double-log graph sheet of modulus 62.5 mm.

(d) Four sets of such auxiliary point charts are available for H, A, K and Q types reproduced in Figs. 4.13 (H and A), 4.14 (K and Q).

4.9.2 Interpretation of a Four-layer HK-type Curve

The procedure for interpretation of a four-layer HK-type curve (referred to as working graph) with the help of two-layer master curves (Fig. 4.9) and corresponding Ebert charts (Figs. 4.13 and 4.14) may be illustrated as follows:

(i) The four-layer field curve comprises three two-layer branches.
(ii) Superimpose the working graph (solid line) on a family of two-layer master curves (Fig. 4.9) and approximate the first branch of the field curve. The origin of the master set read on the field curve at the matched condition is the "first cross" (+) giving h_1 and ρ_1 values. Read ρ_2/ρ_1 from the dashed curve. Here, $\rho_1 = 16\ \Omega$ m, $h_1 = 1.3$ m and $\rho_2/\rho_1 = 1/3$ (Fig. 4.15).
(iii) The working graph is then superimposed on H-type Ebert charts with its origin on the "first cross" and corresponding Ebert line I (dash–dot) is copied for $\rho_2/\rho_1 = 1/3$.

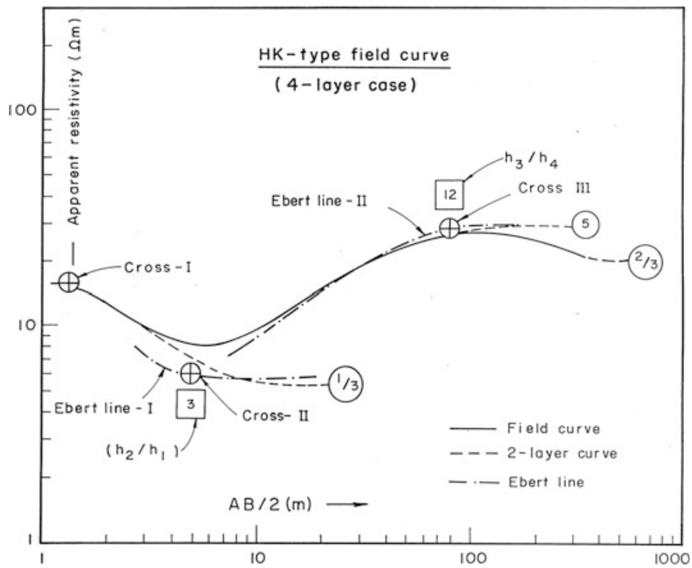


Fig. 4.15 Interpretation of four-layer HK-type curve using two-layer master curves and Ebert charts

(iv) Superimpose the working graph on two-layer set and approximate to the second part of the curve (dashed line) keeping master set-origin on the Ebert line I. Draw the "second cross" (+) as read on working graph. The values read on "second cross" give ρ_H and h_H and the resistivity ratio $\rho_3/\rho_{H.}$ The values here are $\rho_H = 6\ \Omega$ m, $h_H = 5$ m and $\rho_3/\rho_H = 5$.

(v) The step (iii) is repeated and Ebert line II is drawn keeping "second cross" at resistivity ratio "5" on the ordinate of K-type Ebert chart.

(vi) Finally, approximate the last branch of the curve by the two-layer master set keeping its origin on Ebert line II and ρ_4/ρ_k. The origin read on the working graph, and the "third cross" gives ρ_k, h_k values. Last two-layer match gives ρ_4/ρ_k equal to 2/3. Here, $\rho_k = 29\ \Omega$ m and $h_k = 80$ m. Thickness ratios h_2/h_1 and h_3/h_H as read w.r.t. cross-I and cross-II are 3 and 12, respectively.

(vii) Final interpreted layer parameters are as follows (Fig. 4.15):

$h_1 = 1.3$ m, $h_2 = 3.9$ m, $h_3 = 60$ m, $h_4 = \infty$
$\rho_1 = 16\ \Omega$ m, $\rho_2 = 12\ \Omega$ m, $\rho_3 = 30\ \Omega$ m, $\rho_4 = 20\ \Omega$ m

4.9.3 Interpretation of a Multilayer HKQ-type Curve

The procedure adopted here is briefly outlined below:

(a) Approximate the first part of the apparent resistivity field curve by a two-layer descending-type master curve. The cross-I read over the origin gives first layer thickness and resistivity.

(b) Superpose the curve on H-type Ebert chart with origin over the origin and draw Ebert line 1 corresponding to resistivity ratio obtained in step (a).

(c) Next superpose the field curve over a two-layer ascending-type master curve and approximate to the second branch taking care that origin lies on Ebert line I and record this origin as cross-II. This gives third-layer resistivity with reference to cross-II. Read cross-II w.r.t. cross-I to note second-layer thickness w.r.t. cross-I.

(d) Superpose the field curve upon K-type Ebert chart with cross-II on its vertical axis corresponding to resistivity ratio in step(c). Copy this parameter line on the field curve to get Ebert line II.

(e) Superpose the field curve on two-layer descending-type master curve and note the resistivity ratio with cross-III on Ebert line II. Read the thickness ratio on K-type Ebert chart for cross-III w.r.t. cross-II.

(f) The last part of the curve represents descending type. Therefore, superimpose the field curve on a two-layer descending-type master curve taking care that the cross-IV lies over Ebert line III.

(g) The two-layer curve that gives the best fit finally defines the last resistivity ratio. Read the thickness ratio from cross-IV with reference to cross-III on Q-type Ebert chart.

4.10 Inversion of Resistivity Data

Schlumberger vertical electrical sounding data obtained from the field are plotted on double-log transparent graph sheets of modulus 62.5 mm which is also the modulus of the master curve sets available for interpretation. The curve type is identified and interpreted using Ebert chart method (Sect. 4.9). In a computer-assisted process, the theoretical curves generated (Sect. 4.6) through the forward solution (Patra and Nath 1999, pp. 111–116) using interpreted layer parameters are compared with the actual field curves. Modification is done depending on the deviation between the two. This forms the basis of indirect interpretation of Schlumberger VES data.

The layer parameters obtained by curve matching are used as initial guess for the model to generate the corresponding theoretical VES curve through Eq. (4.26). The inversion algorithm minimizes the deviation between the observed and theoretical curves using different established numerical iterative approaches. There are different inversion schemes available for the purpose. In ridge regression technique (Inman 1975; Marquardt 1970), damped least square inversion of the derivative matrix is performed to obtain the incremental parameter values. The new model parameters are obtained after requisite number of iterations till a convergence is achieved wherein both the observed and the theoretical curves coincide. The process of inversion of the derivative matrix always possesses optimization problems of large scale, especially ones where a derived global extremum is hidden among many poorer, local extrema. The simulated annealing method (Otten and Van Ginneken 1989) does the combinatorial minimization optimization. The method of simulated annealing draws an analogy with thermodynamics, especially with the way that liquids freeze and crystallize, or metals cool and anneal. At high temperatures, the molecules of a liquid move freely with respect to each other. If the liquid is cooled slowly, then thermal mobility is lost. Although the analogy is not perfect, there is a sense in which all of minimization algorithms correspond to rapid cooling or quenching. Boltzmann probability distributions express the ideas that a system in thermal equilibrium has its energy probabilistically distributed among all different energy states. Even at low temperature, there is a chance of a system being in a high-energy state. Therefore, there is a corresponding chance for the system to get out of a local energy minimum in favour of finding a global one, and hence, the optimization gate achieved. Thus, simulated annealing probabilistically generates a sequence of states based on a cooling schedule to ultimately converge to a global optimum. This statistical approach used in seismic prospecting is being applied recently in resistivity inversion for solving the final layer parameters. Genetic algorithms (Goldberg 1989; Srinivas and Patnaik 1994) generate a sequence of populations by using a selection mechanism and use crossover and mutation as search mechanisms. The principal difference between genetic algorithms and evolutionary strategies is that genetic algorithms rely on crossover, a mechanism of probabilistics and useful exchange of information among solutions to locate better solutions. Although the simulated annealing and genetic algorithm adopt different approaches, they converge to the global minima. Once the global minima are achieved, the inversion is said to be complete and the final parameters are, therefore, obtained. This probabilistic approach generally used in seismic reflection is being utilized in resistivity inversion also to overcome optimization problems encountered in other conventional algorithms (Inman 1975). The layer parameters (thicknesses and resistivities) obtained through curve matching and subsequent forward approach are utilized for initial parameterisation for the final interpretation. Although the indirect approach (curve matching and use of forward algorithm) of interpretation of VES data is found to be adequate, direct resistivity inversion through algorithms based on singular value decomposition (SVD) and evolutionary programming (EP), for examples, approaches is preferred for evaluation of final layer parameters. The algorithm on inversion of apparent resistivity data by weighted ridge regression aided by SVD and using EP technique is given in Patra and Nath (1999) on pages 119 (Appendix 4.2) and 144 (Appendix 4.3), respectively.

4.11 Resistivity Sounding Case Study

Vertical electrical sounding (VES) by Schlumberger electrode array has been used to investigate the subsurface distribution of water-saturated layers and thereby the aquifer disposition around Edilpur, Burdwan district (West Bengal). The results of the study are given in the following section which outline the utility of resistivity sounding is groundwater prospecting.

4.11.1 Geology of the Area

The study area around Edilpur, Kathgolaghat (Lat 23° 13′ 8″N, Long 87° 49′ 33″E), district Burdwan (West Bengal) is situated on the northern bank of River Damodar as shown in Fig. 4.16. Groundwater investigation, here, is restricted to recent alluvial cover of top 100 m overlying Pliocene–Pleistocene sediments.

4.11.2 Geosounding Studies and Results

Vertical electrical soundings (VES) using Schlumberger electrode array were conducted at forty points around the area (Fig. 4.17). A few representatives of VES curves for the area are presented in Fig. 4.18. The layers with resistivities greater than 250 Ω m represent dry sand lying on the top. The coarse sand bodies show resistivity values between 100 and 250 Ω m, whereas the medium to fine sands correspond to the values between 30 and 50 Ω m. The clay horizons represent the resistivity values in the range of 10–28 Ω m.

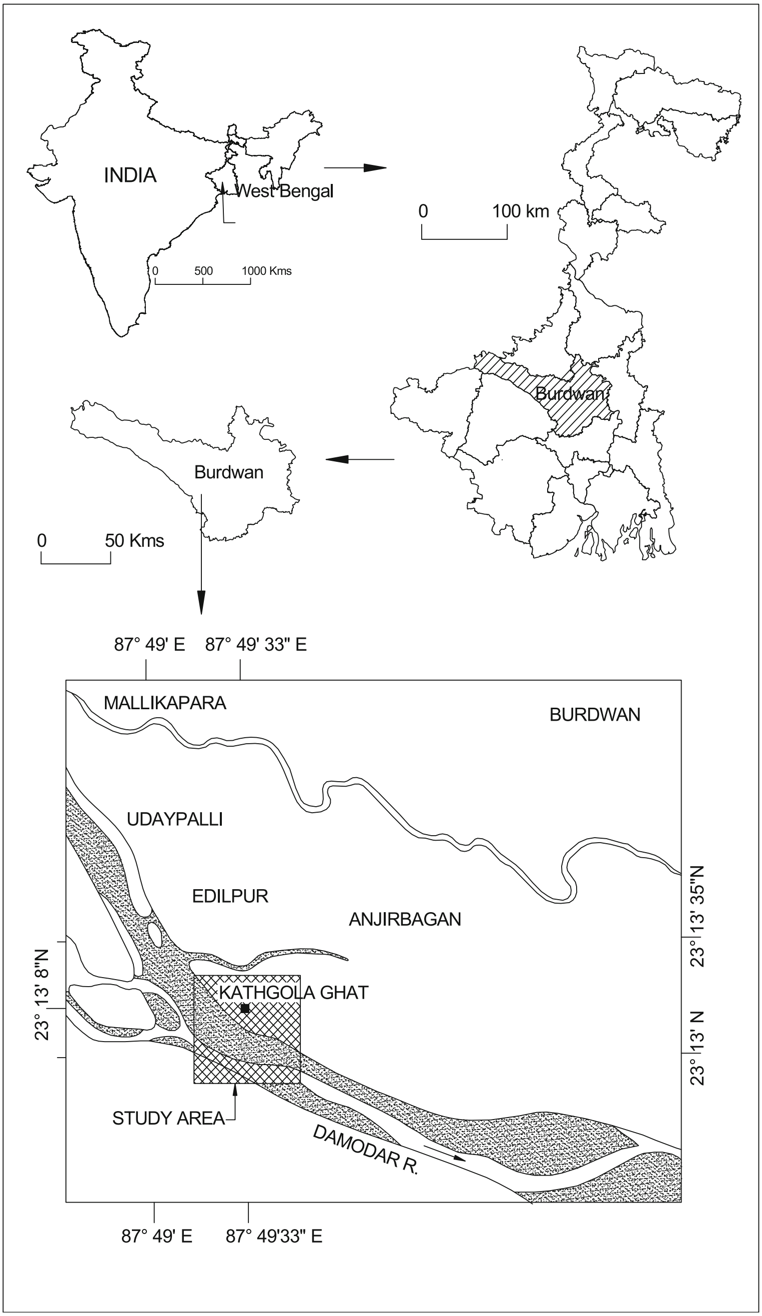


Fig. 4.16 Location map of the study area

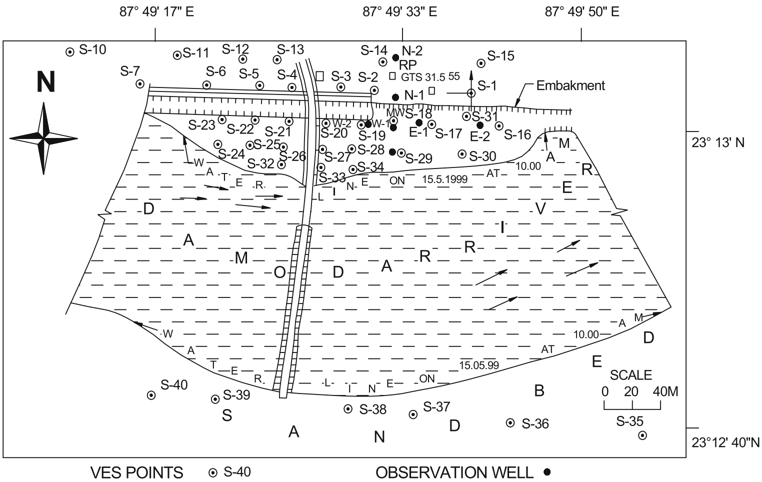


Fig. 4.17 Field layout of the resistivity sounding points and wells for pumping test

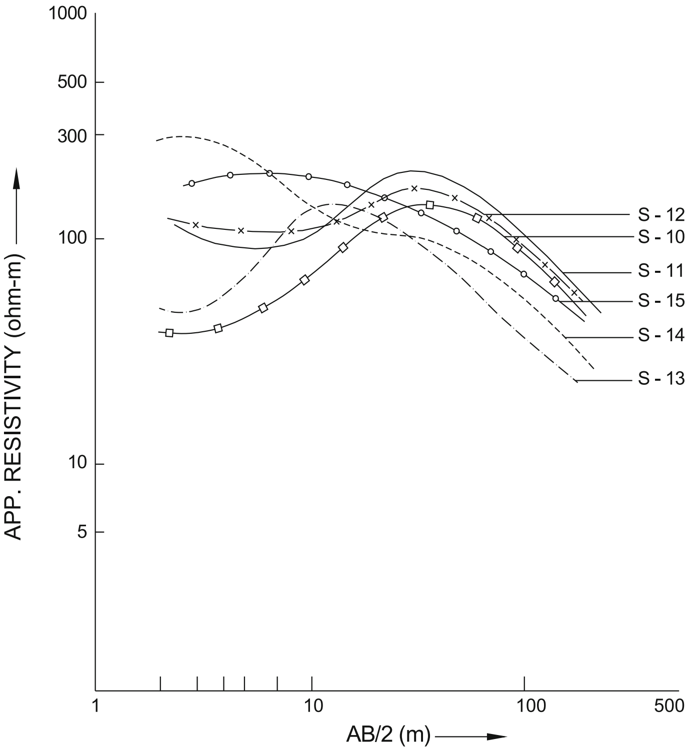


Fig. 4.18 VES Curves for the area

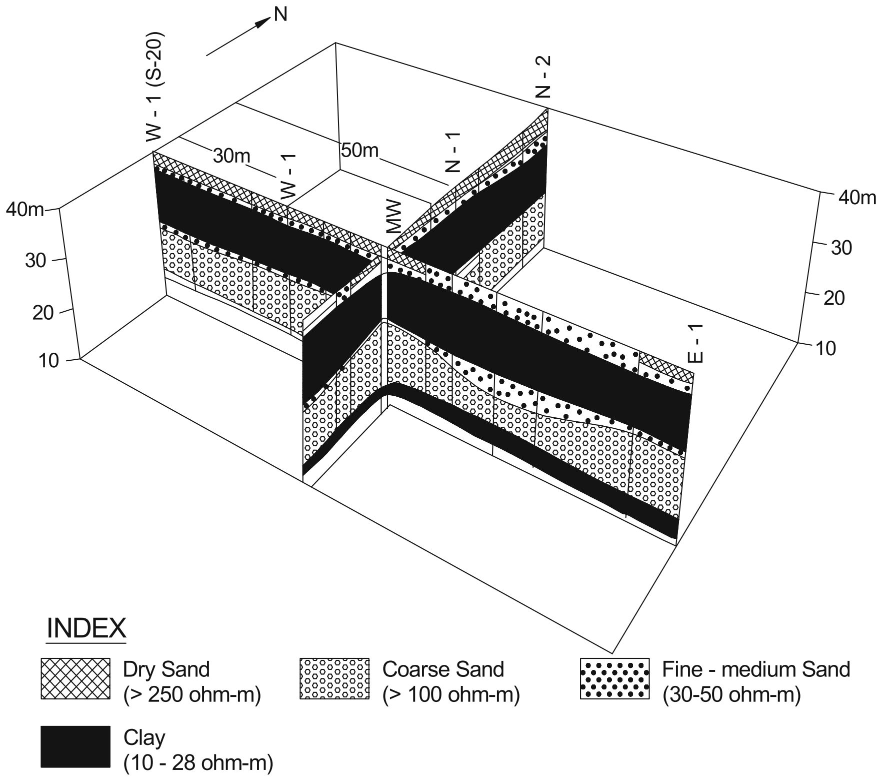


Fig. 4.19 Fence diagram

Based on these resistivity values, at forty locations in the study area, drilling points were recommended. Borehole samples and subsequent correlation with the resistivity values were used to prepare an index and draw a fence diagram given is Fig. 4.19. The surveys carried out in the area established the presence of a confined aquifer with an average thickness of 12 m comprising medium-to-coarse-grained sand with occasional gravels, capable of supplying large quantity of groundwater.

4.12 Seismic Measurement

The seismic method using artificial seismic waves dates back to 1910. By 1925, the exploration refraction seismology was well established as a tool in applied geophysics for resources evaluation and geotechnical investigation. Applied seismology has been highly developed in the petroleum industry, where the seismic reflection method is used almost exclusively to delineate structural and for formational boundaries at greater depths.

The seismic refraction method, used for groundwater studies, utilizes the propagation of elastic waves through the earth and is based on the following concepts:

(i) The elastic waves are propagated in different geological strata with different velocities,
(ii) The velocity contrast is very large,
(iii) The strata velocities increase with depth,
(iv) Thin layers with intermediate seismic velocities are not present and
(v) Interfaces between layers of interest are distinct.

Recent advances in equipment, sound sources and computer interpretation techniques make seismic refraction method highly effective and economical for obtaining data for groundwater modelling studies. A sudden velocity increase in a soil layer can indicate a groundwater table (or a harder layer). In doubtful cases, test drillings should be made. If transverse velocities have been obtained, then the problem can be solved by seismic method since transverse waves unlike longitudinal waves are not affected by varying water content. The same transverse velocity is recorded above or below an interface indicated by an increase due to a water table, while an increase in the transverse velocity below the interface also proves the existence of a harder layer. The volume of the water-bearing strata in the overburden can be calculated using the seismically determined depths. The velocities give some indication of the permeability of various layers. If the seismic measurements are sufficiently comprehensive, contour lines of the groundwater tables may be established and the direction of the water flow can be determined. In the bedrock, the low-velocity zones give indications of fissured, water-bearing sections. A seismic survey cannot prove the occurrence of water as such but is indispensable for tectonic analysis, particularly in areas where the bedrock is covered by relatively thick layers of overburden. Sedimentary rock formation and fractured and weathered upper rock layers with more or less horizontal bedding can be mapped by this method. Whether they are water bearing or not is difficult to say. The velocity pattern is often complex since it depends on the degree of saturation and the porosity of the rock. Sedimentary strata known to have higher water content can, however, be traced by seismic methods. Seismic refraction allows economical collection of subsurface data by test drilling or aquifer test. Table 4.2, wherein the average velocity of longitudinal wave within some common geological formations is listed, shows that lithological composition of rock affects the velocity variation from about 300 m/s for unconsolidated sediments to more than 6000 m/s for limestone. Older sediments display high velocities as compared to newer ones. Rocks possessing moisture display higher velocities. The velocities in saturated strata are somewhat greater than unsaturated ones.

Seismic reflection method has been in widespread use as an exploration tool in the petroleum industry for over 50 years (Dobrin and Savit 1988 and others). However, except for a few isolated cases, reflection techniques were not systematically considered.

Table 4.2 Average velocities of longitudinal waves within some common geological formations (after Jakosky 1957)

Rock formation	Range of velocity (m/s)
Alluvium	500–1500
Basalt-canal zone-weathered and fractured	2740–4270
Cemented sand clay	1150–1285
Chalk	1830–3970
Clay	915–2750
Clayey sandstone	1500–1800
Dolomite	4900–6160
Dolomitic limestone	5700–6500
Dry sand and loose soil	150–400
Glacial till	1700–2260
Granite	4580–5800
Granodiorite	4500–4600
Gravel, rubble or sand (dry)	468–915
Limestone	2140–6100
Metamorphic rocks	3050–7020
Sand (wet)	670–1830
Sandstone	1830–3970
Sandy clay	976–1250
Shale	2750–4270
Top soils:	
Light and dry moist, loamy or silty	180–275 305–400
Clayey	395–610
Semi-consolidated sandy clay	380–660
Wet loam	750–770
Weathered and fractured rock	450–3050
Weathered surface material	305–610

Tomographic surveys use the same mathematical approach as has been used by medical professional, but the technique depends on the measurement of travel time for larger number of paths through the body of earth materials. The technique is computationally intensive and is costly because of the need for boreholes. It often gives very detailed velocity model between the boreholes and does not require any assumption to be theoretically correct. Because of the higher cost involved, it is not viable to be used for groundwater problems.

Since shallow seismic refraction survey is greatly used in combination with geo-electric and other hydrogeologic methods for the delineation and modelling of aquifers, seismic refraction prospecting method will be briefly outlined in the section to follow.

4.12.1 Characteristics of Seismic Refraction Method

A brief review of many textbooks and numerous journal articles presenting detailed theory of seismic refraction method (Slotnick 1950, 1959; Grant and West 1965; Musgrave 1967; Telford et al. 1976; Parasnis 1979; Mooney 1981; Palmer 1986; Dobrin and Savit 1988) indicates the diversity of seismic refraction techniques. Refraction seismic surveying was the first major geophysical method to be applied in the search for oil-bearing structures. Today, however, oil exploration relies exclusively on CDP and other multichannel reflection seismic techniques. Significant advances in refraction seismograph instrumentation have not occurred to the same extent as they have been in the development of sophisticated reflection equipment for oil exploration. Solid-state electronics have improved the portability of engineering-type refraction instruments, to some extent but the basic field practices and methods of interpreting the data have not changed much with time, although the specialized interpretation techniques have been proposed and developed over the years for difficult cases. The conduct of refraction surveys and the interpretation of the data are well established and reasonably straightforward, although they are not invariant. In common with other indirect method of subsurface exploration, there are no rigid, inflexible approaches to making sense of the data, nor are there any handbooks to guide the engineers, geologists, geophysicists or hydrologists to the correct answer. The general case will require conceptual thinking and care so that ambiguity and uncertainties can be resolved successfully. Some previous knowledge of site conditions and geological settings will always assist in transforming raw data into meaningful subsurface information.

4.12.1.1 Limitations of Seismic Refraction Method

The seismic refraction method seeks to measure the spatial variation of petrophysical parameters, such as seismic velocity and absorption, through the analysis of artificially initiated seismic signals. These petrophysical parameters can be related to rock-type, porosity, jointing, weathering and other geological factors and can be used to provide uniqueness in geology.

In the layered earth, a disturbance is created by an explosive or by weight dropping at the surface; the elastic waves generated propagate in all directions in the surrounding medium. At any moment, following the onset of disturbance, two parts of the medium can be identified: one through which the disturbance is passing or has already passed, and the other which has not been reached by the disturbance. The two parts are separated by the wavefront of disturbance. All points on a wavefront have the same travel time from the source. The propagation of the wavefronts can be observed with detectors such as geophones, hydrophones and seismometers. The passage of wavefront through an observation point is marked by rapid increase in signal amplitude.

The propagation of these wavefronts is governed by the classical principles of geometrical optics, viz., Huygens' Principle and Snell's law. Huygens' Principle states that every point of a wavefront can be regarded as a new source of waves. Therefore, if the position of a wavefront known at a given instant, then its position at a later time can be found by determining the envelope of the surfaces which are centred on the original wave front and which have the shape of the velocity, the velocity of energy transport, multiplied by the time increment. These surfaces are commonly known as Huygens' Principle is much easier to use since it accommodates the reflection as well as refraction phenomena. In addition, it provides a convenient approach to the derivation of Snell's law.

As the waves travel from the low-velocity medium into the higher seismic velocity medium, some are refracted towards the lower velocity medium, and some are refracted back into the first medium depending upon angles at which the rays are incident on the interface separating the media as per Snell's law. As the angle of incident of the ray approaches the critical angle, most of the compressional energy propagates along the refraction surface; head waves are generated in the overlying layer that in turn returns to the earth's surface at the critical angle but with the velocity of the upper layer. For seismic refraction survey, therefore, the velocity contrast between the upper and the lower media must be appreciable and the velocity of the underlying layer must be greater than that of the overlying layer. When this condition is satisfied, head waves will be generated and will be the geophones at the ground surface. The geophones will transducer these ground motions into electrical signals to be finally recorded by a seismograph.

We would not look to go into the mathematical derivations for refraction seismic, given in detail in Nath et al. (2000). However, two special cases that ultimately affect the success or failure of seismic refraction method will be mentioned here. These are (1) blind zone problems arising out of the presence of an intermediate thin seismic velocity layer and (2) velocity inversion due to slow seismic velocity layer and the underlying low-velocity layer remains undetected by seismic refraction prospecting. The problem of intermediate thin high-velocity layer is especially critical in water resources investigation, because this layer may be the zone of interest in the study that is saturated unconsolidated material located between unsaturated and consolidated material and bedrock. If the presence of this layer is suspected, calculations can be made to determine the minimum and maximum possible thickness of this unit. In some hydrogeological settings, the seismic velocity in the earth's layer does not increase with depths and low seismic velocity units underlie sand and gravel aquifer underlying compact glacial tills. In this case, the low-velocity unit will not be detected by the refraction technique and the calculated depth of the deeper unit will be in error.

Barring the above limitations, the seismic refraction survey proves a useful tool along with other geophysical techniques in deciphering the shallow subsurface hydrogeological condition.

There are certain limitations in the use of seismic refraction method to make hydrologists aware of potential pitfalls. These situations, recognized early in the study, can be accounted for in the planning, data acquisition, and interpretation phases of the analysis.

Ambient noise, that is the noise produced by constructions equipment, railroads, wind and so on, has a detrimental effect on the quality of seismic refraction data. The solutions to this problem are to: (1) decrease the amplifier gains and increase the input signal by using multistack or more explosives, (2) Reschedule operations for a quiet part of the day and (3) use selection filter on the seismograph to eliminate unwanted frequencies.

Horizontal discontinuities in the low-velocity zone near the surface have a significant effect on seismic refraction studies. The zone is usually the unsaturated zone having velocities of 120–500 m/s. Short spreads are needed to determine the velocity of sound and the thickness of this layer. A variation of 0.3 m in the thickness of a weathered layer consisting material having a velocity of sound of 330 m/s causes the refracted ray to be delayed by 1 ms. Same time interval represents 3 m of material having a velocity of sound of 3000 m/s. The average velocities of longitudinal waves within rocks are presented in Table 4.2.

The accuracy with which the depth to a refractor can be determined by seismic refraction method depends on many factors, some of which are given below:

(i) Type and accuracy of seismic equipment.
(ii) Number and type of corrections made to the field data.
(iii) Quality of field procedures.
(iv) Type of interpretation method used.
(v) Variation of the earth from simplifying assumptions used in the interpretation.
(vi) Procedure.
(vii) Ability and experience of the interpreter.

Further complications arise if the rock surface is not only eroded and irregular, but also weathered. In this case, the rock surface will not be a well-defined boundary but rather a zone of transition. Some materials may be anisotropic; i.e. there may be differences between horizontal and vertical velocities, or even between horizontal velocities in different directions. These differences may be as large as 40 % in some materials. It will be extremely difficult to solve these complex problems by normal seismic refraction technique.

4.12.2 Field Procedures and Instrumentation

There are three components in a seismic survey, namely instrumentation, fieldwork and interpretation, which must be well tuned to each other if reliable results are to be obtained. The time data provided by the equipment must have sufficient resolution, the field operations must yield adequate information and the analyses must do justice to the field data acquired. A fourth factor affecting the reliability of the results is the positioning of the seismic profiles with regard to the geology and the possibilities and limitations of the method. In this section, we will give an overview

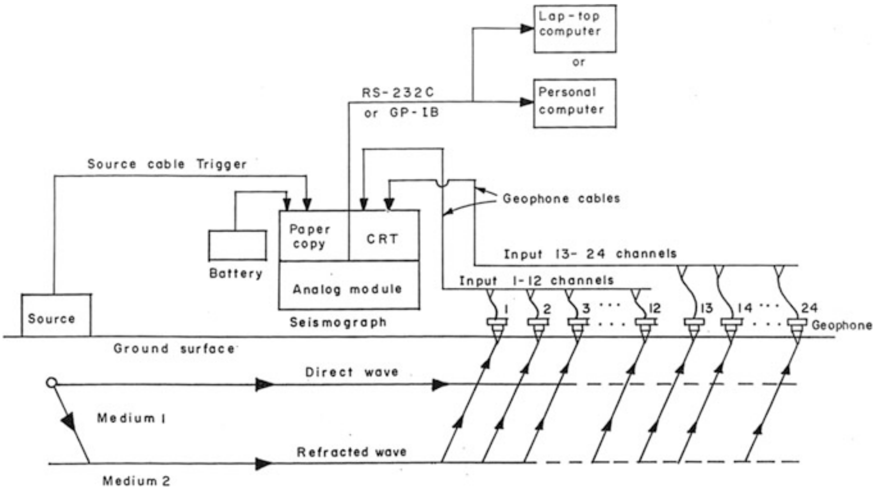


Fig. 4.20 Block diagram of a seismic refraction system

of the general instrumentation and field procedure involved in the seismic refraction prospecting. A block diagram of a representative seismic refraction system is given in Fig. 4.20. A wide variety of signal enhancement seismograph is available from different vendors, namely OYO corporation, Japan; Bison, USA; and EG&G Geometries, USA, ranging from very simple, inexpensive single-channel analogue units to extremely sophisticated expensive multichannel digital units generally used in petroleum industry. With few exceptions, almost all the modern kits record the data digitally, thereby enabling the interpreter to not only do routine interpretation but also carry out complex waveform analysis using high-speed digital computers. The type of equipment best suited for engineering and water resources studies is typically a 12/24-channel signal enhancement seismograph. These units are capable of utilizing a non-explosive seismic source because they have the facility to stack signal from several successive non-explosive impacts to increase the amplitude of otherwise weak-refracted signal more than that of the random noise. The data received can be stored on magnetic tapes and can also be viewed on a cathode ray screen display time reading. A hard copy of the same can be printed out in the form of a seismograph.

Geophones convert the physical movement of the ground to an electrical signal. In seismic refraction survey, low-frequency (8–10 Hz) vertical motion geophones are used. The geophones should, therefore, be planted into the ground in an almost vertical position. The insensitivity of the geophones to horizontal movements is sometimes observed when they are placed on outcropping solid rock. The signals from the geophones are weak because of the near-horizontal wave propagation direction. Special attention should be given to the coupling between the geophone and the ground. Geophones equipped with spikes have to be firmly planted into the ground to increase the reception capacity.

For special measurements, for instance shear wave and vibration determination, three-component geophones are used. The geophones are oriented in three different directions. One geophone records vertical movements, while the other two record horizontal movements in two mutually perpendicular directions. In water-covered areas, pressure sensitive detectors called hydrophones are frequently used. The hydrophones are sensitive not to movements but to the increase in water pressure caused by an impact. In swampy areas, geophones of marsh type, hydrophones or ordinary geophones mounted on top of steel rods driven down to solid ground are used (Fig. 4.21).

Geophone cables come in a variety of lengths with a predetermined distance between each geophone connection. For water resources studies, cables having approximately 7.5, 15 m or 30 m spacing between geophone takeouts are normally used. The distance between impact points generally varies between 25 and 50 m, when the corresponding geophone separation is between 7.5 and 15 m. In order to avoid excessive recording work, the impact points should be 150–250 m apart when the depths approach 100 m. In principle, the measurements in water-covered areas are carried out in the same manner as those on land. The hydrophones and

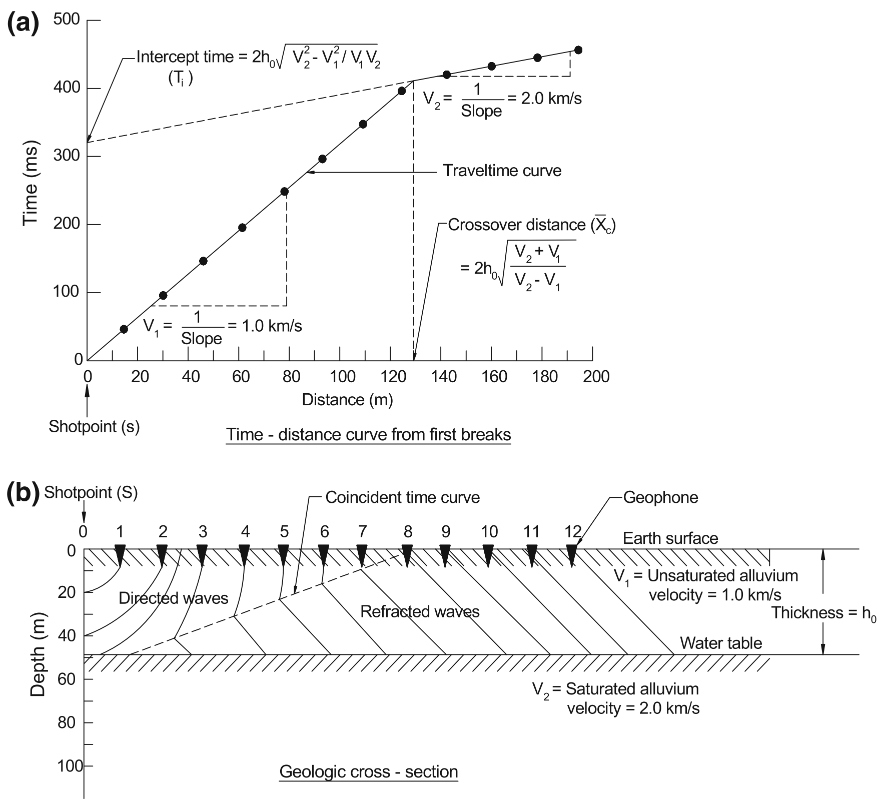


Fig. 4.21 Diagrammatic geologic cross section and resulting time–distance curve

shots are lowered to the bottom. The hydrophone cable supported by the buoys floats on the water surface. The hydrophones are connected to the takeouts on the hydrophone cable by separate cables. The shots are placed between the hydrophones in the same pattern as for the land measurements.

Many types of seismic sources are available for refraction seismograph (Beggs and Garriot 1979; Mooncy 1981). Despite disadvantage of storage and handling, explosives are ideally suited as seismic source for refraction survey also. No other sources can possibly provide such an immense energy under all field conditions. An alternative is either a mechanical or electrical source for the majority of the fieldwork and selective use of explosives are generally needed for (1) deep refraction studies, requiring very long geophone lines to delineate a deeper refractor at 60 m or greater, and (2) thick unsaturated section, especially in loose materials (unsaturated material thicker than 10–12 m).

In shallow refraction surveys for engineering purpose and groundwater prospecting, it is advisable to use the continuous in-line profiling measuring technique wherein a long linear spread of many geophone groups is shot from each end with reverse recording in order to get a sufficient amount of data for reliable analysis. Usually, it is not practical to record simultaneously many geophone groups spread over a long distance, and hence, refraction profiles are usually shot in segments. The geophone distances are to be kept very short to obtain sufficient number of arrival times from the various velocity layers.

In the broadside refraction shooting, shot points and spreads are located along two parallel lines selected so that the desired refraction event can be mapped with a minimum interference from other events. However, usually the criteria for identifying the refraction event are based on in-line measurements and these criteria are not available on broadside records where the offset distance is essentially constant. Thus, if the refractor unexpectedly changes its depth or if another refraction arrival comes, one might end up mapping the wrong horizon. Consequently, broadside refraction shooting is often combined with occasional in-line profiles in order to have a check on the identification of the horizon being mapped.

Besides, depending on the execution of proper seismic work and the geological conditions, the reliability of the seismic results also depends on the positioning of the profiles. For groundwater prospecting in hard bedrock, the profiles are placed normal to the assumed direction of the main structural features. If the structure is unknown, profiles in various directions have to be utilized to detect possible faulted zones, fracture zones or other paths for water. If a promising low-velocity zone is encountered, its direction and extent are traced by additional profiles in order to locate the water.

4.12.3 Corrections to a Datum

During the field operation, seismograph records and tapes are obtained that record the shot break and the arrival times of waves at all geophones. Only the first arrival of energy at the geophone due to compressional wave is utilized. Upon completion of the data acquisition, refraction times must be corrected for elevation and for changes in the thickness of the weathered layer. The former correction removes differences in travel times due to variations in the surface elevation of the shot and detector stations. The weathering correction removes the differences in travel time through the near-surface zone of unconsolidated, low-speed sediments, which may vary in thickness from place to place.

Application of elevation and weathering corrections is routinely recommended for deeper targets. For shallow refraction surveys, difficulties arise in such corrections. In most of the cases, the target is the base of the weathered surface itself. Also the elevation changes are commonly many times larger than the target depth, particularly in geotechnical applications thereby making the selection of datum very difficult. The use of the ground surface as reference is equivalent to using a floating datum. In general, all the interpretation methods which employ migration require correction to a datum. The effect of the low-velocity-weathered layer should be removed from travel time data to be used to define deep refractors. By using the expressions given in Nath et al. (2000), all the first arrival time values are reduced to a floating datum and then passed onto the interpretation phase.

4.12.4 Interpretation of Refraction Data

In seismic refraction survey, only the first arrival of energy at the geophones is utilized. Upon completion of data acquisition in the field and subsequent static removal in the form of weathering and elevation corrections, the interpretation is done.

Since seismic refraction techniques have been used for a pretty long time, many graphical and analytical interpretation schemes have been developed. Mention should be made of some of the well-known methods, namely Wyrobek-Gardner method (Wyrobek 1956), detailing the gently dipping refracting surface up to a dip of 10° using the concept of delay times, Slotnick method (Slotnick 1950) of graphical reconstruction, wavefront method by Thornburgh (1930), plus-minus method (Hagedoorn 1959), Barrys' delay time method (Barry 1967), Mean-minus-*T* method of depth estimation (Parasnis 1984), Tarant's method of irregular subsurface marker delineation (Tarant 1956), migration technique of Hale's method of depth estimation (Hales 1959), generalized reciprocal method (Palmer 1980, 1981, 1986; Chakraborty et al. 1991) and ray inversion technique (Jones and Jovanovich 1985; Nath et al. 1996). The various interpretation methods are summarized by Telford et al. (1976) and Dobrin and Savit (1988). Formulae, nomograph and even computer codes, are available for most of the field problems. Each of these techniques has its strong points and when properly selected and intelligently applied, they usually give satisfactory results. Some interpretation methods, which are more versatile and widely used, namely wavefront method, GRM (generalized reciprocal method), and ray inversion technique, are presented in greater detail by Nath et al. (2000) and therefore are not included in this book.

A graphical technique was developed by Slontick (1950) for interpreting seismic refraction data so that successively deeper marker beds can be delineated. The method involves the optical ray tracing from the surface downwards through various layers in the subsurface and back to the detector. The depths and dips of successively deeper interfaces are determined by working downwards one layer at a time from an arrival time corresponding to wave travel along the top of that layer.

Tarant (1956) method was designed for cases where the subsurface marker is so irregular that it is difficult or impossible to select segments from the time–distance curves for the respective directions of shooting that correspond to the same part at the refractor.

Wyrobek (1956) has developed interpretation technique for two-way continuous coverage over gently dipping markers using intercept time mapping.

Barry's delay time method (Barry 1967) was developed on the basis of total delay times' plotting at respective geophone positions for both the direct and the reverse profiles and shifting the delay times by an offset in such a way that the delay times are directly above the point on the refractor from where the head wave has emerged to the receiver. The shifted segments for both the direct and the reverse profiles must be parallel, and hence, the average offset delay time is calculated. Joining all the plotted delays yields the refractor in time domain. It is then converted into the depth section by a suitable depth conversion factor and the receiver delay time.

ABEM Geophysical Company of Sweden also introduced a modification in the interpretation of refraction method known as ABEM correction method (Sjogren 1984).

ABC method of interpretation is perhaps one of the simplest methods applied to civil engineering problems (Mooney 1981). This method determines the depth of refractor below as receiving point, which has recorded head wave from two shot points placed on either side of it.

Thus, classical exploration refraction seismology has found tremendous applicability in the search for resources and geotechnical investigations. This can also be effectively used in groundwater investigations and modelling studies. Since in most of the cases groundwater aquifers have large seismic velocity contrasts at major hydrologic boundaries, seismic refraction technique can define the geometry of the aquifer. It has also proved to be a valuable and economical method of obtaining input data for modelling, designing drilling programmes and improving modelling results.

In keeping with most geophysical methods, refraction technique has also emphasized vertical resolution. For target depths up to about 10–15 m, the conventional intercept and reciprocal methods are quite appropriate for interpreting the data. For target depth greater than 10–15 m, it is necessary to use a technique, which employs migration, such as GRM and Hales method. With the ability of the present-day digital data-processing facilities using high-speed computers having faster CPUs, enormous data storage and parallel processing environment, an integrated approach to refraction data interpretation solves a lot many ambiguities. However, the sources of error, due to (1) absence of velocity contrast between different types of material (water-saturated soil layer can have the same velocity as an underlying extremely weathered and fractured sedimentary rock layer); (2) inverse velocity relation and (3) a hidden layer, still remain to be solved.

Refraction seismic method finds application in (1) locating the groundwater table (2) determining depth to bedrock or impervious layer (3) locating a buried stream channel and (4) locating faults which may act as groundwater barrier.

In the past 10 years, the development of low-cost digital engineering seismographs and microcomputer has led to the introduction of high-resolution seismic reflection techniques to engineering and groundwater studies. Not unlike other geophysical techniques, the successful application of shallow reflection method is site dependent. When ground condition is favourable, the method can provide resolution of the bedrock topography and of the structure within the overburden. However, it finds limited application in engineering and groundwater investigations mainly due to the cost involved in carrying out the survey.

4.13 Sequential Inversion of Seismic Refraction and Geoelectric Data

4.13.1 General Consideration

Seismic and geoelectric methods often involve mapping of geological units of different grain sizes, interfaces between unconsolidated sediment and underlying bedrock, gentle to conflicting dips of the interfaces and minor to large lateral variations in the physical property of the subsurface. Inverting the recorded data sets separately may lead to incorrect parameter estimation of the underground model (Herring et al. 1995). For example, in an underground structure with a high-velocity layer overlying a low-velocity structure, neither refraction nor reflection seismic alone is capable of resolving the parameter of the low-velocity layer. The geoelectric surveys may also fail to determine the lithounits with low resistively contrast, comparatively thin conductive/resistive layer enclosed between resistive/conductive layers (problem of equivalence), a thin stratum with resistively value intermediate between the enclosing beds (problem of suppression), and a depth of an interface between a conductive layer and a resistive one because of the ambiguity of solutions based on potential methods. Vertical electrical sounding (VES) curves are appropriate when geological units are gently dipping with large lateral extent having minor variations in lithology (Sandberg 1993).

Stability and non-uniqueness problems can be sufficiently reduced by integrating physically different types of data into a single inversion procedure using joint or sequential inversion algorithms. In order to process DC resistivity and magneto-telluric data, Vozoff and Jupp (1975) introduced such a joint inversion method. They proved that some model parameters, which play insignificant roles in determining the solution of an individual inversion problem, can lead to important parameters in a joint inversion, resulting in well-resolved models. Completely different physical data can also be integrated into a joint or sequential inversion if, at least, the measured data are influenced by a subset of the underground parameters. For examples, when using seismic and geoelectrical data representing physically different responses of the near-surface structures, the layer thickness is the only parameter common to both. The boundary between two layers of different resistivities and seismic velocities may not coincide. Thus, it may occur that the number of layers derived by independent inversion of seismic and geoelectric data is not identical. However, in order to be sure that geoelectric and seismic data can be combined in a joint inversion scheme, it is assumed (Herring et al. 1995) that the layer interfaces are the same for both geoelectric and seismic properties. Brcitzkc et al. (1987) tried the parameter estimation and fault detection by sequential seismic and geoelectrical interfaces correlate with the seismic interfaces within an accuracy of 0.5 m. It is now established that the accuracy and reliability of the estimated model parameters are much better in joint/sequential inversion than an independent one. One such algorithm by combining seismic refraction and DC resistivity data is available in Nath et al. (2000).

This sequential algorithm inverts seismic refraction travel time data for the delineation of subsurface velocity and interface depths in the first instant. Following the assumption, of Herring et al. (1995), the seismic depth values are passed onto the direct dissemination of resistivity sounding curves (both Schlumberger and Wenner arrays) using Koefoed's algorithm (Koefoed 1979) for the initial geoelectric parameterization of the subsurface. Subsequently, iterative evolutionary programming is invoked for the generation of final layer parameters till a user-defined criterion is fulfilled. The basic theory for the development of the algorithm is detailed in Nath et al. (2000).

4.13.2 Sequential Inversion

In this seismic-geoelectric sequential inversion method (Nath et al. 2000), the first arrival travel time picked from refraction seismograms and apparent resistivity values for various electrode separations using Schlumberger and Wenner arrays are required as input. Seismic inversion is the initial processing step, wherein the subsurface lithostratigraphic units with seismic velocities and thickness are delineated. Resistivity curve dissemination follows if direct ID geoelectric inversion is the next objective. For 2D pseudo-sections, a number of closely spaced vertical slices simulating continuous vertical electrical soundings are selected for ID approximation of the 2D inversion. In this particular case, the centrally sliced VES curve is disseminated using seismic layer thickness for the generation of starting geoelectric model for the subsequent iterative ID inversion of the created resistivity data sets by EP. A $\pm$ 20 % perturbation is added to the initial geoelectric section to define the upper and lower bounds of the solution. This is important as EP evolves the final solution out of a randomly generated population within this preset ranges. It also takes care of any appreciable differences arising between the seismic and the geoelectric boundaries. In case the initial guess values are derived from noisy data, the prescribed perturbation enhances the possibility of getting closer to the correct solution.

The amalgamation of the above is the proposed sequential inversion package coded in Visual C++ and implemented in Microsoft Windows'95 environment. The source code of main modules is given in Appendix 4.1 (Nath et al. 2000). The supporting hardware is an Intel Pentium II processor ranging from 266 to 333 MHz with 32 MB RAM and a full-screen monitor resolution of 1024 × 768.

4.14 Other Surface Geophysical Methods for Groundwater

Electrical resistivity and seismic refraction methods have so far been detailed with reference to groundwater exploration. Other geophysical methods which directly or indirectly can indicate the presence of porous and permeable zones are briefly outlined in the following section.

4.14.1 Electromagnetic Methods

It is well known that direct current geoelectric sounding has a restricted application in resistive formations, e.g. in crystalline rocks, in loose dry sand and in limestone areas. Here, aquifer porosity is secondary in nature due largely to joints, fissures, crevices and caves. In crystalline rocks (granite, gneiss and schist, for example), groundwater of limited quantity is also found within the weathering zone and its base. In order to locate comparatively conducting water-bearing zones within resistive formations, electromagnetic methods are most useful.

For the success of electromagnetic methods, a preliminary selection of suitable targets in hard rocks is done through remote sensing. This leads to location of lineaments visible on satellite imaginary as weak zones for groundwater storage. Resistivity profiling data may supplement by indicating low-resistivity zones as fractured ones in granite, gneiss and schist.

Horizontal loop electromagnetic (HLEM) and very low frequency (VLF) methods mentioned in Sect. 4.2.2 use time-varying electromagnetic fields. Under certain conditions, the apparent resistivity of the earth can be calculated from measured electric or magnetic field.

The HLEM/VLEM resistivity instrument, EM34 of Geonics (USA), for example, consists of two portable coils: (i) a transmitter (T) and (ii) a receiver (R). The ratio of secondary and primary magnetic fields may be measured and apparent resistivity calculated. Exploration depth depends on T–R spacing, frequency and the orientation of the coils.

The VLF radio wave resistivity instrument, EM 16 of Geonics, for example, uses low frequency radio waves (15–25 kHz) from the existing transmitters. Receiver measures the ratio and the phase angle between the horizontal electric and the magnetic fields. When the instrument is well oriented with respect to the VLF radio station, the apparent resistivity of the ground can be derived from the ratio between the horizontal electric field in the direction of radio station and the horizontal magnetic field perpendicular to it. The exploration depth of VLF is comparable to the skin depth. For a fixed radio station with appropriate frequency, the skin depth depends only on earth resistivity. For EM 16 at a frequency of 20 kHz, the likely exploration depths are approximately 12, 25, 35 and 80 m, respectively, for earth resistivities 10, 50, 100 and 500 Ω m.

A case study given in Nath et al. (2000) shows that the subsurface lithology can be well inferred from HLEM and VLF data in hard rocks. A combination of HLEM, VLF and resistivity profiling together with remote sensing data can delineate the target (in hard rock areas) when geology of the area is judiciously correlated with geophysical data.

4.14.2 Time Domain (Transient) Electromagnetic Method

DC resistivity techniques have been applied for many years for various geotechnical applications. Electromagnetic techniques, recently, have been used with different advantages and (disadvantages) to measure resistivity (or its reciprocal, the conductivity) of the earth materials for delineating aquifer zones in a conductive surrounding and to detect the saline groundwater zones.

4.14.2.1 Principle

Electromagnetic survey is mainly based on two wire loops, one radiates electromagnetic waves and other receives the waves through ground. Electromagnetic technique can be divided into two groups, one frequency domain EM and another time domain or transient EM survey. In frequency domain instrumentation (FDEM), the transmitter current varies sinusoidally with time at a fixed frequency that is selected on the basis of the desired depth of exploration of the measurement (high frequencies result in shallower depths). In most time domain (TDEM) instrumentation, on the other hand, the transmitter current, although still periodic, is a modified symmetrical square wave, as shown in Fig. 4.22.

This constant current is passing through the transmitter loop and produces a primary magnetic field in the ground. A typical TDEM resistivity sounding survey configuration is shown in Fig. 4.23, where it is seen that the transmitter is connected to a square (usually single turn) loop of wire laid on the ground.

When this transmitter current is abruptly reduces to zero for one-quarter period, whereupon, it flows in the opposite direction. The process of abruptly reducing the

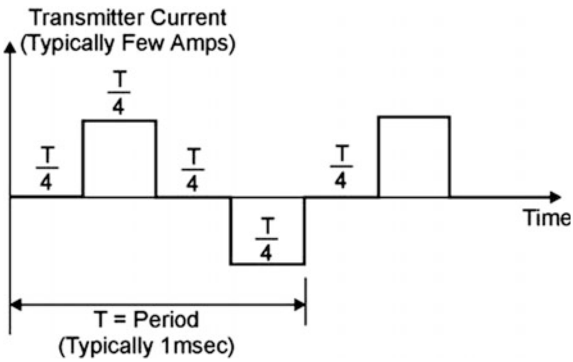


Fig. 4.22 Transmitter current wave form

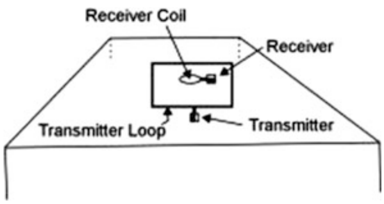


Fig. 4.23 Central loop sounding configuration

transmitter current to zero induces, in accord with Faraday's law, a short-duration voltage pulse in the ground, which causes a loop of current to flow in the immediate vicinity of the transmitter wire as shown in Fig. 4.23. In fact, the constant current through transmitter loop produces a primary magnetic field. Immediately after transmitter current is turned off, the current loop can be thought of as an image in the ground of the transmitter loop and produces a secondary magnetic field. However, because of finite ground resistivity, the amplitude of the current starts to decay immediately. During the rapid decay of current, the change in amplitude of the secondary magnetic field with time induces a voltage pulse that causes more current to flow, but now at a larger distance from the transmitter loop, and also at greater depth, as shown in Fig. 4.24. Due to this decay of current, an electromotive force results in the eddy currents whose strength is largest in conductive parts of the

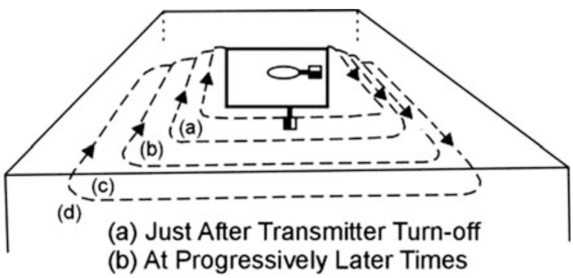


Fig. 4.24 Transient current flow in the ground

ground. This electromagnetic induction phenomenon generates what is called the secondary magnetic field which is measured just after the end of the turn-off using an induction coil as receiver, placed at the centre in Figs. 4.22 and 4.23. The deeper current flow also decays due to finite resistivity of the ground, inducing even deeper current flow and so on. The amplitude of the current flow as a function of time is measured by measuring its decaying magnetic using a small multiturn receiver coil. It is evident that, by making measurement of the voltage out of the receiver coil at successively later times, measurement is made of the current flow and thus also of the electrical resistivity of the earth at successively greater depths.

It may be explained in the way that the response normalized by the primary field is measured at selected time intervals after switching off the primary field. Because response depends on the resistivity of the ground, measurements can yield geo-electrical characteristics of the ground. Immediately after switching off, i.e. at early stage, induced current is concentrated near the surface of the earth. Since the maximum amplitude of induced current diffuses downward and outward, deeper geoelctrical information can be obtained as the time increases.

The transient field decays very fast. The shape of transient curve (voltage decay vs. square root of time or apparent resistivity vs. square root of time) does not represent depth-wise variations as it could be assessed from conventional DC apparent resistivity curve. Actually, the depth of exploration is a function of time and does not depend on transmitter–receiver separation or transmitter frequency.

4.14.2.2 Equipment

Transient electromagnetic system comprises a receiver and a transmitter loop unit. Transmitter loops of different sizes are used for exploring different depth ranges. Generally, the side length of the loop is approximately equal to the desired depth of exploration, except that for the shallow depths (less than 40 m); the length can be as small as 5–10 m in relatively resistive ground. The length of the square-loop transmitter is kept about 2/3rd of the exploration depth. The loop could be of 30 m × 30 m to 500 m × 500 to explore shallow zones to as deep as 2500 m. For better resolution, at early time a small loop size is desired. TEM instrument uses constant current waveform in the range of 3–300 Hz consisting of equal periods of time-on and time-off. A variety of TEM equipment is available with stacking facility. The TEM measurements are made in a time range of 6 μs to 1 s after switching off. The latest measurement time is determined by level of noise. For shallow groundwater exploration measurement up to 10–30 ms is done. Equipment effective up to 1000 m exploration depth is available. In HeliTEM/SkyTEM system, the transmitter and receiver coils are hanging at a certain distance from the helicopter with a desirable height from ground surface to avoid obstacles due to manmade structures, HT lines, etc., for smooth acquisition of data.

4.14.2.3 Procedure

The technique can be employed for sounding as well as profiling. For profiling, moving transmitter–receiver configuration is used. Three types of transmitter–receiver configurations are employed in TEM soundings, viz., grounded line, central loop and loop–loop configurations. The grounded line configuration is used for deep soundings, while central loop and loop–loop configurations are used in shallow applications. The dimension of the transmitter loop in central loop configuration depends on the depth to be explored and is selected based on field testing. A peak current of 2 A could be sent through the loop 30 m × 30 m for shallow exploration. Higher amperage (20 A) and large loop used for deeper exploration. The measurements can start at 6 μs after switching off and shallow zones can be investigated. The latest time could be up to 10–30 ms depending on the level of noise. The minimum detectable signal ranges from 10^{-6} to 10^{-12} V/A m^2. The data can be collected at two base frequencies. Measurement gates can be kept logarithmically spaced with about 10 gates per decade of time. A group of four to six persons are required.

4.14.2.4 Processing and Interpretation

Processing includes time versus voltage decay data are converted to time versus apparent resistivity data. Induced voltage decay curve does not present direct picture of the subsurface geoelectrical condition as in the case of electrical resistivity. Data are normalized for transmitter and receiver parameters and converted to apparent resistivity. Apparent resistivity versus square root of time is plotted on double-log graph paper. Curves are interpreted either by curve matching or by software packages for inversion and forward modelling. Problem of equivalence exists in this technique also.

4.14.2.5 Advantages

(a) Data scattering is not observed in central loop sounding as in the case of electrical resistivity sounding.
(b) It is least affected by lateral variations in resistivity as the induced current flows in rings around the receiver and also transmitter loop size is not changed frequently.
(c) Resolution is high in shallow central loop soundings. It has better resolving capability for (h/ρ) equivalence in comparison with DC resistivity technique and can be used with other techniques to remove ambiguity.
(d) As compared to electrical resistivity sounding, smaller area/smaller loop size is required for survey to achieve same order of depth. Thus, it can be conducted easily in urban areas.

(e) To probe deeper, transients at later times are recorded.
(f) It is highly sensitive to conductive layers than the resistive layer.

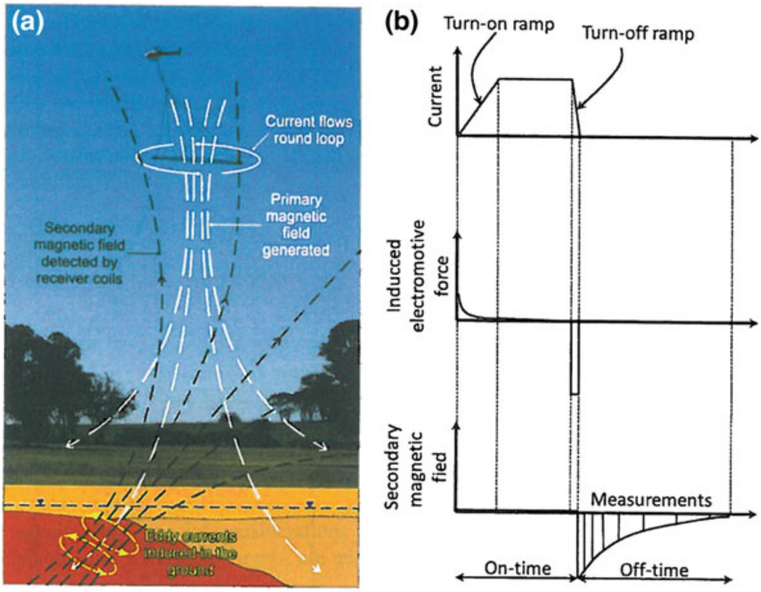
4.14.2.6 Disadvantages

(a) TEM equipment is quite expensive.
(b) Practically, to overcome noise, transmitter loop size has to be increased to investigate deeper targets.
(c) A good estimate of first and the last layer may not be possible, due to equipment constraints. To get information for near-surface layer, very early stage time data are required.
(d) Target of limited lateral extents may not give a good match in the inversion.
(e) Resistive freshwater aquifer underlying thick clay overburden may not get detected accurately.
(f) Also, if the first layer is quite thick and resistive, the deeper relatively conductive layer may not get detected.

4.14.3 Airborne Electromagnetic Method

Airborne electromagnetic (AEM) methods offer the possibility of covering large areas of several hundreds of sq km in a short time and provide information about ground resistivities to depths of several hundred metres. As the principle is same, the AEM method is also two types, i.e. helicopter-borne frequency domain electromagnetic (HFEM) and helicopter-borne time domain or transient EM (HTEM) system. Here, we will discuss only the HTEM as they provide good depth and lateral resolution compared to fixed-wing EM and HFEM systems (Fig. 4.25).

Fig. 4.25 HeliTEM survey operation with transmitter and receivers



Transient AEM principles

Current and magnetic field during an AEM sounding

Fig. 4.26 Transient airborne electromagnetic concept: **a** current and electromagnetic field generated during the acquisition; **b** the corresponding curves of the current and measured electromagnetic field. The different steps of a transient AEM sounding are: (*1*) A primary magnetic field is generated by the transmitter loop (figure after T. Munday, CSIRO); (*2*) the current is turned off, which causes generation of eddy currents in the ground; (*3*) the response from the eddy currents is measured by the receiver coil; (*4*) the measured secondary field is further interpreted to get the resistivity distribution of the ground

The development of AEM was driven by exploration for minerals with its needs for surveying large areas at a reasonable cost. The first attempts with airborne time domain/transient EM (TEM) systems in the 1950s were quite successful for base metal exploration in Canada. In the year 1980s, the use of AEM method turned from anomaly detection to conductivity mapping. In the early 2000s, development of HTEM systems took off and since then they have been the focus of most new developments. With the most recent technical developments, HTEM systems are now the most flexible systems since they provide not only good depth of investigation, but also near-surface lateral/vertical resolution competitive with the one from HFEM systems (Fig. 4.26).

Just after transmitter loop is shut off, the eddy currents in the ground will be close to the surface, and the measured signal primarily reflects the resistivity of the top layers. At later times, the current will run deeper in the ground, and the measured signal contains information about the resistivity of the deeper layers. This electromagnetic induction phenomenon generates what is called the secondary magnetic field which is measured just after the end of the turn-off using an

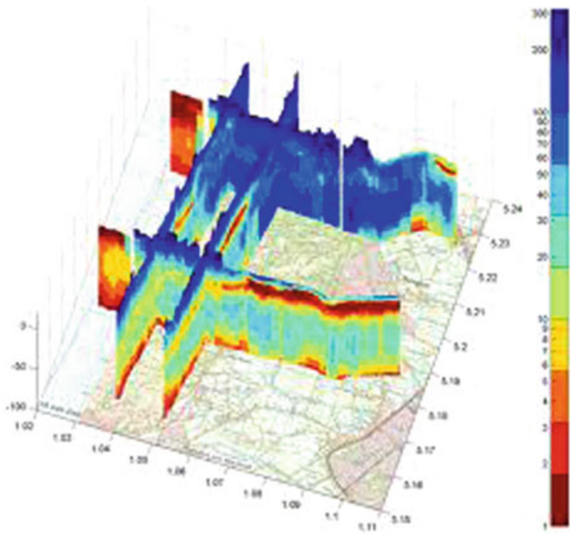


Fig. 4.27 SkyTEM sections where *blue colour* shows the higher conductivity/lower resistivity

induction coil as receiver. Actual measurement is the time derivative of the magnetic flux passing through the receiver coil which is induced electromotive force in the receiver coil and this gives the information about the resistivity can be calculated from the expression (Ward and Hohmann 1988).

The increase of the altitude induces decreases of the measured secondary field. This lowering is much more pronounced at the early times, and the responses from different attitudes become closer and closer at later times. It is calculated the optimum flight height for good result in open field is 30 m. A too high flight altitude generally results in more noisy data because of the decrease in signal level with altitude and also the resolution of the layers decreases (Fig. 4.27).

4.14.4 Electrical Resistivity Tomography

2D resistivity tomography technique is the latest state of the art available to map the complex geological features. The greatest limitation of the resistivity sounding method is that it does not take into account horizontal changes in the subsurface resistivity. A more accurate model of the subsurface is a two-dimensional (2D) model, where the resistivity changes in the vertical direction, as well as in the horizontal direction along the survey line. In this case, it is assumed that resistivity does not change in the direction that is perpendicular to the survey line. In many situations, particularly for surveys over elongated geological bodies, this is a reasonable assumption. In theory, a 3D resistivity survey and interpretation model should be even more accurate. However, 2D resistivity survey is one of the most practical and economic compromises between obtaining very accurate results and keeping the survey costs down. Typical 1D resistivity sounding usually involves about 10–20 readings, while 2D imaging surveys involve about few 100–1000 measurements. In many geological situations, 2D electrical tomography surveys give useful results that are complementary to the information obtained by other geophysical method.

4.14.4.1 Principle

Resistivity changes in the vertical and horizontal direction along survey line in the area of complex geology. Hence to map continuous change, modification over the VES (in survey and interpretation technique) was required. Therefore, unlike four electrodes system in VES, number of electrode was increased to 24, 48, 64, 96, 120 or more. These electrodes are connected with the multicore cable which is attached with automatic switching unit. The whole system is governed by computerized software fitted within the instrument. When the machine is made on the different four numbers of electrodes are selected, apparent resistivities are calculated automatically in the straight line. The measuring unit includes relays, which automatically carries out the sequence of readings introduced in its internal memory. The system takes readings for many combinations of transmission and reception pairs so as to achieve a mixed profiling and sounding pairs. Continuously different sets of apparent resistivities are calculated and stored in the unit. The total length of the cable is equal to the spacing of electrodes which determines the depth of investigations. The final depth of the investigations depends on the geometry of cables (type of array, number of electrodes, and spacing between electrodes and number of segments) and the measurement of signal by the equipment, namely the amplitudes of the signal, existing noise, power specifications of the equipment and its ability of filtering the noise through the stacking process. With the help of software, the computer will give a coloured simulated depth section with interpreted lithology (Fig. 4.28).

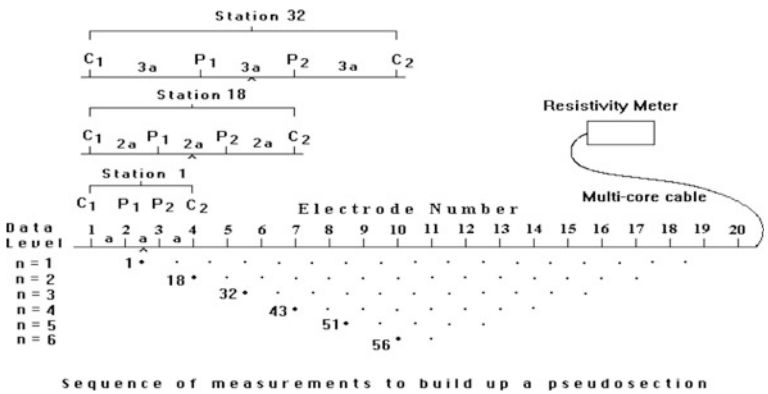


Fig. 4.28 Sequence of measurements to build up a pseudo-section using computer-controlled multielectrode survey set-up

Fig. 4.29 Multielectrode resistivity instrument from IRIS instrument, ABEM Sweeden and Advance Geosciences Inc., USA

4.14.4.2 Equipment

With the recent advancement in hardware and software, multielectrode resistivity tomography survey equipment with all accessories has been development globally by the different geophysical instrument manufacturing companies, viz., IRIS Instrument, ABEM Instrument and AGI (advance geosciences Inc. USA). For acquiring large number of data points in 2D and 3D survey, the instruments are supported with additional switch boxes and power transmitter for deeper penetration in adverse geological conditions. Equipment is available as single channel and multichannel. Multichannel equipment is faster in data acquisition compare to single-channel equipment (Fig. 4.29).

4.14.4.3 Pseudo-Section Data Plotting

To plot the data from a 2D ERT survey, the pseudo-section contouring method is normally used. In this method, the horizontal location of the point is placed at the mid-point of the set of electrodes used to make that measurement. The vertical location of the plotting point is placed at a distance, which is proportional to the separation between the electrodes. Another method is to place the vertical position of the plotting point at the median depth of investigation (Edwards 1977), or pseudo-depth, of the electrode array used. The pseudo-section plot obtained by contouring the apparent resistivity values is a convenient means to display the data. The pseudo-section gives a very approximate picture of the true subsurface resistivity distribution. However, the pseudo-section gives a distorted picture of the subsurface because the shape of the contours depends on the type of array used as well as the true subsurface resistivity. The pseudo-section is useful as a means to present the measured apparent resistivity values in a pictorial form and as an initial guide for further quantitative interpretation.

4.14.4.4 Inversion Method

All inversion methods essentially try to find model for the subsurface whose response agrees with the measured data. In the cell-based method used by the 2D RESINV programmes, the model parameters are the resistivity values of the model blocks, while the data are the measured apparent resistivity values. It is well known that for the same data set, there is a wide range of models whose calculated apparent resistivity values agree with the measured values to the same degree. Besides trying to minimize the difference between the measured and calculated apparent resistivity values, the inversion method also attempts to reduce other quantities that will produce certain desired characteristics in the resulting model. The additional constrains also help to stabilize the inversion process. The programme uses an iterative method whereby starting from an initial model, the programme tries to find an improved model whose calculated apparent resistivity values are closer to the measured values. One well-known iterative inversion method is the smoothness-constrained method that has the following mathematical form.

$$(JTJ + uF)\,d = JTg - uFr \tag{4.49}$$

where

- F a smoothing matrix
- J Jacobian matrix of partial derivatives
- r a vector containing the logarithm of the model resistivity values
- u the damping factor
- d model perturbation vector
- g the discrepancy vector

The discrepancy vector, g, contains the difference between the calculated and the measured apparent resistivity values. The magnitude of this vector is frequently given as a RMS (root-mean-squared) value. This is the quantity that the inversion method seeks to reduce in an attempt to find a better model after each iteration. The model perturbation vector, d, is the change in the model resistivity values calculated using the above equation which normally results in an "improved" model. The above equation tries to minimize a combination of two quantities, the difference between the calculated and measured apparent resistivity values as well as the roughness (i.e. the reciprocal of the model smoothness) of the model resistivity values. The damping factor, u, controls the weight given to the model smoothness in the inversion process. The larger the damping factor, the smoother will be the model but the apparent resistivity RMS error will probably be larger. The basic smoothness-constrained method as given in equation (4.49) can be modified in several ways that might give better results in some cases. The elements of the smoothing matrix F can be modified such that vertical (or horizontal) changes in the model resistivity values are emphasized in the resulting model. In the above equation, all data points are given the same weight. In some cases, especially for very noisy data with a small number of bad datum points with unusually high or low apparent resistivity values, the effect of the bad points on the inversion results can be reduced by using a data-weighting matrix. Equation (4.49) also tries to minimize the square of the spatial changes, or roughness, of the model resistivity values. This tends to produce a model with a smooth variation of resistivity values. This approach is acceptable if the actual subsurface resistivity varies in a smooth and gradational manner. In some cases, the subsurface geology consists of a number of regions that are internally almost homogeneous but with sharp boundaries between different regions. For such cases, an inversion formulation that minimizes the absolute changes in the model resistivity values can sometimes give significantly better results.

4.14.4.5 Applications

2D ERT image provides subsurface information both horizontally and vertically in continuous manner. Therefore, multielectrode resistivity tomography survey has wide application in the field of groundwater exploration, mineral exploration and in geotechnical engineering (Figs. 4.30, 4.31, 4.32 and 4.33).

- Measures bedrock and water table depth
- Detects solution features and voids
- Locates buried alluvial channels
- Identifies fractures zones and discontinuities
- Maps leach ate contamination
- Finds abandoned mineshafts and workings
- Time lapse monitoring of saline water intrusion in fresh aquifers in coastal area
- CO_2 sequestration in time lapse monitoring
- Gold exploration (both placer and massive sulphides)
- Mineral exploration

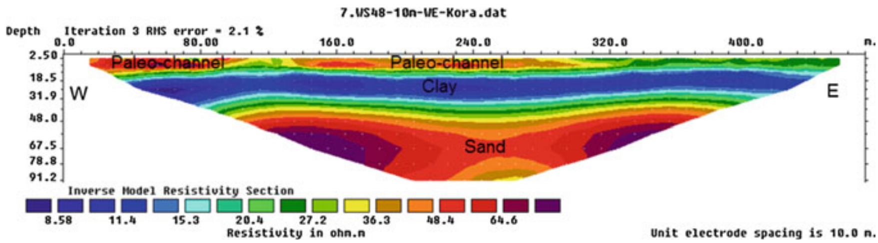


Fig. 4.30 Calculated apparent resistivity pseudo-section

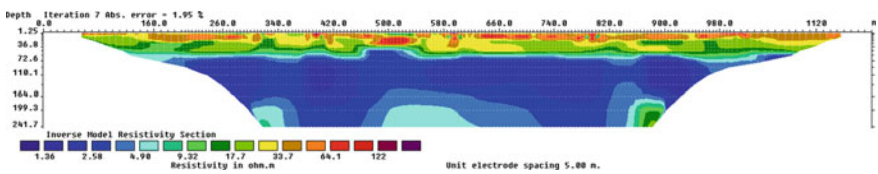


Fig. 4.31 2D ERT section showing deep saline water-saturated zone

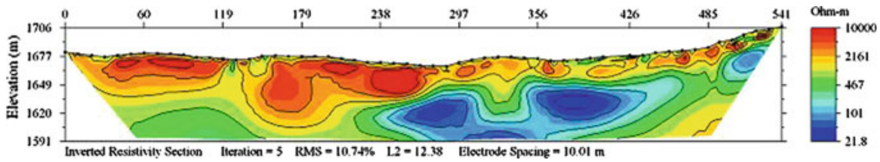


Fig. 4.32 2D ERT section to decipher the saturated zone in hilly area

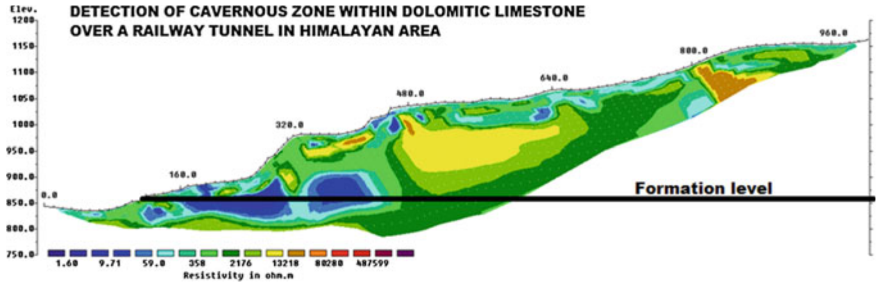


Fig. 4.33 2D ERT section to decipher the cavernous zone within dolomitic limestone over a tunnel in Himalayan area

4.14.5 Gravity and Magnetic Methods

These methods are not normally used in groundwater exploration. However, the gravity and magnetic anomaly maps prepared mainly for oil prospecting and sometimes for mineral exploration may be used as additional tools for an indirect approach for groundwater. The possibility of delineating water-saturated aquifer by gravity and magnetic methods is already mentioned in Sect. 4.2.

4.15 Some Additional Case Studies

4.15.1 Case Studies in Hard Rock Area

(A) Nawapara district (Orissa)

The resistivity surveys were carried out (Adhikari 1992) in parts of Nawapara district previously in Kalahandi district which lies within latitude 20° 40′ to 21° 00′ and longitude 82° 25′ to 82° 45′ (Fig. 4.34).

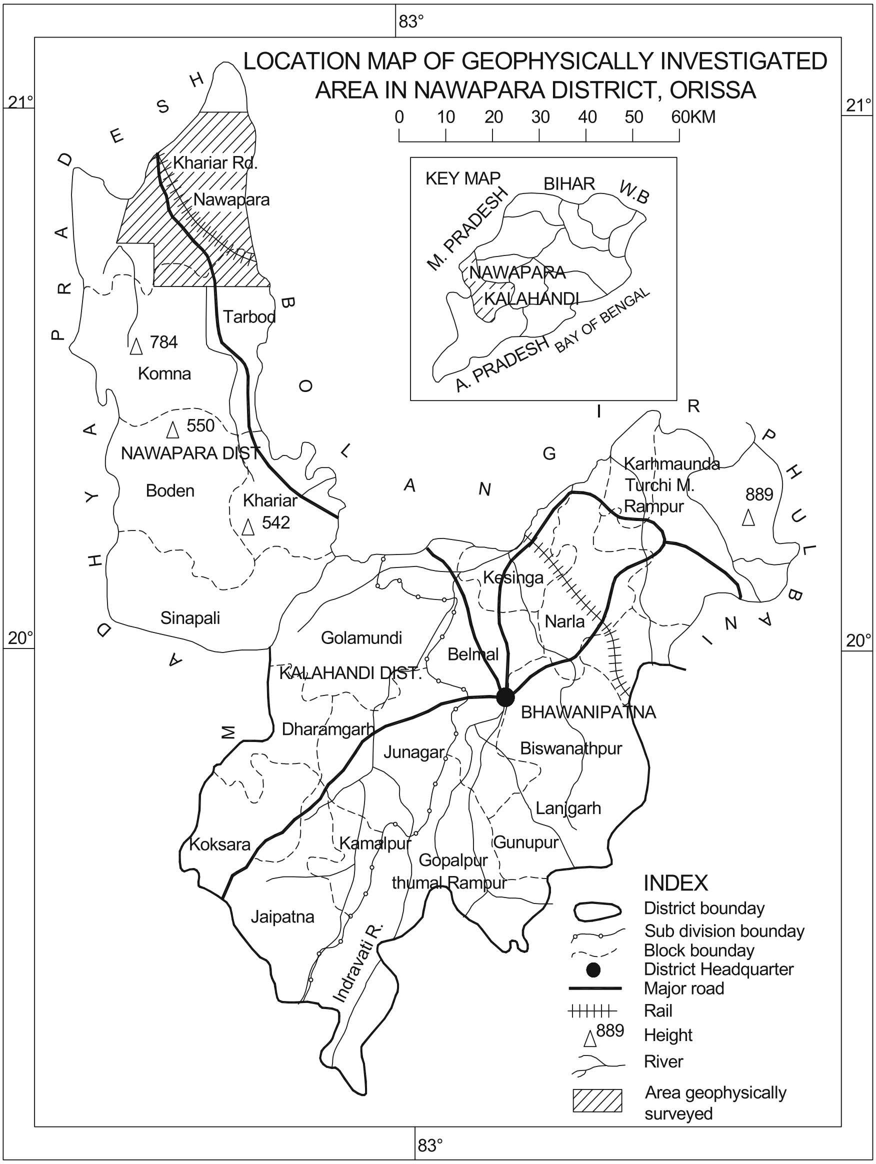


Fig. 4.34 Location Map of Nawapara district

The area is almost flat in topography barring a few exposures of the granite gneiss in the southern and south-western parts of the area.

A total of one hundred and four numbers of VES (vertical electrical sounding), three hundred and six line metres of mise-a-la-masse survey, six hundred line metre

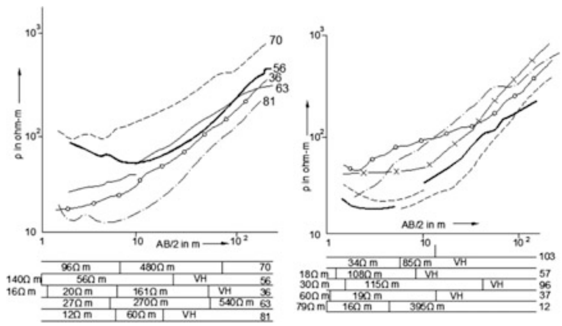


Fig. 4.35 VES curves in pars of Nawapara district

of gradient profile and two hundred and eighty line metre of dipole–dipole sounding were conducted.

Field VES data show mainly “A”-type curve in the area. A few H- and HA-type curves are also available in the area (Fig. 4.35). From VES interpreted data three-to-four layer subsurface structure is established; i.e. top surface soil of resistivity range 0–30 Ω m (dry soil) and 30–700 Ω m (wet soil) lies within the depth range 2–7 mbgl, weathered layer of resistivity range 30–150 Ω m lies within the depth range 4–52 mbgl and below this a fractured zone of resistivity range 150–700 Ω m is observed generally within the depth range 4–70 mbgl. A massive rock of resistivity range more than 700 Ω m is detected below these layers.

The mise-a-la-masse survey, gradient profiling and VES were done at Lakhna to find out the fracture orientation and depth of the fractures. It is found that the fracture is extended along 4th line of the mise-a-la-masse survey (Figs. 4.36 and 4.37). If the tube well is constructed along the fracture orientation, it must be successful.

Based on the interpreted results, the geoelectrical cross section, depth to fresh rock contour, apparent resistivity contour and fence diagram have been drawn to get a clear three-dimensional view of the underground groundwater formation (Figs. 4.38, 4.39, 4.40 and 4.41, respectively).

(B) Tiger Hill and Mirik Lake area, Darjeeling, W.B

Six numbers of VES were conducted in **Tiger Hill and Mirik Lake area, Darjeeling** district, **West Bengal** (Figs. 4.42 and 4.43).

The geological formations of the Darjeeling district consist of unconsolidated alluvial sediments of Quaternary age confined to high-level terraces and alluvial flats, unaltered sedimentary rocks restricted to the hills of the Permian and Tertiary periods. The area of investigation consists of gneissic complex of Archaean age.

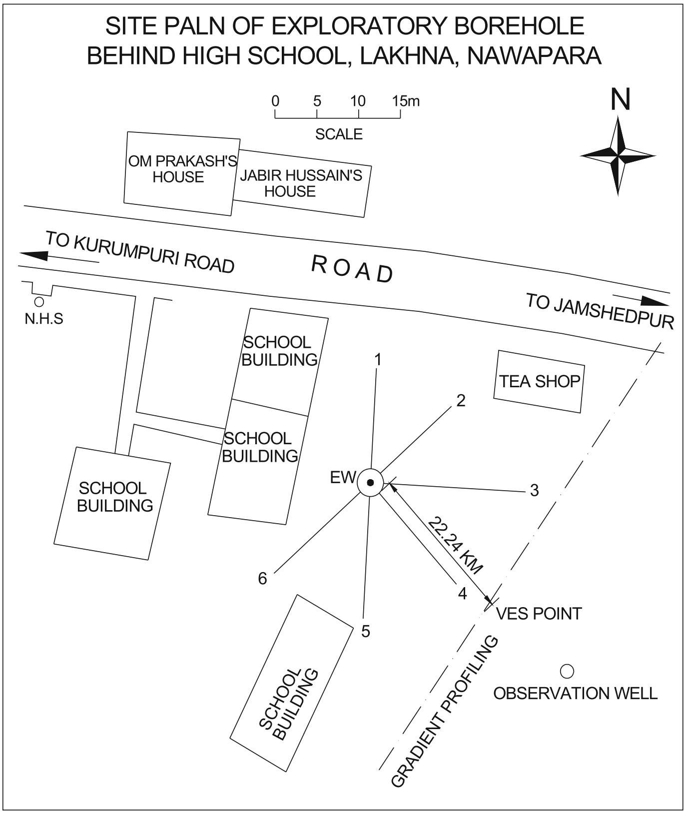


Fig. 4.36 Exploratory borehole proposed through VES survey

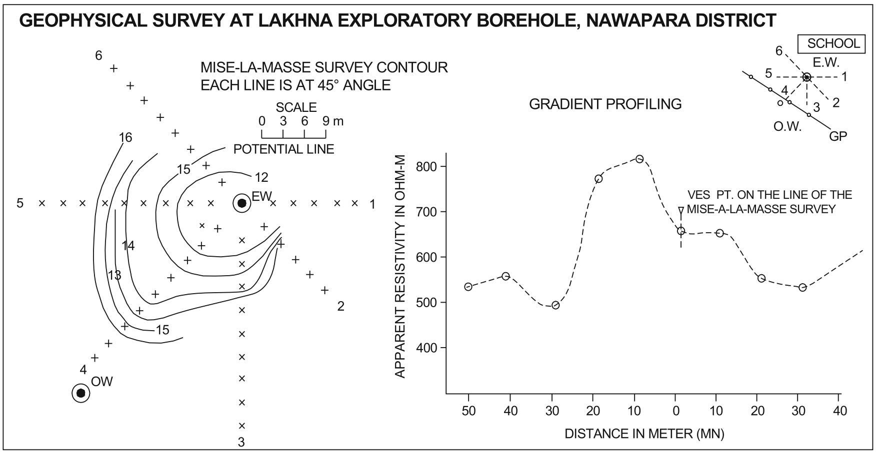


Fig. 4.37 Mise-La-Masse and gradient profile at exploratory borehole site

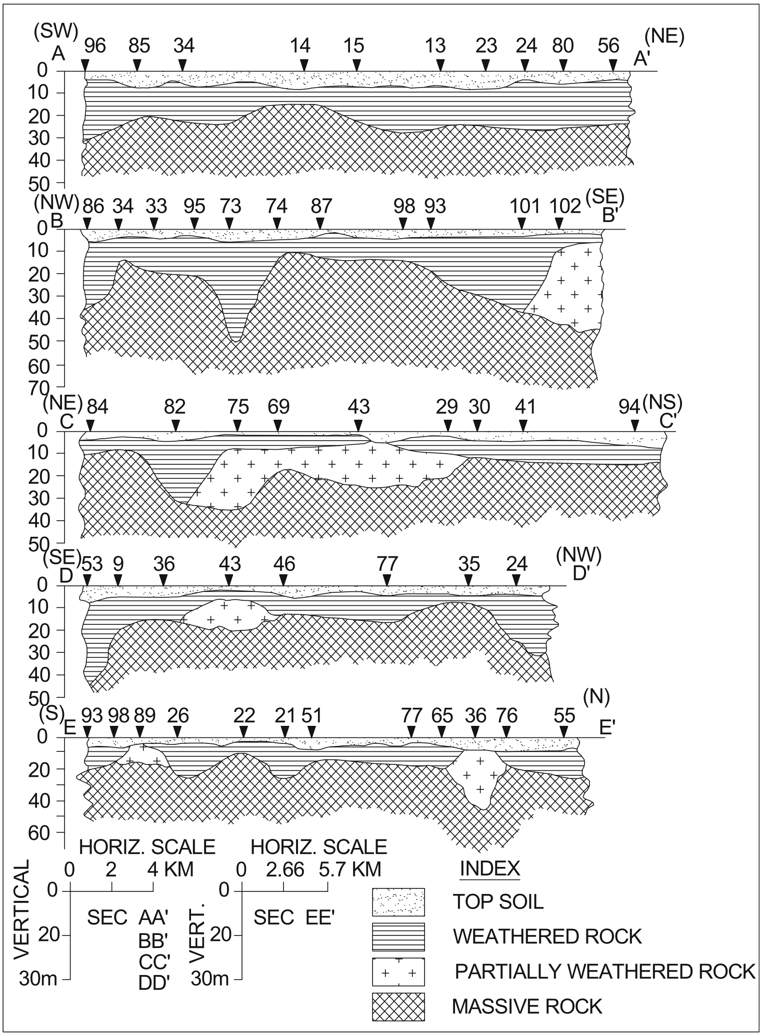


Fig. 4.38 Geoelectric sections based on VES survey in Nawapara district

The types of VES curves obtained for Tiger Hill and Mirik Lake area are HKH, KQ, KHKH and HA (Figs. 4.44 and 4.45). On the basis of interpreted results of VES curves, resistivity ranges for different formations are evaluated.

Unaltered gneissic rock shows resistivity range >2000 Ω m, weathered to semi-weathered gneiss/partially fractured formation shows 1000–2000 Ω m and

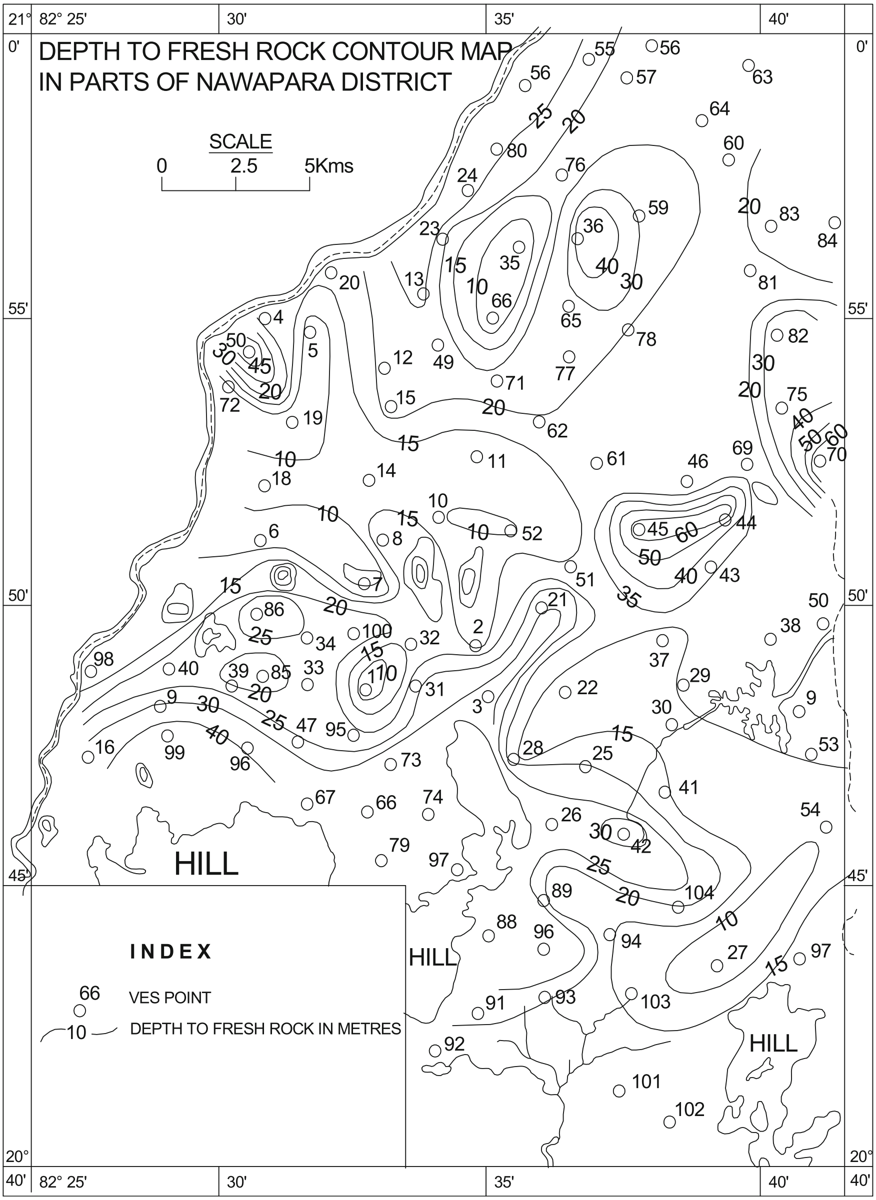


Fig. 4.39 Bedrock contour based on VES survey

highly weathered gneiss, presence of fractures, joints, etc., in the gneissic complex represent <1000 Ω m. SP and Wenner profiling were carried out in these areas to get conductive zones (Figs. 4.4 and 4.45) then VES were carried out at the lowest

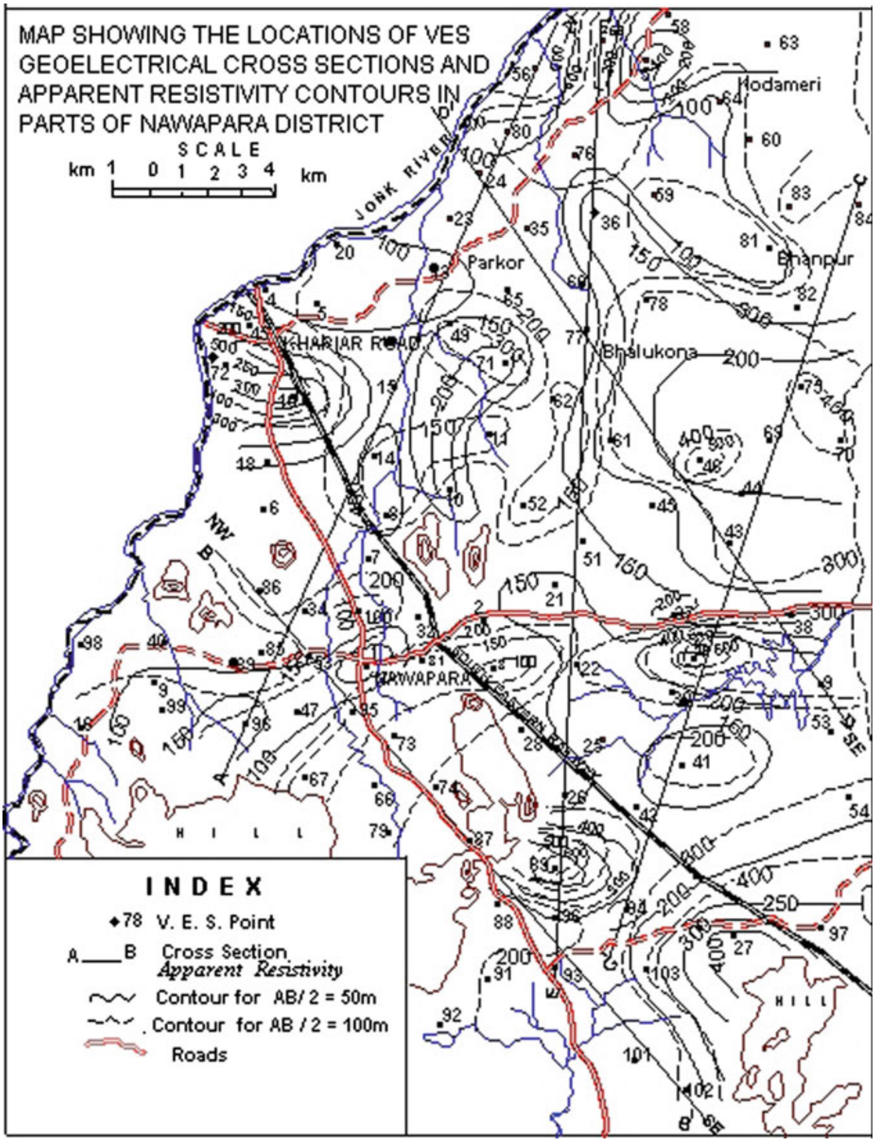


Fig. 4.40 VES location, apparent resistivity contours in Nawapara district

resistivity points, i.e. conductive zones to get the depth of the aquifers (Adhikari 2000). From the interpreted resistivity data, following recommendations are made for drilling (Table 4.3):

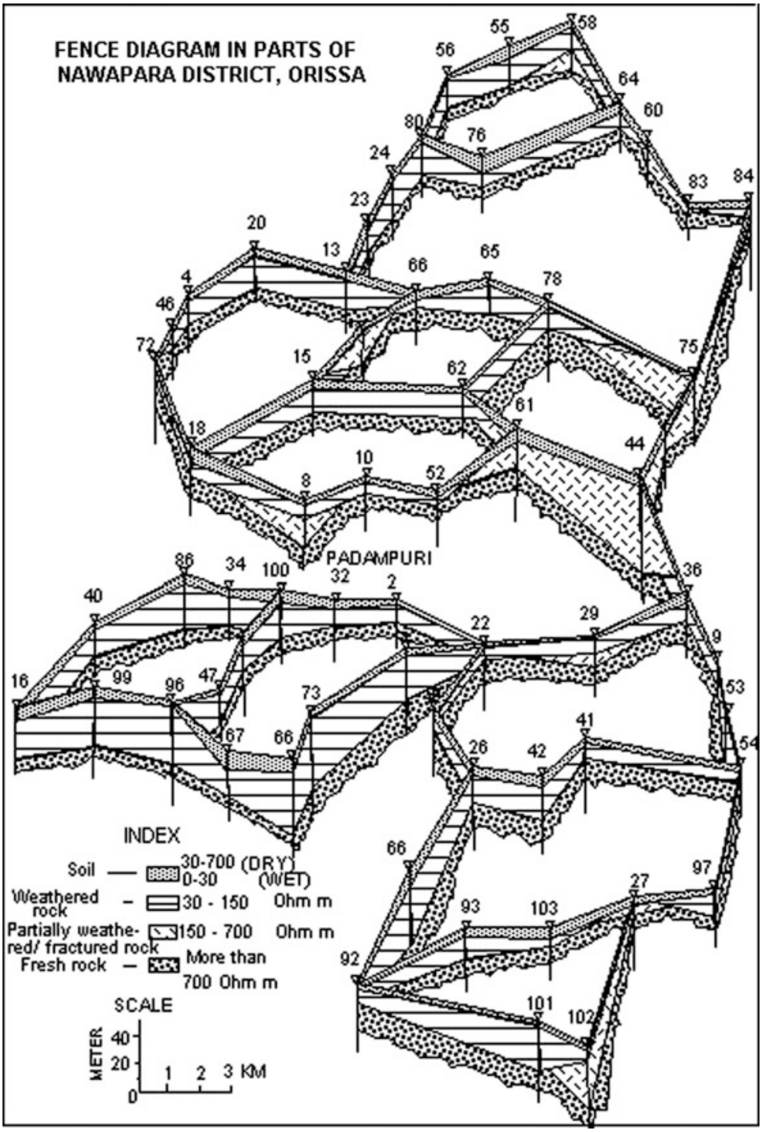


Fig. 4.41 Fence diagram based on VES sounding results in Nawapara district

4.15.2 Case Study from Alluvial Area: Ramkrishna Mission Complex, Narendrapur (West Bengal)

Total eight numbers of VES and three numbers of Wenner profiling were conducted within the Ramkrishna Mission Complex, South 24 Parganas, West Bengal (Das et al. 1999) to demarcate (i) the impervious clay horizons and its thickness so that

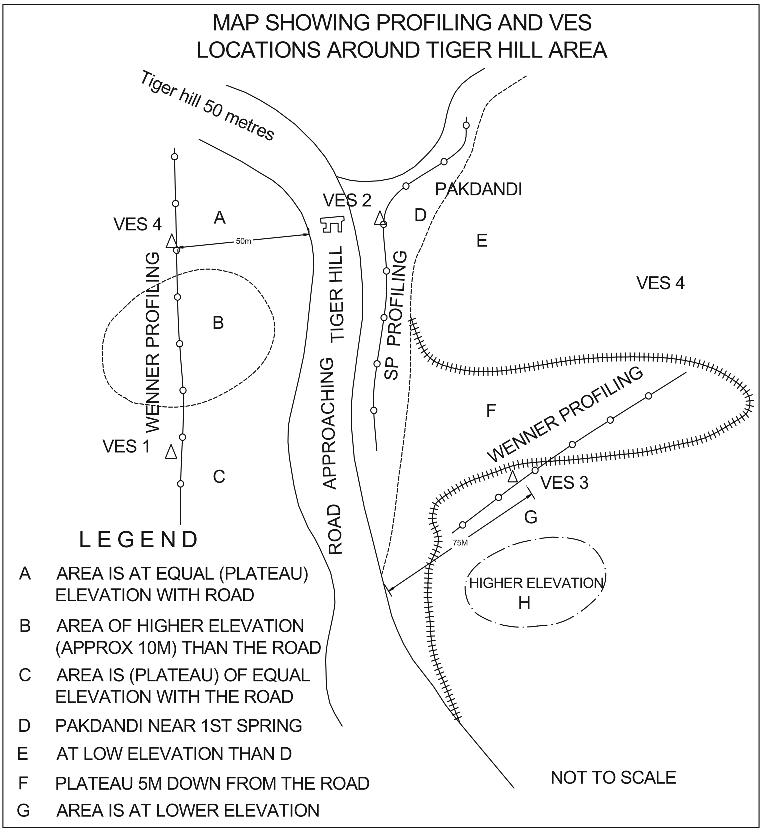


Fig. 4.42 Map showing VES location in Tiger Hill area

the seepage loss of groundwater from the aquifer may be checked and (ii) the groundwater-bearing horizons for the construction of piezometer for monitoring of water level and groundwater quality in the area.

The investigated area is covered by alluvium of quaternary age deposited by the Ganga and its tributaries. The top of the alluvium is clayey in nature. Fine sand and silty clay capping also occur in small patches in the alluvium.

The types of field curves obtained in the area are mainly KQ, KHKH, HK and KH (Fig. 4.46).

These curves are interpreted by partial curve-matching technique, standardized with the borehole lithology and established different subsurface layers as furnished below (Table 4.4):

Profiles I and III (Fig. 4.35) show the lateral change of the lithology. The depths of the lithounits are interpreted from the VES data and furnished in Fig. 4.47.

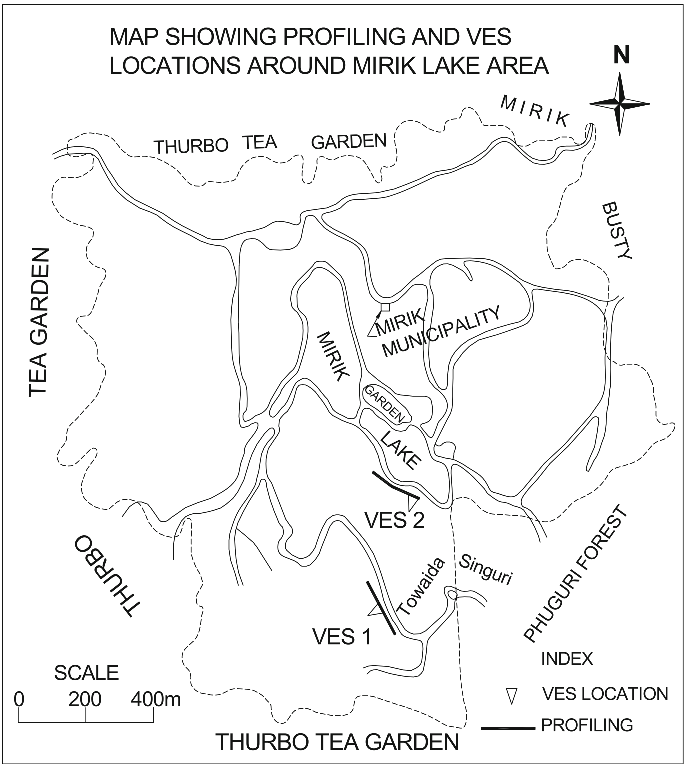


Fig. 4.43 Map showing VES location in Mirik Lake area

From the interpreted VES data, a fence diagram is drawn (Fig. 4.48). This diagram will be very much useful in locating the areas (i) for fishing project (clay layer), (ii) for groundwater withdrawal, (iii) for artificial recharge, etc.

4.15.3 *Case Studies at Island Coast Little Andaman Island After Tsunami and Earth Quake Calamities*

A total seventy-five numbers of vertical electrical sounding (VES) were carried out at different parts of the island (Figs. 4.49 and 4.52), i.e. (i) Hut Bay, (ii) Harminder Bay, (iii) Vivekanandapur, (iv) Rabindra nagar, (v) Ramkrishnapur, (vi) Netaji nagar and (viii) Dugang Creek area to find out the fresh drinking water sources as well as to assess the feasibility of groundwater exploration through drilling in the

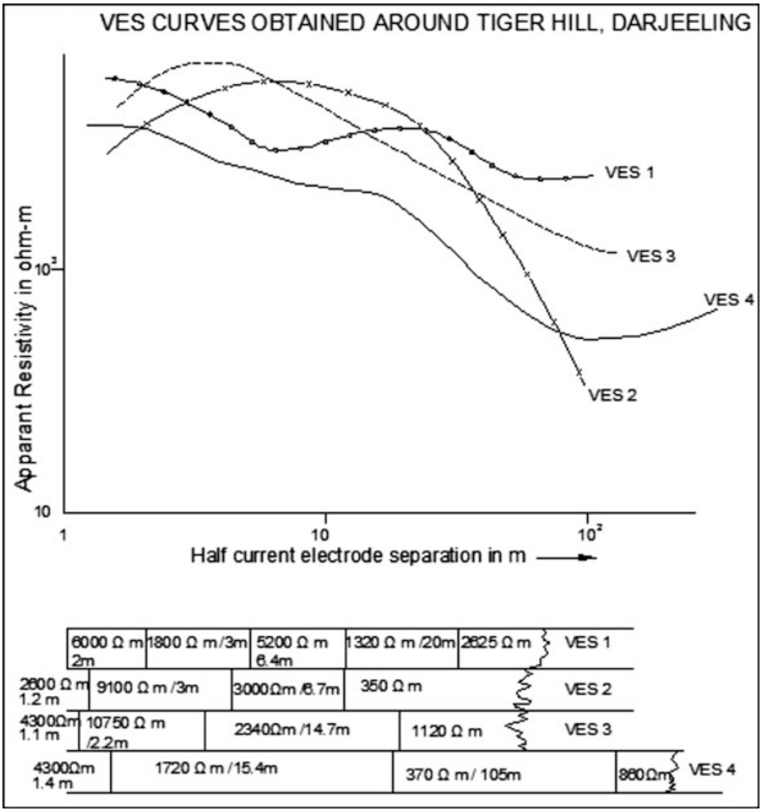


Fig. 4.44 VES curves with processed results in Tiger Hill area

areas after the effect of tsunami and earth quake in connection with relief and rehabilitation work for victims (Kar et al. 2006).

The island is underlain by extensive Miocene limestone and in the low-lying areas. Recent to subrecent coralline sands with coral rags are observed. In the core of the island at places, small ultramafic bodies were observed. The limestone bodies are highly cavernous and occasionally fractured. Coralline sands are highly friable and highly porous.

The curve types obtained in Little Andaman are K, A, Q, HA, KQ, KH and H types (Figs. 4.50 and 4.51).

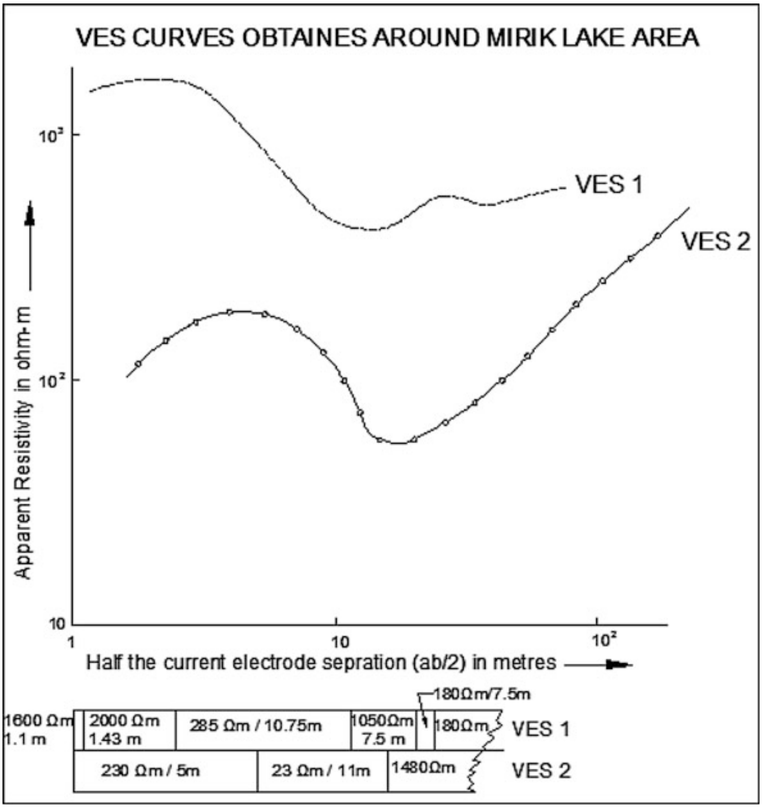


Fig. 4.45 VES curves with processed results in Mirik Lake area

Table 4.3 Exploratory drilling recommendations with proposed depth

VES No.	Area	Drilling recommendation (depths of saturated weathered/fracture formation (mbgl)
4	Tiger Hill	15–170
2	Tiger Hill	10–64
3	Tiger Hill	11–55
1	Tiger Hill	2–5 and 10–26
2	Mirik Lake area	5–22
1	Mirik Lake area	2–29

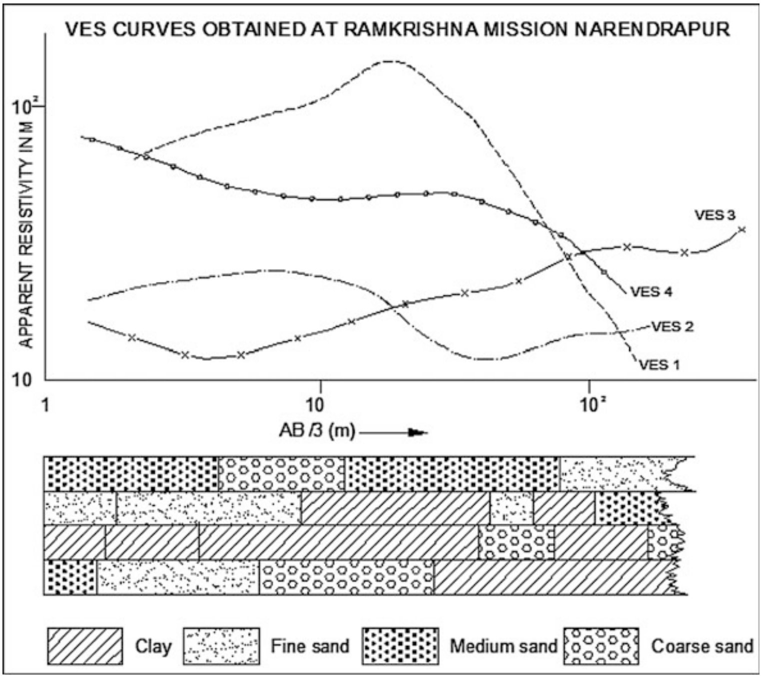


Fig. 4.46 VES curves with processed results in alluvium area

Table 4.4 Standardized resistivity for alluvium soil in Narendrapur, West Bengal

Range of resistivity (Ω m)	Interpreted lithology
<20	Top soil/clay
20–40	Fine to medium sand
40–120	Medium to coarse sand
>120	Coarse sand

The interpretation of these VES curves made with the curve matching, standardized with the available lithology, is furnished below (Table 4.5).

VES results are discussed with the help of two sections broadly in Hut Bay area (Figs. 4.50 and 4.51). In both sections, it is clearly visible that subsurface water was contaminated with the invading saline water during Tsunami due to proximity of the coast lines. On the spot, observation of the electrical conductivity of dug well and the resistivity results corroborate the same (Fig. 4.52).

The section AB (Fig. 4.53) shows that below the top soil, a resistivity range of 135–325 Ω m in the second layer indicates to have freshwater in the cavernous limestone. The depth of this layer varies from 2.6 to 17.6 mbgl. Below this pocket

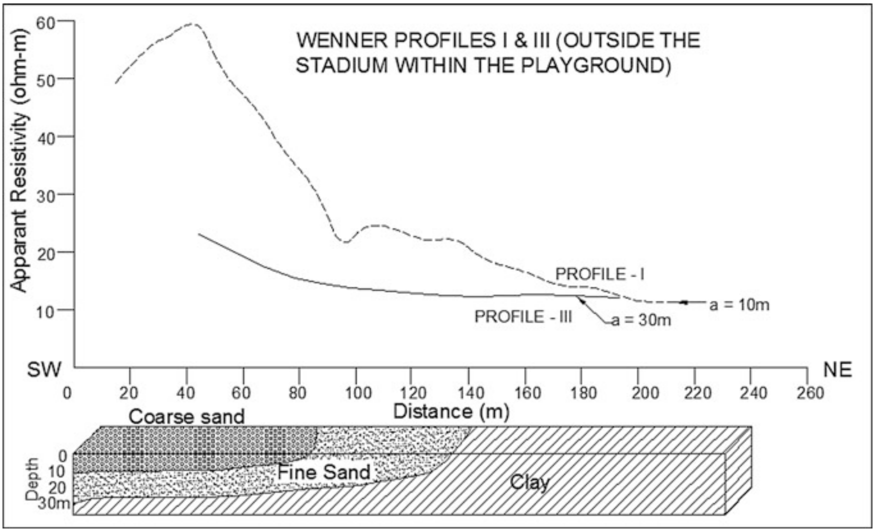


Fig. 4.47 Wenner profile with interpreted section

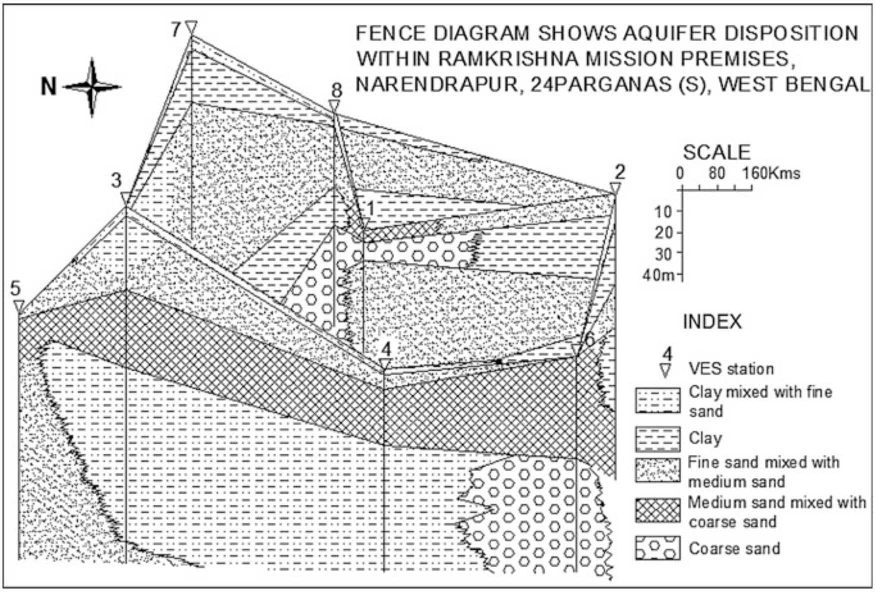


Fig. 4.48 Fence diagram based on VES survey showing disposition of aquifer in alluvium

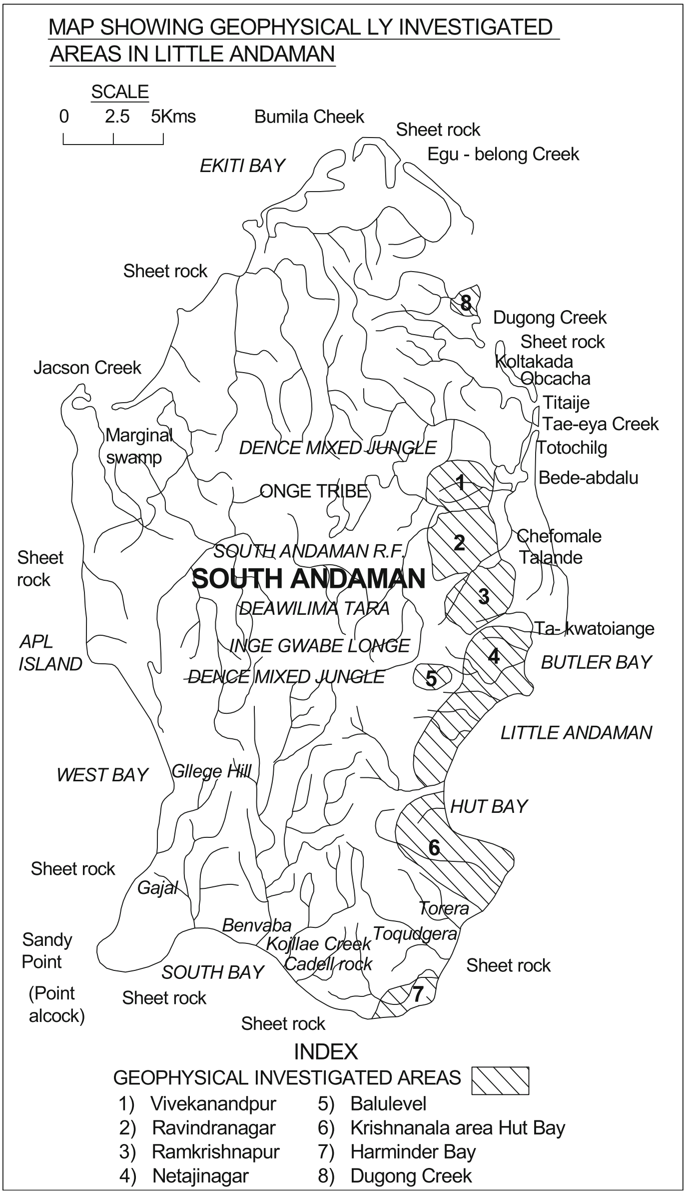


Fig. 4.49 Map showing the geophysical survey area

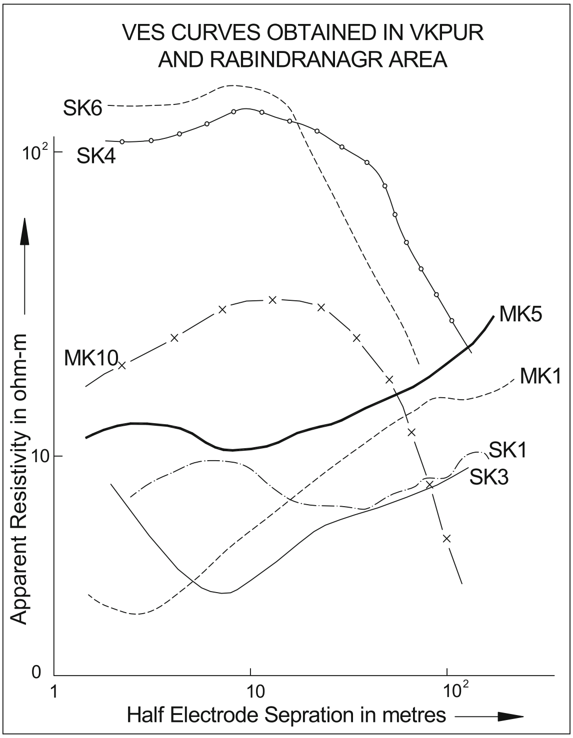


Fig. 4.50 VES curves in the eastern coast of Andaman

of fresh water aquifer, the third layer shows partly brackish (in the western part) and partly saline formation (in the eastern part) as the resistivity values show 10 and 8 Ω m, respectively. From this section, it is clear that saline water, mixed with groundwater at eastern part (close to sea and underlain by coralline sand), entered into the ground at western part (cavernous limestone). Freshwater and brackish water are floating over saline water in the western part.

In section CD (Fig. 4.54), below the top soil, a freshwater-bearing layer of 3.08 m to 6.5 m thick and 30 to 345 Ω m resistivity is available in partly cavernous limestone (in the western part) and in partly coralline sand (in the eastern part) and is floating over the brackish coralline limestone of resistivity range 11 to 18 Ω m. At VES SK16, a dry massive formation of resistivity 1250 Ω m is identified below the top soil of resistivity 1000 Ω-m. At VES SK 21, a thin layer (1.8 m) of resistivity 27 Ω m (brackish to freshwater) is floating over the brackish water layer

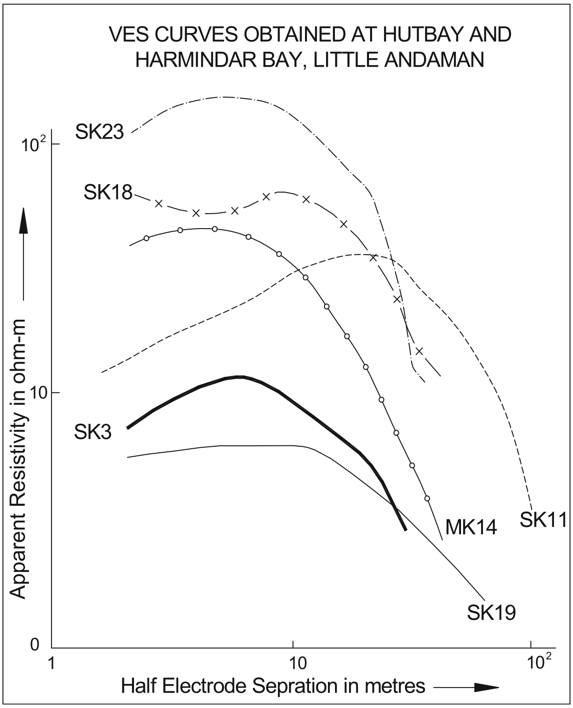


Fig. 4.51 VES curves in the eastern coast of Andaman

Table 4.5 Standardized resistivity's for different formations in Andaman

Resistivity (Ω m)	Formation
4–1250	Top soil
30–480	Freshwater in cavernous limestone/coralline sand
8–18	Brackish water in cavernous limestone/coralline sand
20–29	Brackish to freshwater in cavernous limestone/coralline sand
12–14	Highly weathered formation/clay
0–7	Saline formation water/clay
560–3075	Hard formation (dry)

of resistivity 9–12 Ω m. Below these layers, the bottom layer is of saline formation of resistivity ranging 0.8–4 Ω m. In both the sections, it is observed that middle portion is bulging; hence, the aquifer is thick at these zones.

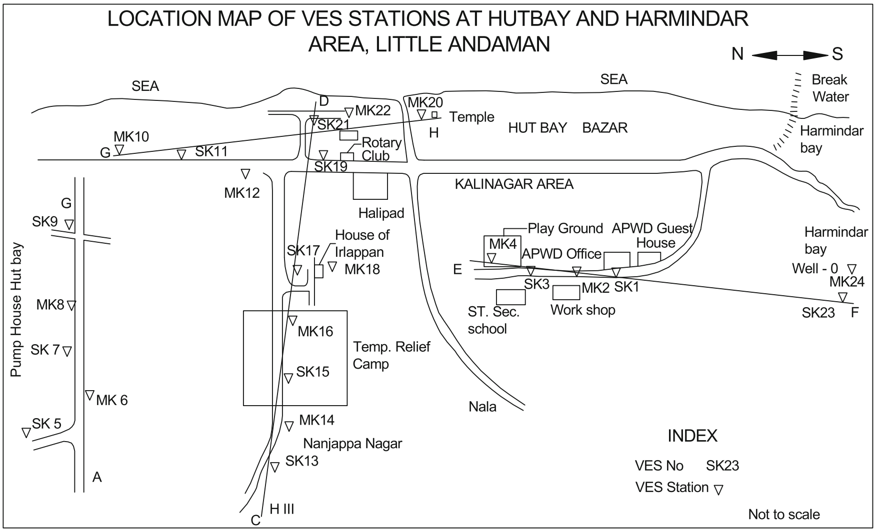


Fig. 4.52 Location plan showing VES point in Little Andaman

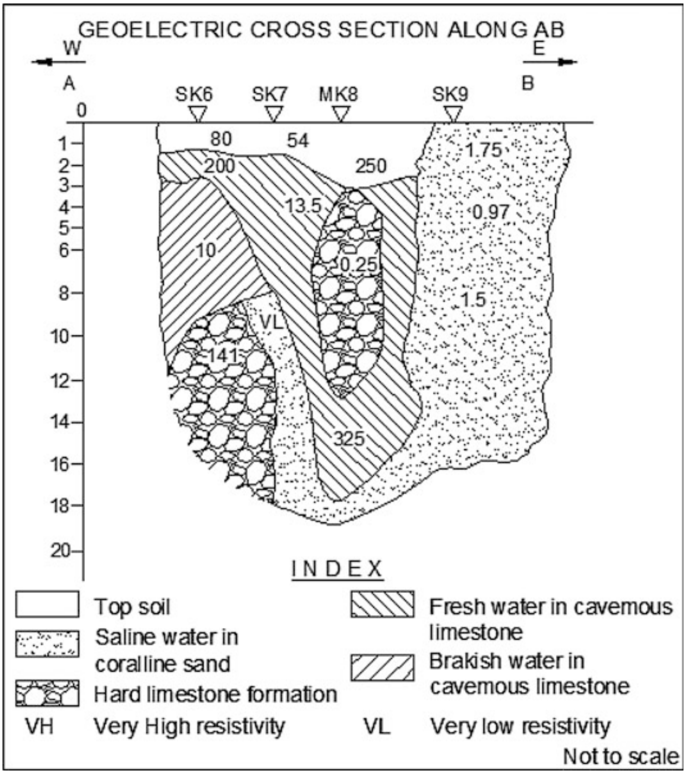


Fig. 4.53 Geoelectric section showing saline and freshwater

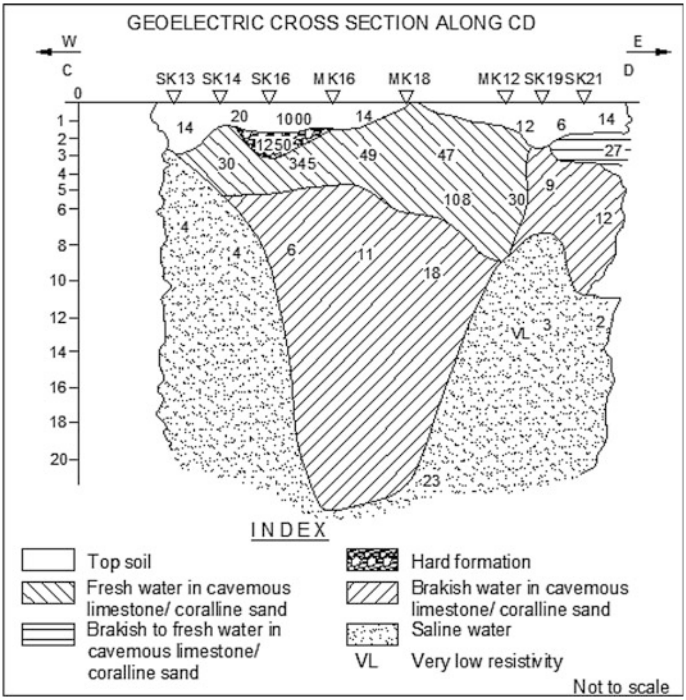


Fig. 4.54 Geoelectric section showing saline and freshwater zone through VES survey

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Chapter 5
Borehole Geology and Well Logging

Abstract Generally, after geological and geophysical surveys the drilling is carried out. Strata chart prepared from drill-cut samples is called geological log, which is not always reliable because of mixing of samples during recovery at the time of drilling. Therefore, geophysical logging is very much required to perform after drilling to know actual lithology with accurate depth. The record of any characteristic information with depth in the borehole is known as well log. When sensor is lowered gradually inside the borehole, continuous recording is made, and it is called geophysical log. These logs are used to detect bed boundaries, porous and non-porous zones, saline water-bearing zones, groundwater flow pattern, fracture zones, etc. There are different types of logs used for different purposes. Generally, SP log is used to detect the saline fresh boundaries. The resistivity logging is used for the detection of porous and permeable freshwater-saturated zones against low-resistivity adjacent shale and clay beds and estimation of their thicknesses. Porosity can also be calculated from this log. Natural gamma log is used to detect clay or shale content. Neutron, sonic and density logging are also used for determination of porosity of the aquifer. The calliper log is the record of diameter of the borehole with depth. It locates the fractures and other openings. Temperature log gives the record of variation of temperature with depths in a borehole.

Keywords Drilling · Geological log · Geophysical log · Lithology · Drill-cut samples · Shale content · Neutron log · Sonic log · Calliper log · Temperature log · Fractures

5.1 General Considerations

It has been noted earlier in Sect. 4.2 that subsurface geophysical methods referred to as well logging methods are essential tools in groundwater exploration and development. These tools, mainly developed in oil industry, have a restricted utility in water wells. The record of any characteristic information of the formations with depth in the borehole is known as well log. In borehole geophysics, a suitable

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sensor is lowered to the bottom of the borehole and the logs are continuously recorded in terms of depth when the sensor (called "Sonde") is drawn upwards gradually with a uniform speed.

Normally, geophysical logging is carried out in water wells drilled as test boreholes or regular boreholes recommended after thorough geological and surface geophysical surveys. Geophysical logs help in understanding the subsurface hydrogeology of the area clearly as the strata chart prepared from the mixed-up samples recovered at the time of drilling is not reliable. While the logs are used for stratigraphic correlation from well to well, these may be used for the detection of bed boundaries, porous and permeable zones, saline water-bearing zones, fractured zones and groundwater flow pattern, having a strong bearing on groundwater development and management in large-scale water supply schemes.

Electrical resistivity and seismic refraction methods dealt with in the earlier chapter (Chap. 4) help us in the selection of drilling points recommended for test boreholes in both hard- and soft-rock areas. The point is recommended after the geoelectric section, time–depth section and the subsequent lithological sections are obtained after necessary correlation of data. As soon as the drilling of the borehole is completed, well logging is carried out for in situ evaluation of the aquifer characteristics through measured physical properties.

5.2 Geological and Geophysical Log

Geological logs are prepared as soon as drilling is completed. The samples collected in course of drilling are used to prepare geological log or litholog or strata chart. In water wells, logs are likely to give (i) the thickness of the aquifer and (ii) depth to the porous and permeable zones. Drilling time log acts as a supplement to geological log which gives penetration rate and bit behaviour. This indicates the character of the materials encountered, distinguishing hard rocks from soft ones.

Geophysical logs supplement the geological logs in (i) exact location of sand–shale boundary and (ii) quantitative assessment of the aquifer parameters, e.g. porosity and water quality. Geological log cannot give the exact boundary due to a time lag in drilling and sample collection. Geological and geophysical logs, thus, are most useful in detailing and development of aquifer zones.

5.3 Logging in Groundwater Development

The subsurface geophysical methods (logging techniques) available for oil, water and mineral exploration have been listed earlier in Sect. 4.2. Of these, the following logs may play an important role in detailing water wells and in related groundwater development:

(i) Self-potential (SP) logging,
(ii) Point resistance logging,
(iii) Conventional resistivity logging (normal and lateral),
(iv) Natural gamma and radioactive tracers (radioisotopes like I^{131} with a half-life of 8 days and Br^{82} with a half-life of 36 h, for example, are used as tracers),
(v) Calliper logging (in the absence of calliper log, drilling time log is used for detailing fractured zones) and
(vi) Temperature logging (typical geothermal gradient of 1–1.3 °F per 100 feet is taken as a substitute for temperature log when temperature log is not recorded).

Other logs such as neutron, sonic and gamma–gamma ray (density) logs known as porosity tools are not routinely run in water wells but may be used if logs for shallow depths run in oil wells are available. Groundwater economy is such that it has to be sold very cheaply and exploration cost be kept to the minimum compared to oil and mineral exploration. Therefore, the cheapest borehole tools comprising SP, resistivity (sometime point resistance) and natural gamma ray logs are used for small-scale groundwater supply projects.

5.3.1 Groundwater Development

Surface electrical resistivity surveys can be cheaply carried out to locate the drilling point for groundwater. Once the borehole is drilled and geophysically logged, the formation water resistivity value can be used for noting the chemical quality of groundwater. The thickness of porous and permeable zones and their lateral extent obtained from geophysical surveys help in fixing the spacing and yield of wells, phasing the annual recharge and discharge of the aquifer causing no overdraft and minimizing mutual interference among the pumped wells in the area. Thus, the well logging methods together with pump test play a dominant role in the development, planning and management of the groundwater resources.

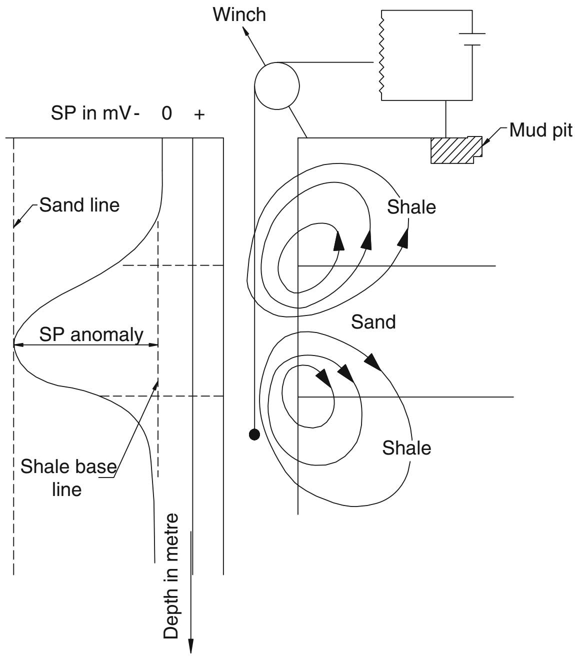
5.4 Logging in Water Wells

The logs listed earlier and meant for water wells will now be outlined briefly as follows.

5.4.1 SP Logging

SP is the self-potential or spontaneous potential of electrochemical origin controlled by the concentration difference of the electrolytes in the boreholes (drilling mud)

Fig. 5.1 Record against shale base line up to the sand line



and the formation (formation water) within boreholes drilled with freshwater mud. The SP (mV) across a porous and permeable bed is given by the expression:

$$\text{S.P.}(\text{mv}) = -K \log \frac{R_{\text{mf}}}{R_{\text{w}}} \tag{5.1}$$

Here, SP is read from the record against shale baseline up to the sand line (Fig. 5.1). K is a constant, dependant on absolute temperature (value equals to 80 at 24 °C, for example), R_w is the resistivity of formation water and R_{mf} is the resistivity of the mud filtrate (R_{mf} = 0.8 R_m) calculated from the resistivity of mud (R_m) at the corresponding temperature.

SP (normally negative) log plotted to the left of the record (Fig. 5.2) has three major applications: (i) definition of bed boundaries using the method of half deflection, (ii) correct location of porous and permeable zones and (iii) determination of formation water resistivity (R_w). The resistivity of the water sample may also be measured in the laboratory to get R_w. The total dissolved salt (TDS) may be calculated for the formation water in parts per million (ppm) from the empirical relation

$$\text{TDS} = 0.64\,X\ \text{EC in micromhos/cm} \tag{5.2}$$

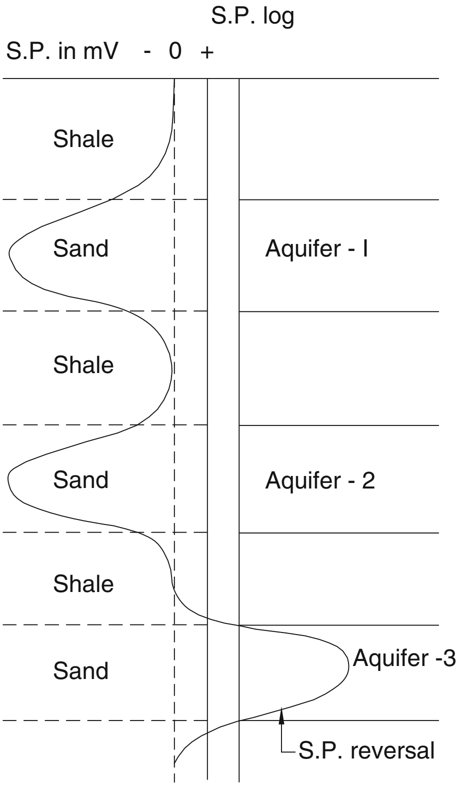


Fig. 5.2 A typical SP record showing SP reversal

where EC = electrical conductivity of formation water given by,

$$EC = 10,000/R_w (R_w \text{ in Ohm-m}). \tag{5.3}$$

The conductivity of formation water may also be measured in the laboratory. Normally, TDS in water up to 750 ppm may be used for drinking and up to 1000 ppm for irrigation purposes. Once TDS is known, chlorinity of the water may also be found out using the empirical relation

$$\text{Chlorinity (in ppm)} = 0.6\ (\text{TDS} - 400). \tag{5.4}$$

5.4.1.1 SP Reversal

When salinity of formation water is less than that of mud, positive SP anomaly is recorded. This is termed SP reversal and is an important diagnosis for freshwater aquifers, normally encountered in the coastal areas. When SP is used in combination with resistivity logs, the following situations may occur.

(i) No SP and a high resistivity means: (a) NaCl concentration in the formation water is porous and permeable sand and the borehole mud are the same, or (b) a hard non-porous bed which shows a high resistivity but no SP to be resolved through sonic log.
(ii) A strong negative SP but no distinct resistivity anomaly means a saline water aquifer.

5.4.2 Point Resistance Logging

This is the simplest and cheapest approach where a constant and regulated amount of current is fed through two spherical lead electrodes, one at the surface mud pit and the other in the borehole. Normally, this is recorded simultaneously with SP (plotted to left) and plotted to the right side of the record. The measured resistance becomes proportional to the resistivity of the material close to the electrode. This is used for the detection of resistive porous and permeable freshwater-saturated zones against low-resistivity adjacent shale and clay beds and estimation of their thicknesses. The water-saturated porous and permeable zones interpreted from SP log are confirmed through point resistance log.

5.4.3 Resistivity Logging (Normal and Lateral)

Besides point resistance, normal and lateral logs are used for both qualitative and quantitative interpretation in water wells. Schematic diagrams for normal and lateral systems and the corresponding logs are shown in Figs. 5.3 and 5.4, respectively. The apparent resistivities read against two-electrode (AM; Fig. 5.3) normal arrangement and the three-electrode lateral (AMN; Fig. 5.4) arrangement give the true resistivity (R_t) of the formation. The $R_t = R_0$ (read from the log) is the resistivity of the bed completely saturated with formation water. From a knowledge of R_0 from resistivity log and the value of R_w already known from SP log, resistivity formation factor (F) and porosity (Ø) can be calculated from the simple relations

$$F = R_0/R_w \tag{5.5}$$

$$F = (1/ø^2) \tag{5.6}$$

where F *is* a measure of porosity of the path for groundwater flow. Using Archie's relation $F = (a/ø^m)$, where $a = 1$ and cementation factor $m = 2$, the porosity (ø) of the formation is calculated using Eq. (5.6).

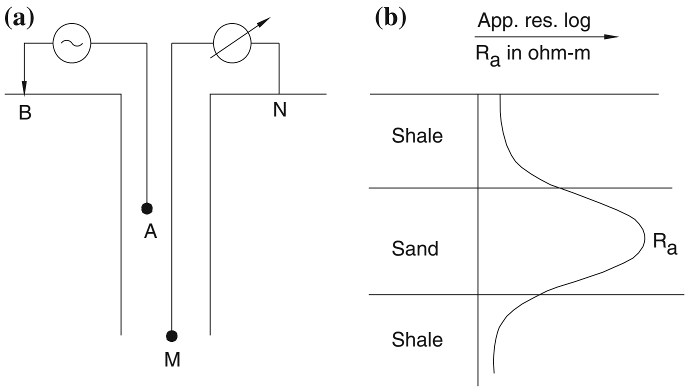


Fig. 5.3 Resistivity logging (normal). **a** Two-electrode system; **b** typical normal log

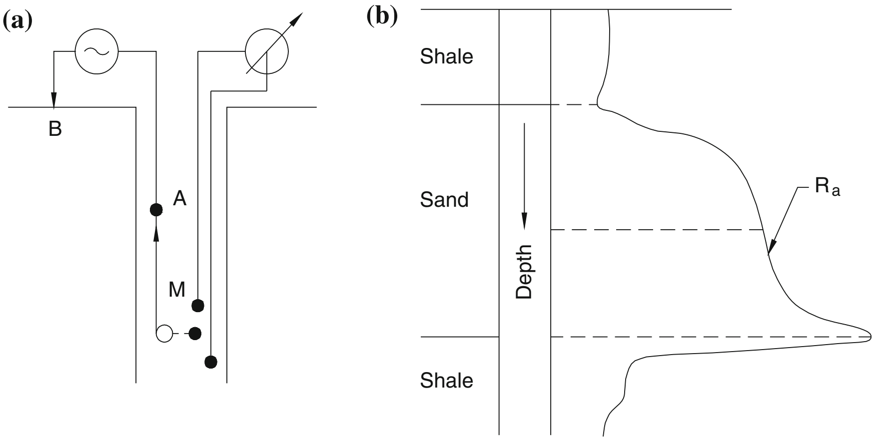


Fig. 5.4 Resistivity logging (lateral). **a** Three-electrode system; **b** typical lateral log

5.4.4 Natural Gamma Ray Logging

This is the record of natural gamma ray intensity originating mainly from radioisotope potassium-40 (K^{40}) present only in clay or shale. The shale or clay bed shows much higher gamma ray counts compared to sand.

Gamma ray log serves as a substitute for SP log, which becomes practically non-existent in case of boreholes drilled with saline mud. Thus, when SP log fails to demarcate bed boundaries of clay or shale from adjacent sand, gamma ray log is the only alternative. In hydrogeology, the volume proportion of shale in shaly sand is generally obtained from gamma ray intensity amplitude indicated by the counts per second (CPS).

In tracer technique, weak radioactive sources like bromine-82 (half-life = 36 h) and iodine-131 (half-life = 8 days) are used as the tracers for the determination of the direction of the movement of the groundwater within boreholes, through single-hole and multiple-hole measurements. Other logging tools such as neutron, sonic and density, if available, may be used for the determination of porosity of the aquifer.

5.4.5 Neutron Log

Neutron log records the response due to neutron-capture gamma rays which depends on the hydrogen content of the formation. While hydrogen content is a measure of the porosity for non-shaly sand, the log is used for the calculation of porosity. A straight-line calibration curve is obtained on a semi-log paper with porosity on log scale versus neutron deflections (with reference to a tight formation porosity 1–2 %, shale porosity 40 % and completely water-saturated sand porosity 100 %).

5.4.6 Sonic Log

Sonic log records the time required for a sound wave to travel through unit length of formation, and the following expression is used for the calculation of porosity for uniform intergranular porosity:

$$\phi = \frac{\Delta_{\mathrm{log}} - \Delta t_{\mathrm{matrix}}}{\Delta_{\mathrm{liquid}} - \Delta t_{\mathrm{matrix}}} \tag{5.7}$$

where Δt*'s* are the travel times (in microsecond) for unit length of formation (recorded from the log), matrix and the liquid filling the pores.

5.4.7 Gamma–Gamma Ray or Density Log

Gamma–gamma ray or density log measures the intensity of scattered gamma rays which is dependent on the density of the formation. Both neutron and sonic logs are affected by shale content of the formation, and the porosity values are altered considerably. Density log, however, is independent of chemical behaviour of the formation, and the porosity given by the following equation is not affected by shale contamination:

$$\phi = \frac{d_{\mathrm{g}} - d_{\mathrm{b}}}{d_{\mathrm{g}} - d_{\mathrm{f}}} \times 100 \text{ (percent)} \tag{5.8}$$

Here, d_g—the grain density (gm/cc)—is known from the constituents of the formation (2.65 for sandstone, 2.70 for limestone and 2.85 for dolomite, for example); d_b—the bulk density—is obtained from density log; and d_f indicates the average fluid density.

As soon as the experimental borehole is drilled, logging of the borehole is carried out. This helps in getting the total thickness of the aquifers and fixing of the strainer positions. The observation wells are completed and full-length strainers are placed. Pump test is carried out continuously for 36–48 h and the drawdowns recorded in the main borehole and the observation wells. The static water levels (SWL) in all the wells before pumping are recorded. After the completion of the pump test, recovery test is made until water level comes to the original SWL.

The time–drawdown data collected during pump test at known discharges are analysed to determine the aquifer parameters, namely storage coefficient (S') and transmissivity (T'), using Jacob's straight-line method (Raghunath 1987), modified Theis method (Raghunath 1987) and Hantush method (Hantush and Jacob 1955; Hantush 1956). These aspects of the aquifers are dealt with in greater detail in Chap. 6.

5.4.8 Calliper Log

The calliper log is a record of the diameter of a borehole with depth. Important use of this log is to help in the evaluation of other logs with regard to caving and related corrections for hole-diameter effects. Calliper log is also used for the identification of lithology and for stratigraphic correlation from well to well. Calliper log locates fractures and other openings as a guide to well construction. Location of fractures in igneous and metamorphic rocks and of solution openings in limestone are some examples of utility of calliper log in combination with the cheap and simple point resistance log.

5.4.9 Temperature Log

Temperature log gives the record of variation of temperature with depth in a borehole. Temperature log helps in providing information on the source and movement of groundwater. The log is used for temperature correction of physical properties of drilling fluid and mud. When temperature log is not available, the typical normal average gradient of temperature variation with depth within the earth may be used as a substitute.

5.5 Case Studies

Two field examples of electrical logging are presented in the following sections. Two additional case studies (resistivity and logging combined) are also included in the next two sections.

5.5.1 A Case Study in the Lateritic Terrain

5.5.1.1 Geology of the Area

Salboni (22°39′ N, 88°21 E′) is located about 30 km north of Kharagpur Town (Fig. 5.5) on State Highway No. 5 linking Kharagpur–Midnapore–Bankura–Raniganj. The New Note Press (NNP) project area is about 4 km south-west of Salboni.

The formations in the area belonging to the Quaternary age (Niyogi 1972) show mainly four geologic units, viz. (i) lateritic upland, (ii) older deltaic sediments, (iii) younger deltaic deposits and (iv) recent sediments (Fig. 5.5). The area under investigation is covered by the older alluvium deposits capped by massive lateritic cover of Pleistocene age. These older alluvial sediments are comprised mainly of clay, silt and sand. The general elevation of the land surface in the area is about 60 m above the mean sea level. The average annual rainfall is approximately 1500 mm.

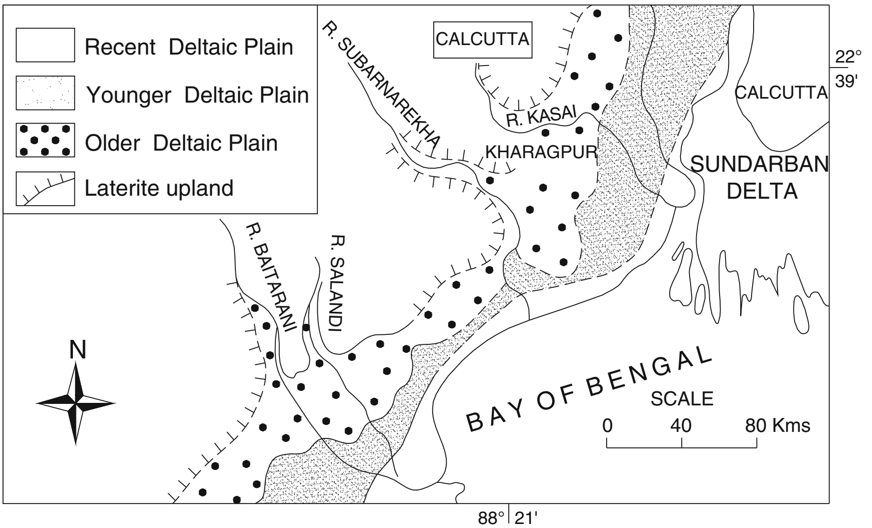


Fig. 5.5 Quaternary geological map of West Bengal and Orissa (location of logging site Salboni)

5.5.1.2 Geophysical and Hydrogeological Results

The water requirement of about 3200 m^3/day in the first phase of the work for Salboni NNP project was originally planned by Central Ground Water Board through a battery of wells at safe distances, in and around the project area. In view of the lateritic cover, some problem was faced leading to a probable marginal shortfall in projected supply. However, the shortfall could also be due to overestimation of transmissivity of subsurface aquifer or due to inappropriate design of tube well. In order to examine the subsurface disposition of the water-bearing sandy horizons, electrical resistivity soundings were planned at several locations. The electric logs comprising self-potential (SP) and point resistance were also used together with the subsequent yield test data (Shahid et al. 2000). Electrical logs of a representative borehole TW-3 are reproduced in Fig. 5.6.

VES data together with the geologic charts and electric logs show that there exists a silt–sand–clay section with variations at short intervals as indicated by resistivity values. The electric log (SP and point resistance) presented in Fig. 5.6 clearly indicates the zones recommended for strainer positioning. However, smaller SP and resistivity values indicate finer sand and a low porosity. This has caused a slow recuperation ultimately affecting the yield.

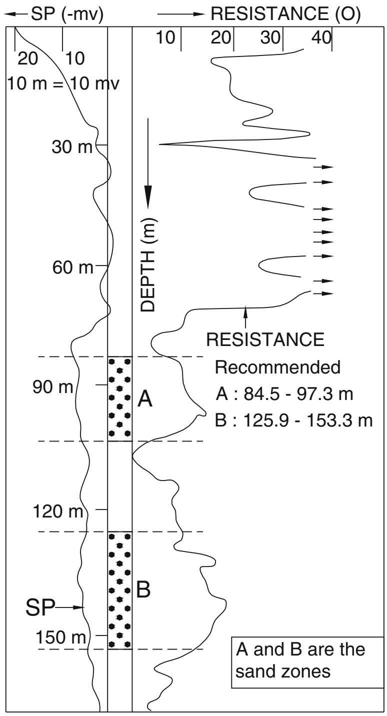


Fig. 5.6 Electrical-log (S.P. & Point resistance at Salboni)

5.5.2 A Case Study from Coastal Areas of Orissa

5.5.2.1 Geology of the Area

The coastal tract of Orissa is mostly underlain by recent alluvium, clay, silt and gravel of Quaternary group of sediments (Fig. 5.7). The unconsolidated formations of upper Tertiary group comprise finer sediments underlain by the recent formations and occur in the northern parts of Baleshwar District (Ramkrishna et al. 2000), Orissa.

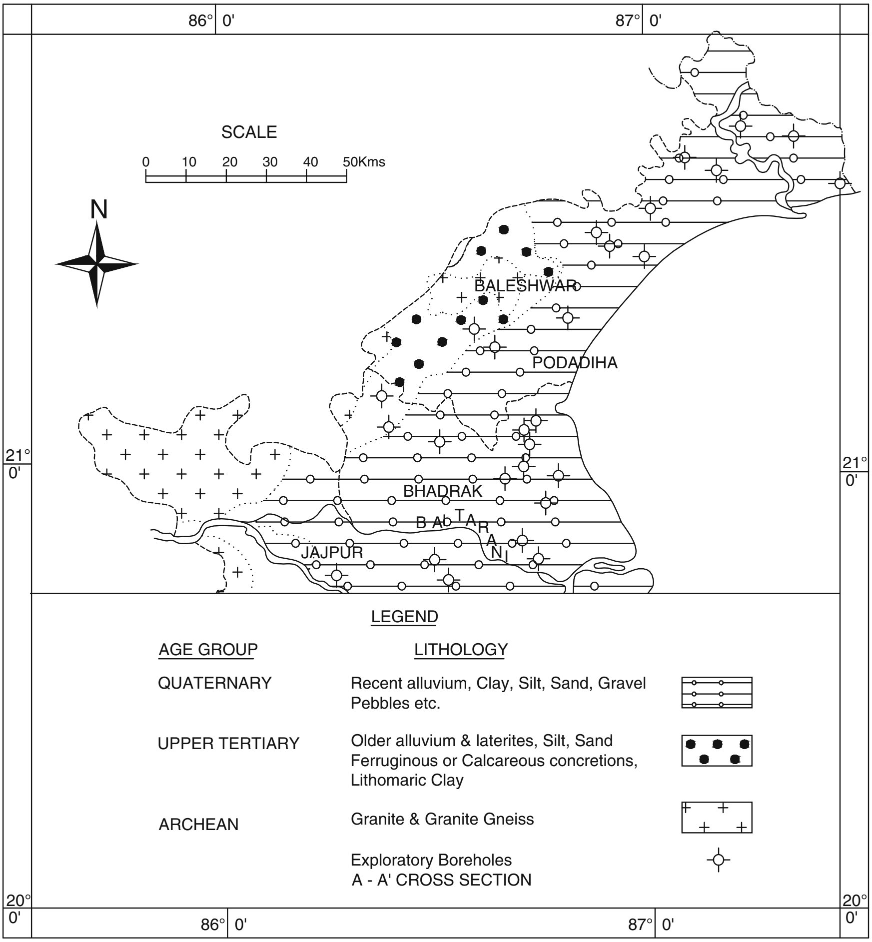


Fig. 5.7 Location map of coastal area of Orissa (Logging site—Podadiha)

5.5.2.2 Geophysical and Hydrogeological Results

The SP, short and long normal resistivities and natural gamma ray logs were recorded within a borehole at Podadiha (Fig. 5.7), Balasore District. The borehole was drilled up to a depth of 247.5 m and logged up to 246 m. The log is presented here up to a depth of about 120 m only (Fig. 5.8), beyond which a monotonous clay layer is encountered.

The record (Fig. 5.8) presents SP, short (16″) and long (64″) normal resistivities and natural gamma ray CPS. Low SP variation and corresponding higher resistivity for the sandy zone indicate fresh formation water. While SP log records a negative potential variation of 10–15 mV corresponding to 28 ohm-m normal log resistivity, natural gamma ray log gives 60 CPS. All three logs (SP, normal and gamma ray) clearly delineate the sandy zone at a depth of 81–104 m and indicate the presence of good-quality (fresh) water in the aquifer.

5.5.3 Resistivity Survey and Correlation of Electrical Logs in Arsenic-Infested Areas of N-24 Parganas (West Bengal)

A total of twenty-three vertical electrical soundings (VESs) were carried out (Adhikari et al 2007) in grid pattern in and around Saibona, Barasat, N-24 Parganas (north latitude 22°43′49″ to 22°44′26″ and east longitude 88°25′21″ to 88°27′02″, toposheet no. 79B/6), to study the characteristics of resistivities in arsenic-rich near-surface lithounits (Fig. 5.9).

One VES was conducted near the borehole at Buniadi School, Saibona (current electrode separation = 700 m). The pattern of curve was HKHA type (Fig. 5.10). This curve was interpreted initially with partial curve matching technique and detected five layers. Finally, another two layers (deeper clay and sand) are predicted from the interpretation of inverse-slope method.

Comparing the interpreted resistivities with the nearby borehole litholog and other VES results, the following standardized ranges of resistivity data for different lithology are furnished in Table 5.1.

Considering fourteen numbers of VES data, a fence diagram is prepared (Fig. 5.11). It is observed that there are mainly four types of layers, i.e. topsoil, sandy clay, clay and sand. Only at VESs 8, 10 and 11 a clay layer is found between the topsoil and sandy clay (as observed in VES near Buniadi School; Fig. 5.10).

Below the topsoil, the sandy clay layer which is mixed with carbonaceous material varies in its thickness from 2.88 to 11.2 m. Different test results show high arsenic content in this zone; therefore, it is assumed that carbonaceous material may be the source of the arsenic. This layer is having maximum thickness at VES 9 and

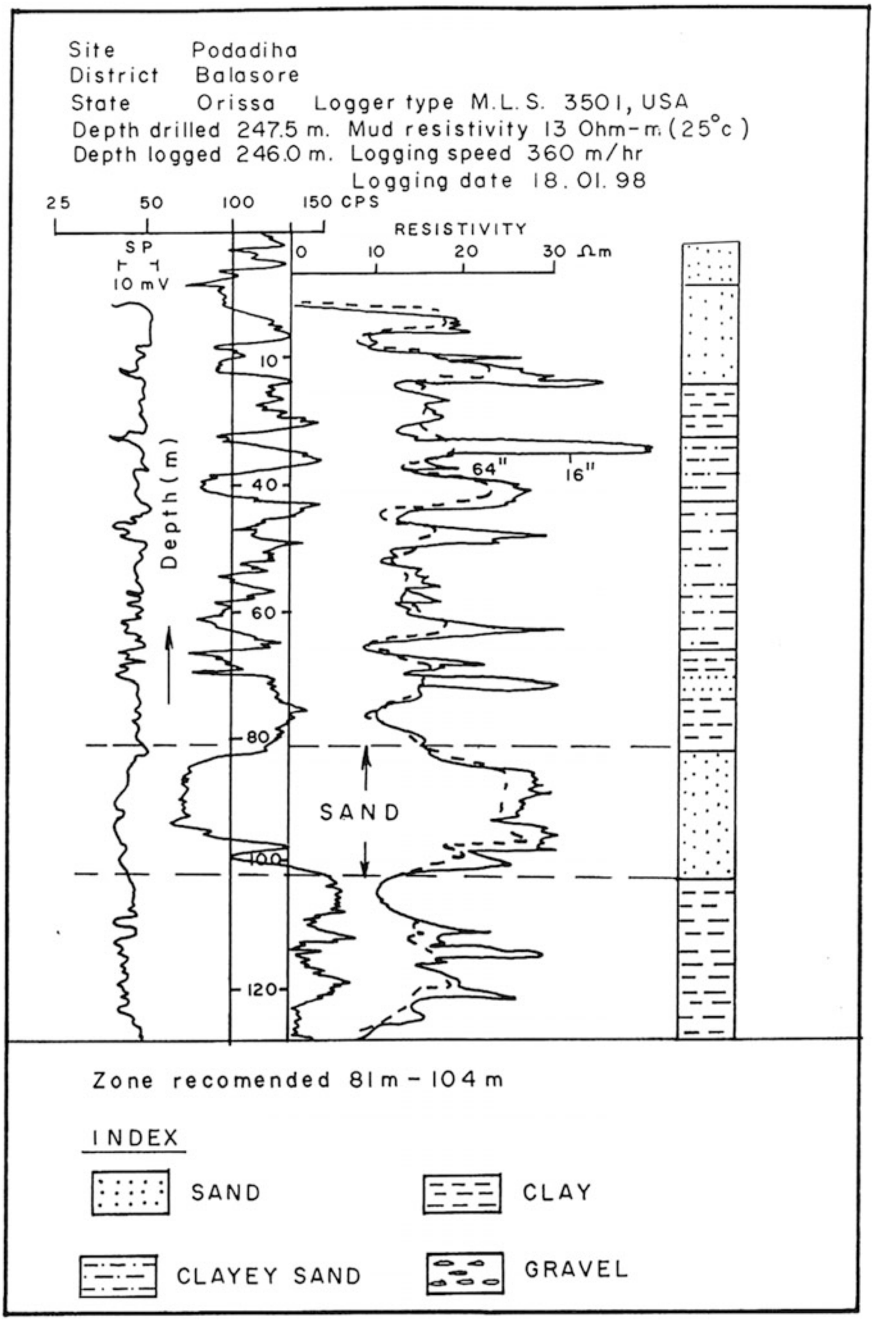


Fig. 5.8 The record presents SP, short (16″) and long (64″) normal resistivities and natural gamma ray counts per second (CPS)

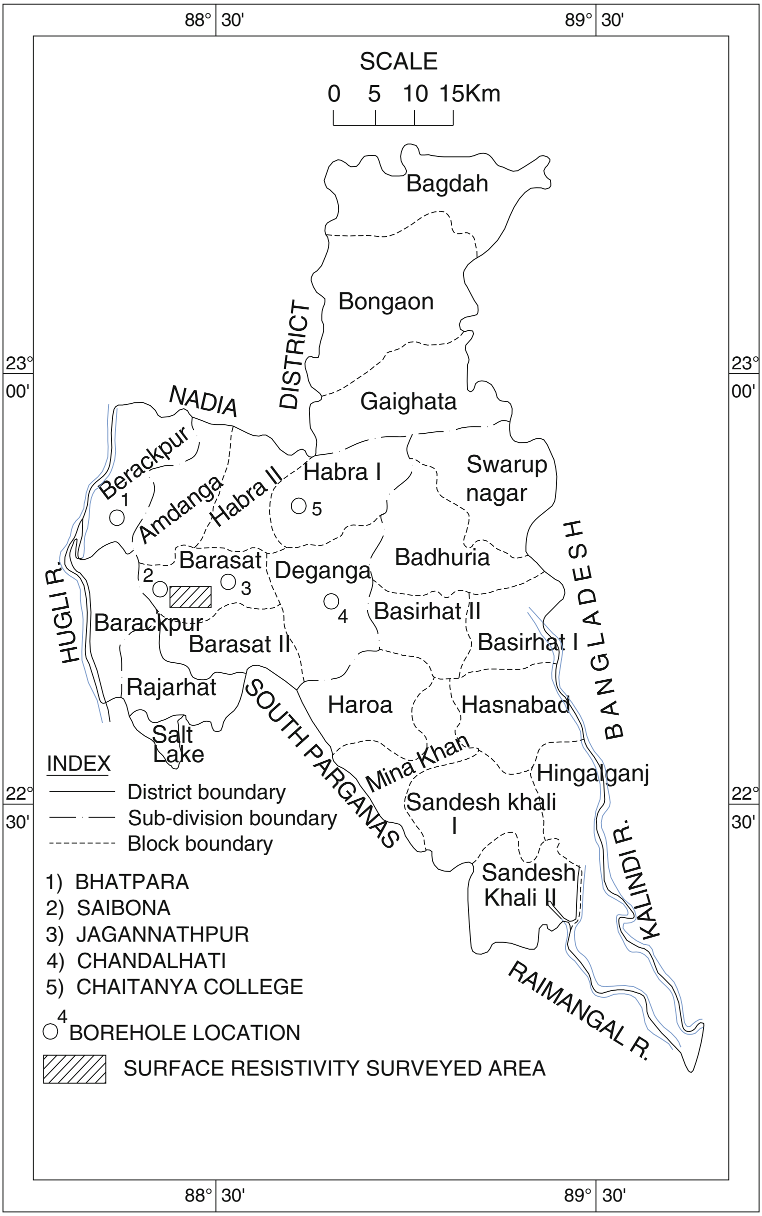


Fig. 5.9 Borehole location map, North 24 Parganas district, West bengal

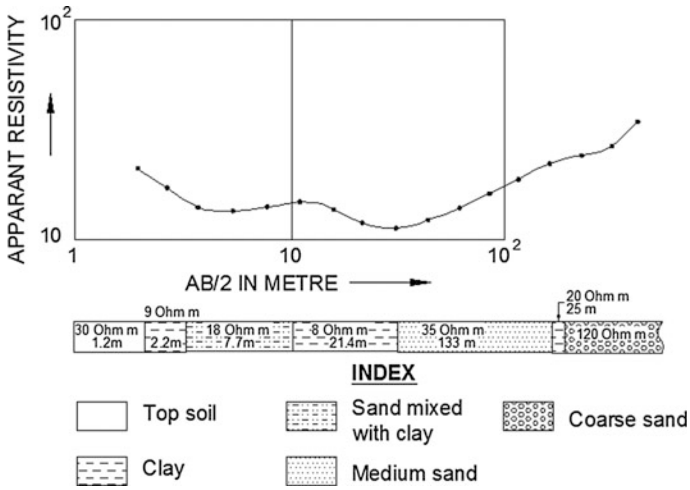


Fig. 5.10 VES curve obtained in Saibona, Barasat

Table 5.1 Standardized range of resistivity for alluvium soil in N-24 Parganas

Layers	Range of resistivity (Ω m)	Lithology
I	11–40	Topsoil
II	7–11	Clay/shallow
III	11–36	Sandy clay
IV	24–56	Sand medium
V	50–124	Coarse sand
VI	20–25	Deeper clay

minimum thickness at VES 16. It is observed that the thickness of this layer increases towards SW and decreases towards NE. The resistivity range of this layer varies from 11 to 30 ohm-m. Below this sandy clay layer, a lower resistivity layer of resistivity range 7–11 ohm-m is recorded. This stratum is assumed to be clay layer. This clay layer varies in its thickness from 20.8 to 50.4 m. Below this thick clay layer, a layer of resistivity range 24–123 ohm-m is available, which is due to the presence of sand of different grain sizes at different locations. This layer is found at the depth range 33–60.8 mbgl. The deeper clay layer is not detected because during the survey the current electrode separations and interpretations were made in such a way that the near surface in homogeneities got much more emphasized. Existence of clay layer is established in one VES near Saibona (Fig. 5.10), and this clay layer is also confirmed in the log in Saibona (Fig. 5.12).

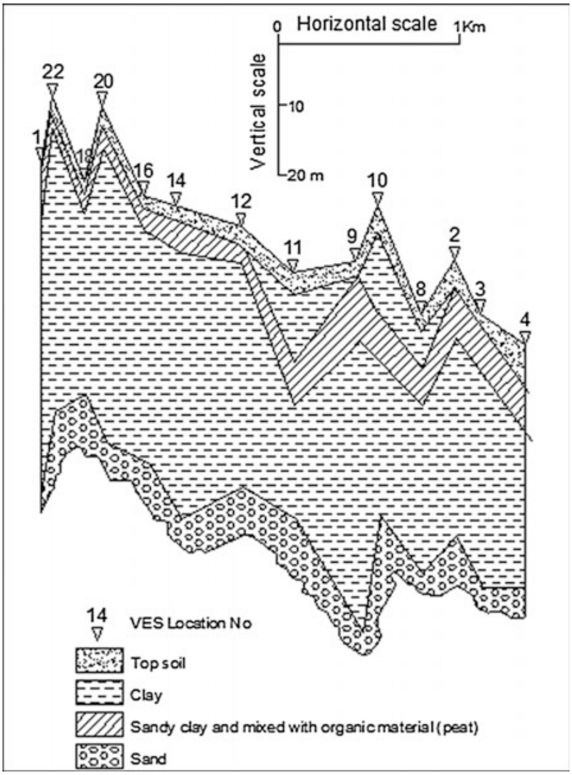


Fig. 5.11 Fence diagram prepared with geophysical data in and around Saibona, Barasat, North 24, Parganas

Correlation of Electrical Logs and Discussions of Results

Five numbers of electrical logs from sites Bhatpara, Saibona, Jagannathpur, Chandalati and Chaitanya College located in four blocks were selected for the purpose of correlations. Broadly, four aquifers with depths are demarcated as **A, B, C and D** zones (Fig. 5.12). On the basis of the resistivity orders, these four zones for all five numbers of electrical logs are connected and a panel diagram is prepared to get a three-dimensional view of changing geometry of the different layers laterally and vertically.

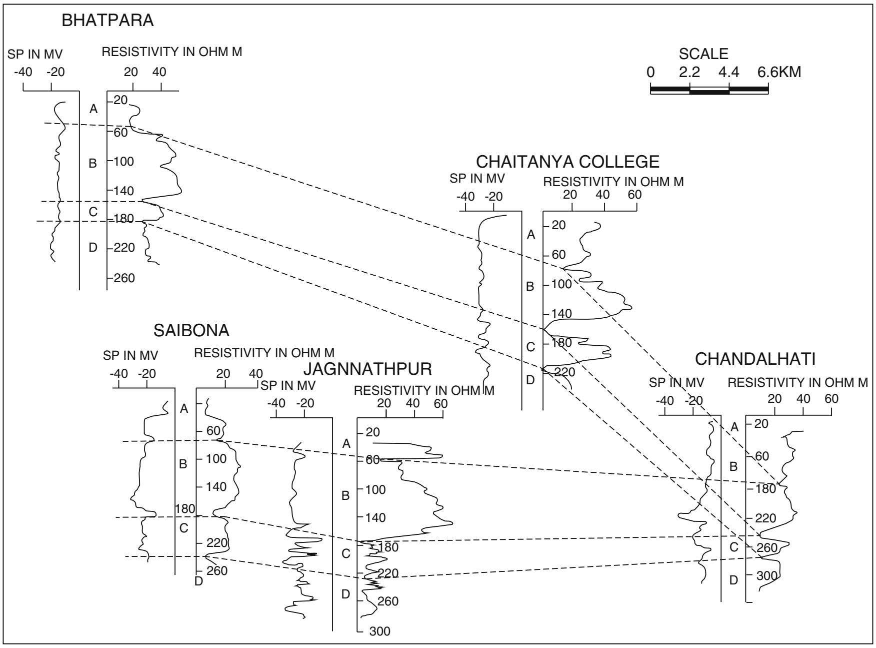


Fig. 5.12 Correlation of different electrical logs, North 24 Parganas, West bengal

The presence of different lithology and their resistivities with depths are recorded in a tabular form. Correlating all the log results, the deeper clay layers are confirmed and resistivities of different sand zones with arsenic are compared (Table 5.2).

5.5.4 A Case Study in Madhubani Area (Resistivity and Logging)

Systematic resistivity surveys with ninety VESs and four electrical logs were completed in Madhubani and Sitamarhi districts, Bihar (Adhikari and Prakasam 1996). The area of investigation in Madhubani District lies between north latitudes 26°13′ to 26°28′ and east longitudes 85°48′ to 86°28′ (sheet no. 72F & 72 J). In Sitamarhi District, the investigated area lies between north latitudes 26°27′ to 26° 49′ and east longitudes 85°22′ to 85°35′ within the Survey of India sheet 72F (Fig. 5.13).

Table 5.2 Interpreted electric log results with arsenic values in vertical sections in North 24 Parganas District, West Bengal

Borehole no.	Location	Depth range (m)	Lithology	Average resistivity in ohm-m	SP in mV	Zone tapped	Arsenic values (ppm)
1	Bhatpara	28–42 (A)	Sand	24	−13 (A)	162–180	A > 0.05
		42–62	Clay	16	−9 (B)		B—not reported
		62–153 (B)	Sand	54			
		153–162	Clay	23	−7 (C)		C—0.01
		162–182 (C)	Sand	42			
		182–190	Clay	25	−8 (D)		D—not reported
		190–250 (D)	Sandy clay	40			
2	Saibona	38–68 (A)	Sand	20	−15 (A)		A > 0.05
		68–73	Clay	12	−18 (B)		
		73–167 (B)	Sand	31			
		167–181	Clay	11	−13 (C)		
		181–232 (C)	Sand	25			
		232–244	Clay	06	−9 (D)		
		244–250 (D)	Sand	18			
3	Jagannathpur	35–55 (A)	Sand	45	−28 (A)	261–276	A > 0.05
		55–60	Clay	13	−24 (B)		-
		60–172 (B)	Sand	60			
		172–177	Clay	03	−20 (C)		-
		177–206 (C)	Sand	20			
		206–214	Clay	04	−15 (D)		D—0.002
		214–242 (D)	Sand clay	22			
		242–261		04			
		261–276 (E)		15			
4	Chandalati	34–64 (A)	Sand	34	10 (A)	180–190 212–230	A > 0.05
		64–98	Clayey sand	25	−20 (B)		B > 0.05
		98–154 (B)		40			
		154–176	Sand	12	−15 (C)		C & D <0.05
		176–192 (C)	Clay	34			
		192–204	Sand	13	−10 (D)		
		204–206 (D)	Clay Sand	29			
5	Chaitanya College	20–74 (A)	Sand	34	−14 (A)	187–205	A > 0.05
		74–82	Clay	23			B > 0.05
		82–154 (B)	Sand	65	−14 (B)		
		154–177	Clay	03	−07 (C)		C & D <0.05
		177–219 (C)	Sand	40			
		219–224	Clay	02	−08 (D)		
		224–249 (D)	Sand	23			

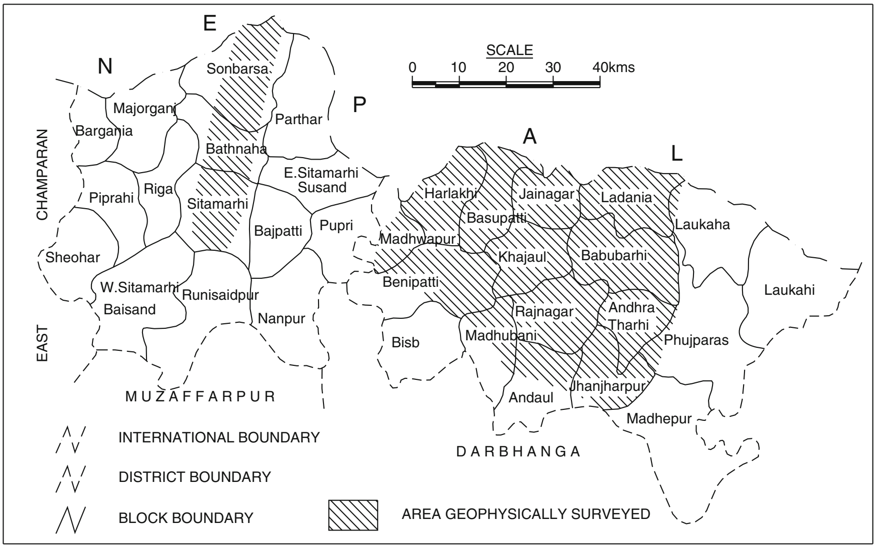


Fig. 5.13 Location map of geophysically investigated are in Madhubani and Sitamarhi district, Bihar

The area is underlain by the Quaternary alluvium, deposited by the rivers originating in the Nepal Himalayas in the north. Recent geological and geophysical study reveals that the thickness of the deposit is more than 100 m and the slope of the bedrock is towards north. The deposits consist chiefly of various grades of sand, silt, clay, kankar, gravels, pebbles and boulders. As the Siwaliks are exposed on the northern boundary of Kosi Basin, it is presumed that the Quaternary sediments might be underlain by the Mesozoic (Gondwanas) which is underlain by the Precambrian.

Fig. 5.14 Some representative Schlumberger VES curves (Benipatti, Pharchahia, Sonbarsa, Dharampur & Tulsiahi) in parts of Madhubani & Sitamari district, Bihar

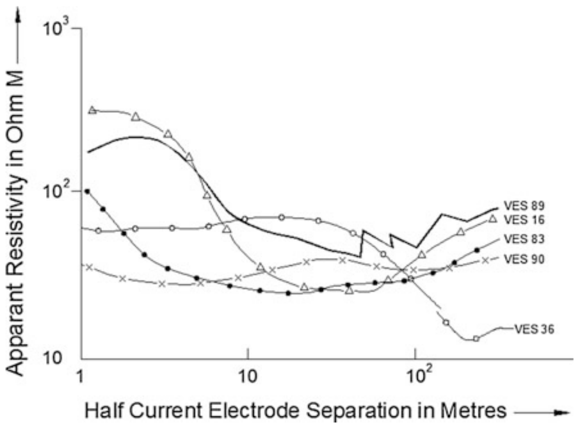


Table 5.3 Standardized resistivity for alluvium soil in Madhubani District, Bihar

Resistivity range (in ohm-m)	Lithology
15–40	Wet topsoil
40–525	Dry topsoil
15–25	Clay
25–60	Clay mixed with little sand or concretions
30–150	Sand saturated with water

All the VES curves from geophysical surveys are in the pattern of AKH, QHK, HK, KA, KHK and HKH (Fig. 5.14). A correlation of the interpreted VES data with the available nearby existing well data can be made as follows (Table 5.3).

A section is shown within the area of investigation to explain the different lithology of the area. Generally, alternate sand and clay beds are visible in the section. The depths and resistivity ranges are shown in the section (Fig. 5.15).

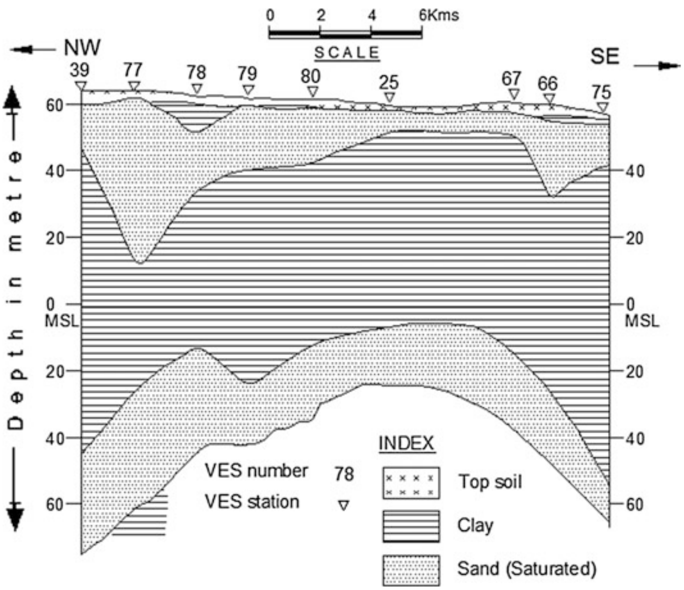


Fig. 5.15 Geoelectric section in parts of Madhubani district Bihar

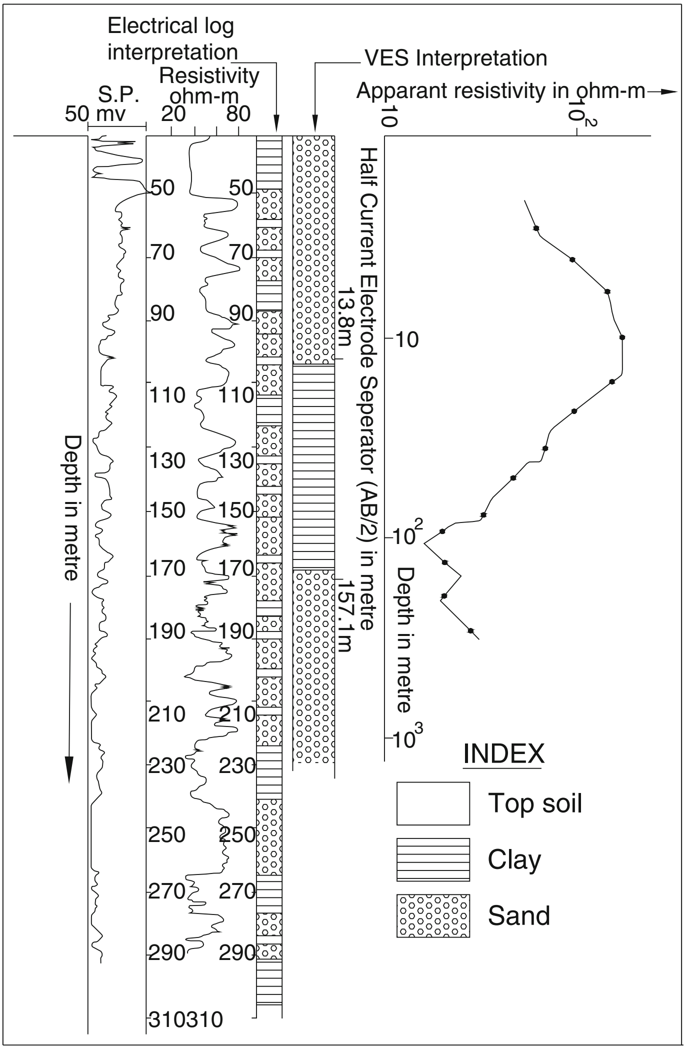


Fig. 5.16 Vertical electrical sounding versus electrical log interpretation of drilling site at Khajidi, Madhubani district, Bihar

Resistivity surveys were carried out near different boreholes also to standardize the VES data. Here, VES versus log interpretation data are shown for the area Khajedih and Kaluahi Village (Figs. 5.16 and 5.17), which are self-explanatory.

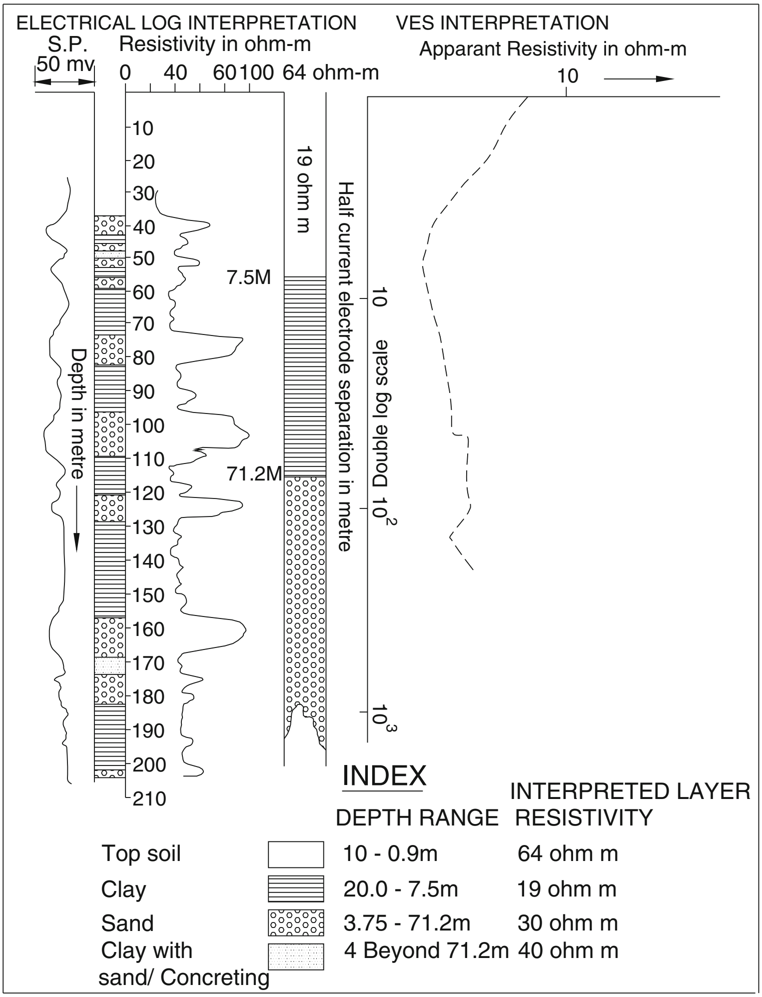


Fig. 5.17 Vertical electrical sounding versus electrical log interpretation of drilling site, Khluahi, Madhubani district, Bihar

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Chapter 6
Aquifer Parameters, Pumping Test and the Yield

Abstract The terms hydraulic conductivity (*K*), transmissibility (*T*) and storage coefficient (*S*) are useful for computation of yield. The hydraulic conductivity of an aquifer is its capacity to transmit and to yield it. The transmitting capacity for the entire thickness is known as transmissibility (*T*), and storage coefficient (*S*) of an aquifer is the volume of water discharged through unit prismatic volume. During pumping test, a time–drawdown curve is generated. From this curve, *T* and *S* values are calculated by different methods. As the drilling and pumping tests are expensive, time-taking and laborious geoelectrical measurements are used for alternate approach to estimate the aquifer characteristics. In this process, a few drillings are carried out in the area of investigation. The *T* and *K* are calculated in these boreholes with the help of pump test. Vertical electrical sounding (VES) is carried out near the boreholes. Transverse resistance (T') and formation factors (*F*) are calculated from all the VES results. Then, a straight-line relation between transmissibility and transverse resistance and hydraulic conductivity and formation factor is brought out. Now, if the entire area is surveyed by VES and the T' and *F* are calculated for each point, the hydraulic conductivity (*K*) and transmissibility (*T*) can be found out using the relations for the entire area of investigation. A contour can also be drawn for hydraulic conductivity and transmissibility for the area.

Keywords Aquifer characteristics · Hydraulic conductivity · Transmissibility · Storage coefficient · Pump test · VES · Yield · Transverse resistance · Formation factor

6.1 General Considerations

Various important aquifer parameters for unconfined and confined conditions have been outlined in Chap. 3. The terms hydraulic conductivity, transmissibility (T') and storage coefficient (S') useful for computation of yield have been explained in Sect. 3.5. These are also defined in various textbooks on groundwater (e.g. Todd 1995;

H.P. Patra et al., *Groundwater Prospecting and Management*,
Springer Hydrogeology, DOI 10.1007/978-981-10-1148-1_6

Raghunath 1987; and others) published from time to time. We would like to avoid repetition of these definitions and move directly over to the useful formulae for the estimation of T' and S'.

6.2 Estimation of Permeability, Transmissibility and Storativity (Storage Coefficient)

Permeability or hydraulic conductivity of an aquifer is its capacity to transmit water and to yield it. This is expressed in metres per day (m/day) and denoted as K. The product of hydraulic conductivity and the thickness of the aquifer (b) gives the water-transmitting capacity for the entire thickness of the aquifer known as transmissibility ($T' = Kb$) expressed in quadratic metre per day (m^2/day).

Storage coefficient or storativity (S') of an aquifer is the volume of water discharged from a unit prism, i.e. a vertical column of aquifer standing on a unit area (1 m^2) as water level falls by a unit depth (1 m) (Raghunath 1987). For unconfined aquifers (water-table conditions), the storage coefficient is the same as specific yield. The coefficient is a dimensionless quantity involving a volume of water per volume of aquifer (Todd 1995).

6.3 Pumping Test Analysis and Recovery Test

Aquifer storativity and transmissibility values are normally evaluated under actual field conditions. Lowering of water level below the static water level (SWL) in the pumping well and several observation wells (radially placed) is observed under a constant and steady discharge. After the pump is started, the water levels are measured in the pumping and observation wells for several days (1–3 days) until a saturation is obtained. The time–drawdown curves are utilized for computation of T' and S' values using different methods available. After the pump is stopped, the water levels in all the wells are measured for a few hours until original static water levels are almost reached. This recovery test data may be used for computation of transmissibility through a separate approach.

6.3.1 Cooper–Jacobs Straight-Line Method

In this method, time-drawdown data from the pumping well as well as observation wells are plotted on semi-log graphsheet (time on log scale). This gives a straight line. The drawdown Δs per cycle is used to compute T' (m^2/day) through the standard equation (Raghunath 1987, for example)

$$T' = \frac{2.3Q}{4\pi\Delta s} \tag{6.1}$$

where
T' transmissibility (m^2/day),
Q constant discharge through the pump (1 pm) and
Δs drawdown per cycle (m).

By extrapolating the straight line of the semi-log plot to intersect the zero drawdown axis at t_0, the time for $s = 0$ is noted on the graphsheet and S' computed using standard equation.

$$S' = \frac{2.25T' t_0}{r^2} \tag{6.2}$$

where
S' coefficient of storage/storativity,
t_0 the time at zero drawdown (min) and
r distance of the observation well from main pumping well (m).

The above equations (Eqs. 4.80 and 4.81 in Raghunath 1987) may be used to compute T' and S' with the help of pumping test data by Jacob's method.

6.3.2 *Modified Theis Method*

In this method, a composite drawdown graph is drawn by plotting drawdown (s) versus (t/r^2) on a semi-log paper for all the observation wells, Δs per log cycle of t/r^2 is measured, and the aquifer properties T' and S' are determined from standard equations (Raghunath 1987):

$$\boldsymbol{T'} = \frac{\mathbf{2.3}\boldsymbol{Q}}{\mathbf{4}\boldsymbol{\pi\Delta s}} \quad \text{and} \quad S' = 2.25T'(t/r^2)_0 \tag{6.3}$$

6.3.3 *Hantush Inflection Point Method*

For semi-confined leaky aquifers, Hantush method is used for analysis of pumping test data. Hantush and Jacob (1955) and Hantush (1956) have given the following equation for steady-state drawdown in a leaky aquifer:

$$S' = \frac{Q}{2\pi T'} K_0 \left(\frac{r}{B'} \right) \tag{6.4}$$

where

B' leakage factor (dimension of metre) and

K_0 (r/B') modified Bessel function of the second kind and zero order.

From the above, Hantush developed a method for determining T' and S' from the time–drawdown data by reading on the plot (s versus $\log t$) the values of s_i and t_i where i refers to inflection point, i.e. the point where the drawdown (s_i) is one-half of the final or equilibrium drawdown. In this method, the drawdown measured in an observation well during pumping is plotted against time on a semi-log paper, and the data are extrapolated until the maximum drawdown s_m is reached. The inflection point (s_i) is located on the drawdown curve by taking $s_i = s_m/2$, where s_i is the drawdown at the inflection point. The slope of the drawdown curve at the inflection point is determined graphically, and t_i is read corresponding to the inflection point.

6.3.4 Transmissibility from Recovery Test Data

In a pumping test operation with main pumping well and several observation wells at a site, it is customary to record water levels in all the wells after pumping is stopped for a period until original static water levels are almost reached. This gives residual drawdowns, analysis of which may give transmissibility, an independent check on the earlier result.

The residual drawdown (S') may be expressed (Todd 1995, p. 133) for small r and large t' values as follows:

$$S' = \frac{2.30Q}{4\pi T'} \log \left(\frac{t}{t'} \right) \tag{6.5}$$

where

t time from the start of the pump (interval over the pumping plus recovery period) and

t' time from the stoppage of the pump (recovery interval only).

A straight line is obtained from a plot of residual drawdown S' on linear scale against t/t' *on* log scale, and slope of the straight line gives the value of

$$\Delta s' = \frac{2.30Q}{4\pi T'} \log \frac{t}{t'} \tag{6.6}$$

If calculations are made over one log cycle of t/t'

$$\Delta s' = \frac{2.30Q}{4\pi T'} \tag{6.7}$$

where $\Delta s'$ is the residual drawdown per log cycle. The storativity is not determined directly with this method (Domenico and Schwartz 1990, p. 163).

6.3.5 Step-Drawdown Pumping Test

In earlier Sects. (6.3.1–6.3.4), the methodology for aquifer property (T' and S') determination is given. However, for computation of well losses, step-drawdown pumping test data are essential.

The total drawdown S_w is made up of head loss due to laminar flows (formation loss) and well losses in the zone close to well face (from turbulent flow), in the well casing and through the well screen (Raghunath 1987, p. 225). The equation controlling the nature of these losses is given by (Raghunath 1987, Eqs. 5.89 and 5.90).

$$S_w = BQ + CQ^2 \tag{6.8}$$

or,

$$S_w/\mathrm{Q} = B + CQ \tag{6.9}$$

where

B coefficient of formation loss (dimension of T^2/L^5),
C coefficient of well losses (dimension of S_w/Q),
BQ formation loss and
CQ^2 well loss.

Step-drawdown pumping test is normally conducted at four to five different discharge rates of pumping or steps being of the same duration of 80–120 min after pumping for 1-h duration. It starts initially at a low rate. The discharge is gradually increased through a series of sufficient steps. S_w/Q versus Q (abscissa) plot on linear scale gives a straight line (Eq. 6.9), slope giving well loss coefficient, C. Intercept on ordinate gives the formation loss coefficient B. The values of well loss and formation loss are utilized for proper design of well and development of the well to keep the well loss to the minimum. Specific capacity of a well is the ratio of discharge and drawdown in a pumping well. This is a measure of the productivity of the well.

For a specified duration of pumping, the well efficiency (E_w) is given as a percentage by (Todd 1995, p. 159):

$$E_W = 100 \times \frac{Q/S_W}{Q/BQ} = 100 \times (BQ/S_W) \quad (6.10)$$

6.4 Estimation of Aquifer Properties from Surface Geoelectric Data

Exploration possibility of groundwater resources of an area depends largely on the aquifer characteristics, e.g. transmissivity, hydraulic conductivity and storage coefficient. Long-duration pumping test is needed in order to estimate these aquifer parameters. Pumping test is an expensive process, and long-duration pump test data collection is rarely carried out. Surface geoelectric measurements provide an alternate approach to the estimation of some of the aquifer properties. Though the geoelectric methods alone, even under favourable conditions, do not replace test drilling to ascertain groundwater condition, in many cases these can reduce the amount of test drilling by giving a better selection of test borehole locations. Several investigators have tried to establish empirical relations between aquifer parameters and geoelectric properties. The investigations have established a linear relationship between hydraulic transmissivity and transverse electrical resistance (Kelly 1977; Kosinski and Kelly 1981; Niwas and Singhal 1981a, b, 1985; Singhal et al. 1998; Yadav and Abolfazil 1998), and a direct correlation between hydraulic conductivity and formation factor (Singhal et al. 1998; Yadav and Abolfazil 1998). Heigold et al. (1979), however, found an inverse relationship between aquifer resistivity and hydraulic conductivity for sites located in glacial outwash sediments.

6.4.1 Theoretical Background

From well-known Darcy's law, the water discharge, Q (m^3/s), may be expressed in the form:

$$Q = KI'A \quad (6.11)$$

The differential form of Ohm's law can be written as follows:

$$J = \sigma E \quad (6.12)$$

where

K hydraulic conductivity (m/day),

I' hydraulic gradient,

A area of cross-sectional perpendicular to the direction of flow,
J current density (A/m^2) and
σ electrical conductivity (inverse of resistivity (ohm-m) in a homogeneous, isotopic medium).

The two fundamentals of fluid flow and current flow may be utilized to find a probable relationship between electrical and hydraulic characters of the formation.

The equation in Chap. 4, Sect. 4.8, can be rewritten in the form

$$T = h\rho \tag{6.13}$$

and

$$S = \frac{h}{\rho} = h\sigma \tag{6.14}$$

This is on consideration of a prism of aquifer material having unit cross-sectional area and thickness h. T and S are Dar Zarrouk parameters with T as transverse resistance and S as longitudinal conductance.

From relations (6.13) and (6.14), the transmissivity T' (the product of hydraulic conductivity and aquifer thickness) can be derived in terms of T and S, given by

$$T' = K\sigma T \tag{6.15}$$

and

$$T' = (K/\sigma)S \tag{6.16}$$

It has been observed (Niwas and Singhal 1981a, b) that either of the two propositions ($K\sigma =$ constant or $K/\sigma =$ constant) could be true for an area under study with similar geological setting and water quality.

Yadav and Abolfazli (1998) have used the well-known Archie's relation in order to calculate resistivity formation factor (F) and correlate it with hydraulic conductivity (K) using the relation

$$\boldsymbol{F = R_0/R_W} \tag{6.17}$$

where
R_0 resistivity of the formation completely saturated with water, obtained from surface geoelectric measurements and
R_w resistivity of the formation water, obtained through analysis of water samples.

A case study is presented in Sect. (6.4.2) with detailed electrical resistivity soundings followed by long-duration pump test at several sites in an area with a similar geological setting.

6.4.2 Geosounding Measurements: A Case Study

6.4.2.1 Geology of the Area

The study area (87° 10′E, 22° 15′N to 87° 22′ 30″E, 22° 27′ 30″N) which is a part of Kasai River basin (shown in map, Fig. 6.1a, b) covers an approximate “area of 35 km^2”. The area falls within the district of Midnapur, West Bengal, India, where the average annual rainfall is 1520 mm. Geologically, the study area (Fig, 6.1a) comprises of three lithounits (Roy and Niyogi 1961), namely (i) laterite, (ii) older alluvium and (iii) newer alluvium. From the existing borehole information, the groundwater-bearing zones are located within shallow (up to 25 m) and deeper (80–150 m) levels.

For the area, an adequate amount of water supply is a problem, particularly in the summer months (May and June). The water scarcity has progressively been more acute with industrialization and the growth in population in the towns. Water demand has been projected (Patra et al. 1993) to be around 32 MLD by the year 2010 for the area. Detailed investigations comprising vertical electrical sounding (VES) and pumping tests were carried out on Kasai River bed near Midnapur Town (inset, Fig. 6.1b) in order to design a radial collector well, now in operation.

6.4.2.2 Estimation of Geoelectrical Parameters

A total of forty-two VES was conducted using Schlumberger electrode arrangement with a maximum spread of 250–300 m. The VES curves are interpreted by evolutionary programming (EP) approach (Shahid et al. 1999). EP is an advanced version of genetic algorithm (GA) where the search is random but is guided by the stochastic process which helps the system to learn the minimum path leading to the solution. However, the difficulties of GA lie in the premature convergence, as after successive generation, the entire population converges to a set of coding such that the crossover no longer generates any new chromosomes. This may happen even before finding an optimal solution. Although mutation allows for diversity, the mutation rate is usually low, so that practically no improvement can be achieved in the final generation of the population. The problem can be solved by using EP (Sect. 4.10, Chap. 4).

For the interpretation of layer parameters, in the first step, the field curves are interpreted through curve matching technique (Patra and Nath 1999). The layer parameters, thus obtained, are used as initial model for the estimation of final layer parameters accurately using EP. The layer parameters are compared with nearby borehole lithology. Two representative sample VES curves from Tata Metalik (tm) and Mohanpur (mh) sites (Fig. 6.1b are presented in Fig. 6.2a, b) processed through EP.

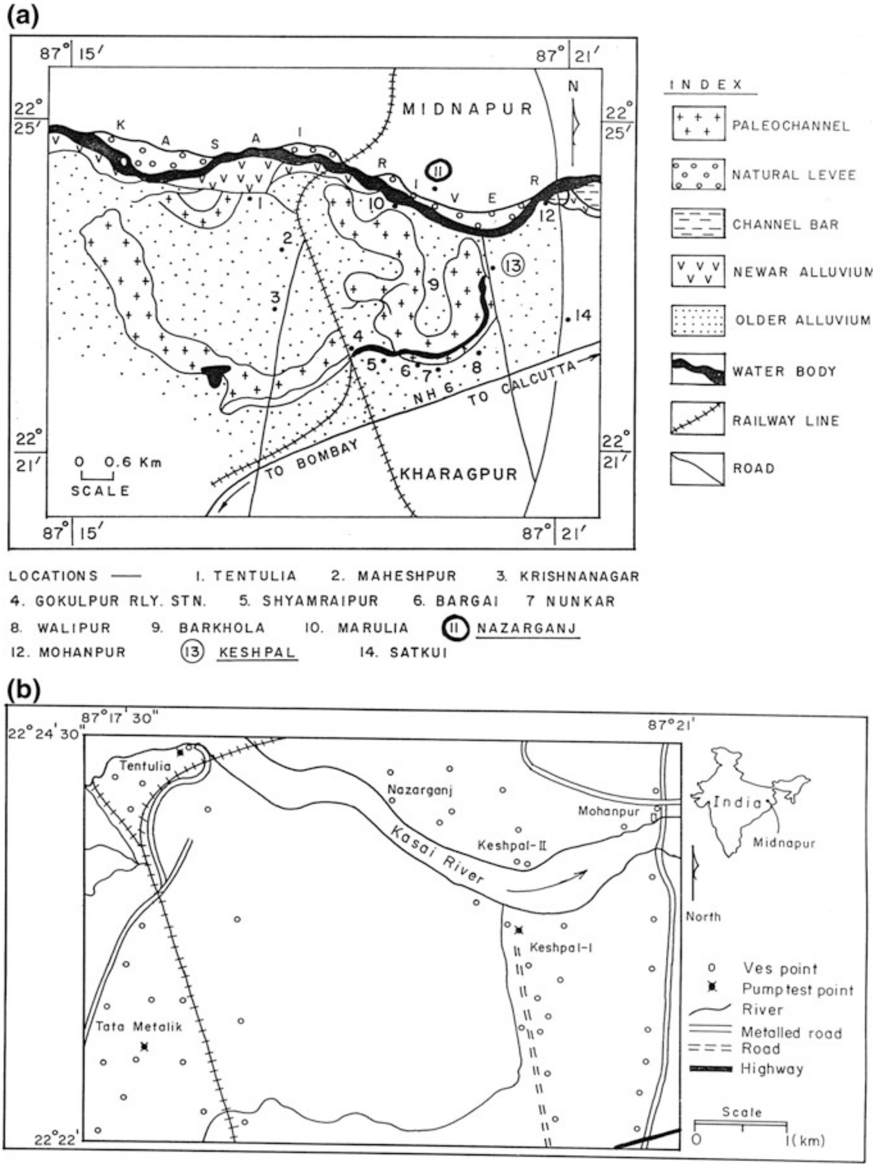

Fig. 6.1 **a** Geology of the area based on remote sensing data and **b** location map of different sites in the study area

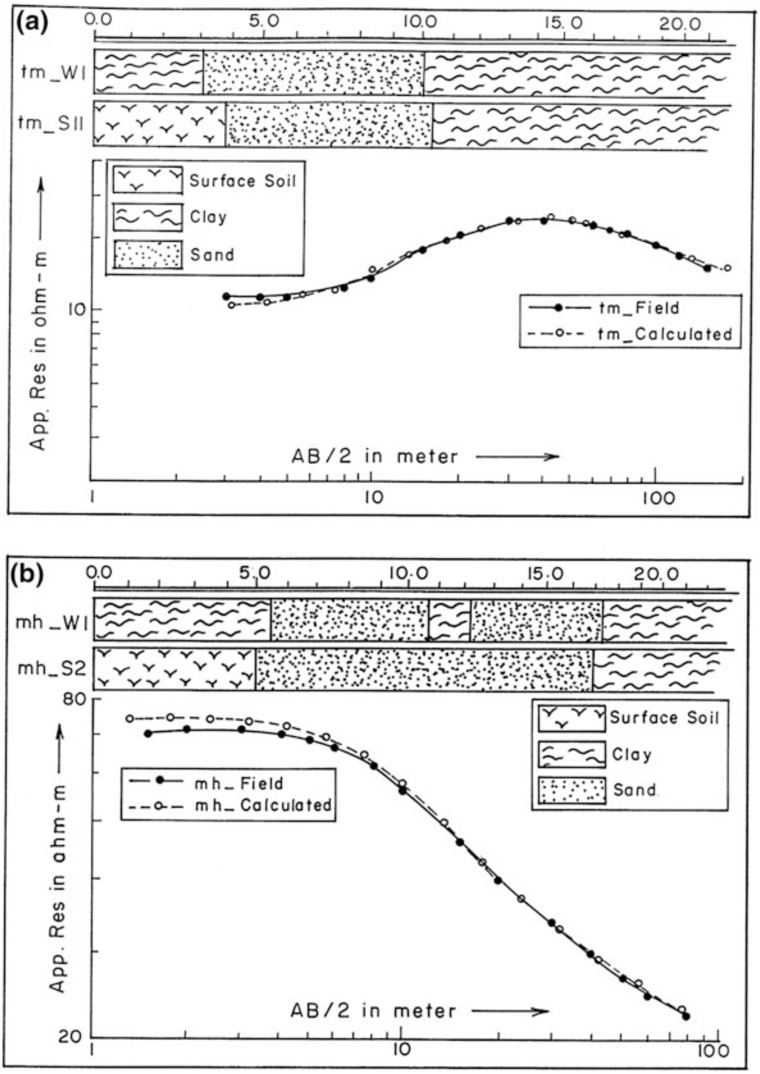

Fig. 6.2 VES curves processed through EP

6.4.2.3 Estimation of Transmissivity and Hydraulic Conductivity (From Pump Test Data)

For the estimation of transmissivity and hydraulic conductivity, pumping test data were obtained from six sites (Mohanpur, Keshpal I, Keshpal II, Nazarganj, Tentulia and Tata Melalik) shown in Fig. 6.1b. The sites fall within the area with same geological set-up. Long-duration pump tests 36–48 h were carried out at the given six locations selected after detailed soundings. The pump test data were processed to compute the transmissivity (T') values for the aquifer. The hydraulic conductivity (K) is calculated using the equation

$$K = T'/h \tag{6.18}$$

where h, the average aquifer thickness, being known.

6.4.2.4 Transmissivity and Transverse Resistance

In hydrogeological investigations, transverse unit resistance (T) has been found to be functionally analogous to hydraulic transmissivity (T'). The value of T computed from VES data and transmissivity of the aquifer computed from pumping test data at six sites are presented in Table 6.1a, b. The plot of T along abscissa and T' along ordinate is shown in Fig. 6.3a. This shows the linear relation of T' with T in the form:

$$T' = 83.4 + 0.8795T \tag{6.19}$$

Table 6.1 Aquifer parameters from six selected well sites

Location	Mohanpur	Tentulia	Nazarganj	Tata Metalik	Keshpal (I)	Keshpal (II)
VES No.	Mh-S2	tn-S8	Nz-S4	Tm-Sll	Kp-Sl	Kp-S10
(a)						
Thickness h (m) from VES data	12.1	6.38	10.8	8.43	7.1	7.0
Resistivity R_0 (ohm-m) of the aquifer	80.0	143.0	81.4	47.2	99.0	120.0
Transverse resistance T (ohm-m^2)	968.0	912.34	870.12	397.9	702.9	840.0
Predicted transmissivity T' = 0.8795T + 838.4 (m^2/day)	1689.76	1640.8	1603.67	1188.35	1456.6	1577.18
Transmissivity T' = (m/day) from pumping test	1830.95	1580.98	1622.63	1230.85	1424.0	1467.0
(b)						
Resistivity R_0 (ohm-m) of the aquifer	80.0	143.0	81.4	47.2	99.1	120.0
Pore water resistivity R_w	45.0	49.0	48.0	43.0	52.0	53.0
p_w (ohm-m)						
Formation factor $F = \rho_o/\rho_w$	1.78	2.92	1.7	1.1	1.91	2.26
Predicted conductivity K = 92.75F + 16.02 (m/day)	181.11	286.85	173.69	118.04	193.17	225.63
Conductivity K (m/day) From pumping test	152.71	305.21	160.57	146.01	195.06	218.95

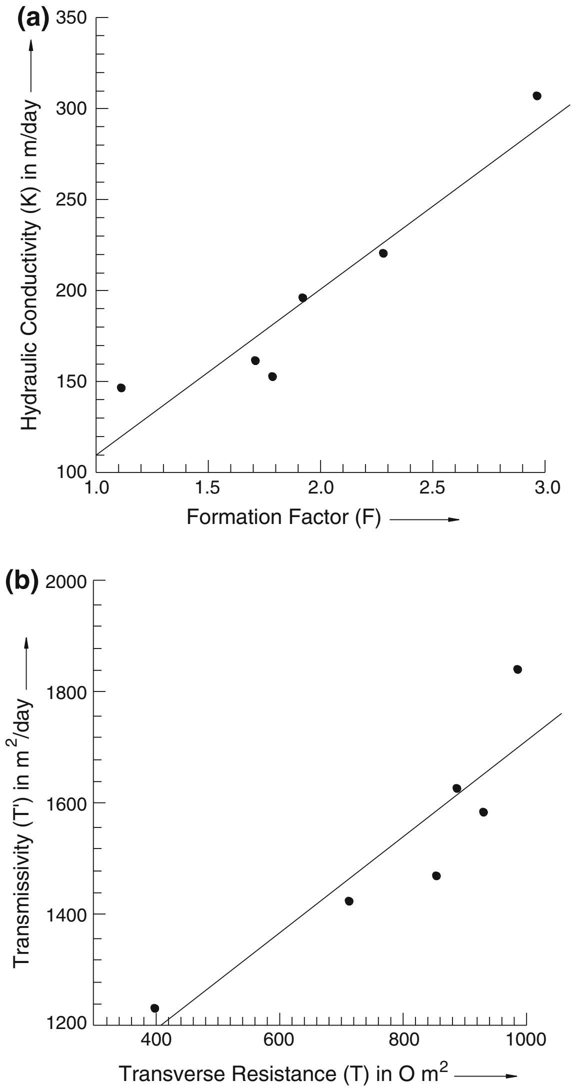

Fig. 6.3 A plot of aquifer parameters versus geoelectric parameters

6.4.2.5 Hydraulic Conductivity and Resistivity Formation Factor

The values of formation factor (F) are calculated from the value of the resistivity of completely water-saturated aquifer (R_0) computed from VES data and the resistivity of formation water (R_w) measured for samples from the pumping wells. The formation factor (F) at six pumping sites and hydraulic conductivity (K) computed through Eqs. (6.17) and (6.18), respectively, are presented in Table 6.1. The plot of formation factor along abscissa and hydraulic conductivity along ordinate is shown in Fig. 6.3b. This also shows a linear relationship between K and F and written in the form as follows:

$$K = 16.02 + 92.75F \quad (6.20)$$

From the derivations and discussions made in the earlier sections of this chapter, it is obvious that transmissivity of an aquifer can be calculated from a knowledge of transverse resistance obtained through surface geoelectric measurement.

Transmissivity can also be computed from knowledge of resistivity formation factor calculated from surface geoelectric measurements.

This is true for an area where such equations have been established through detailed VES and pumping tests. Such studies help in evaluating approximate transmissivity only and do not act as a substitute for long-duration test and the aquifer properties derived from pump tests.

6.5 Pump Test and Design of Radial Collector Well: A Case Study

6.5.1 Introduction

The groundwater investigation of an area involves evaluation of hydraulic properties of the aquifers along with delineation of the lateral extent and thickness of the associated layers. Pumping tests are the most suitable means for computing reliable and representative values of the hydraulic characteristics of aquifers. The water-level changes in the pumping and observation wells help in determining well performance, well efficiency and aquifer properties.

The main purpose of the present work is to investigate the subsurface water condition of Damodar River bed near Edilpur, Kathgolaghat, Dist. Burdwan, West Bengal, to recommend a system of collecting large amount of groundwater for industrial demand.

A comprehensive study of the hydrogeological properties of the aquifer around Edilpur, Kathgolaghat (lat. 23° 13′N, long. 89° 49′ 33″E), Burdwan District (W.B.), was carried out on Damodar River bed. Geological and geophysical investigations on the river bed established the presence of extensive sandy formations by trial boreholes. This is shown in Sect. 4.11 of this book (Chap. 4) on “Resistivity sounding case study” (Fig. 4.16).

6.5.2 Geology of the Study Area

The study site encompassing the area around Edilpur, Kathgolaghat (lat. 23° 13′N, long. 87° 49′ 33″E), Burdwan District, West Bengal, is situated in the northern bank of Damodar River as shown in Fig. 4.16. The site is located 5-km south-west of Burdwan Town and can be reached by metalled road to the present site. The topography of the area is flat with alluvium at the river bank. The site represents the typical tropical humid climate with an annual rainfall of about 1500 mm.

Although the site has been covered by recent alluvium, the subsurface lithology can be delineated from the available deep boreholes from the nearby areas. The lithological section at the study area is shown in Fig. 4.19, prepared from geological, geophysical and available borehole data.

6.5.3 Aquifer Parameters for Well Design

In order to develop parameters required for the design of a suitable method for exploiting groundwater, a long-duration continuous pump test is required. Usually, coefficient of transmissibility (T') and storage coefficient (S') are the two aquifer parameters considered for the design. Usually, the storage coefficient lies in the range of 0.05–0.3 for unconfined aquifer and 0.005–0.00005 for confined aquifer. The transmissibility coefficient more than 1300 m^3/d (900 lpm/m) represents a good aquifer regardless of the nature of the aquifer. However, for the collector well to be viable, the aquifer must have a saturated depth of approximately 15 m and a transmissivity of approximately 1500 m^2/d. The capacities of a collector well can be as low as 5 MLD or as high as 150 MLD. At lower capacities, a collector well may not be as economical as several vertical wells constructed in the same aquifer.

6.5.3.1 Generation of Pump Test Data

The Kathgolaghat site on Damodar River was found to be suitable for pump test. Main bore well of 200-mm-diameter mild steel pipe and 9 observation wells of 50-mm galvanized iron pipes were completed, and the typical arrangement of wells is shown in Fig. 6.4 (or the location of pumping well near Sl, see Fig. 4.17, in Chap. 4). The main tube well was washed and developed with air compressor for 8 h of continuous pumping, while the observation wells were developed using hand pump.

After the site was ready, the necessary pumping arrangements were made. A submersible pump of 100 m^3/h discharge provided with a 125-mm-diameter column assembly complete with suitable sluice valve, reflux valve and pressure gauge was used for pumping test. The power was provided at site by means of two generators of 50 kVA each.

Once the required arrangement for pumping was made, pump test was carried out for 72 h followed by recovery test. The flow rate during pump test was kept constant throughout 72 h and was monitored at site by a 90° V-notch. The actual

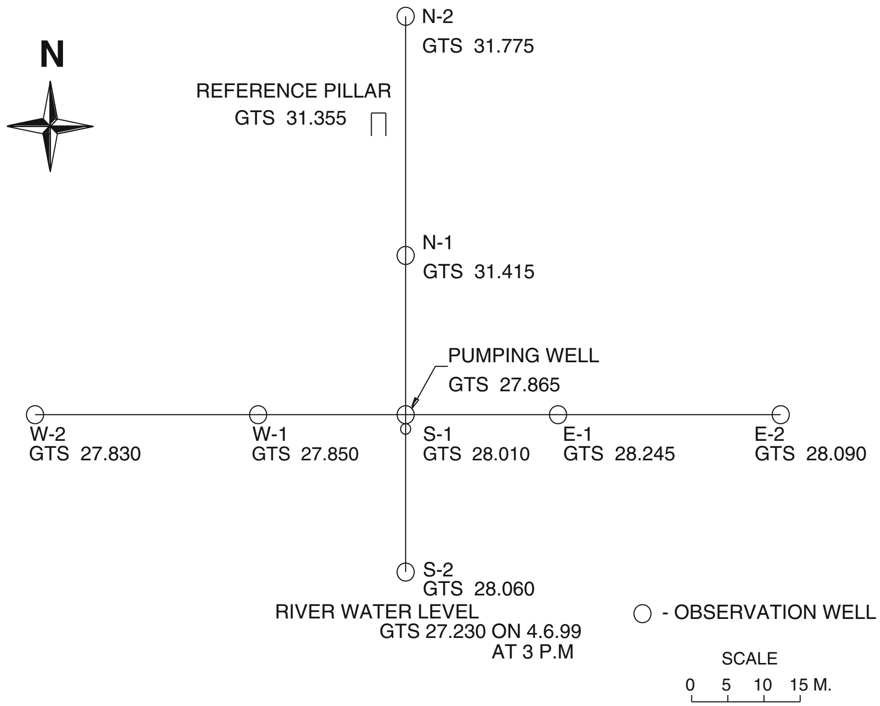

Fig. 6.4 Layout plan of observation wells

flow rate was found to be 25.6351 ps (20,300 GPH or 92.2 m^3/h). The complete details on time versus drawdown data at various observation wells recorded during the pump test are contained in the report titled "Pumping Test Data from Damodar River Bed, Edilpur, Kathgolaghat, Burdwan (West Bengal)" by Geo-Exploration Services (1999), Kharagpur.

6.5.3.2 Analysis of Pumping Test Data

The generated pumping data were analysed at the Indian Institute of Technology, Kharagpur, by various methods (Bandopadhyay et al. 2000). Some typical outputs are shown in Figs. 6.5, 6.6, 6.7 and 6.8. The average values of storage coefficient (S') and transmissivity (T') were estimated as 0.00006 and 3250 m^2/d, respectively.

Since the transmissivity of aquifer was more than 1500 m^2/d and thickness of confined aquifer was about 13 m, a collector well system has been planned. A collector well offers the best combination of high capacity from a single location and improved water quality by filtration through aquifer materials.

Well Ident.	Description
E1	Edilpur, Bardwan

Distance(m)	Avg. Pumpng Rate	Duration (min)	Initial Sat Thickness
20.00	21.34523m^3/day	4320.00	

RESULTS			
Transmissivity(m^2/day)	Storage Coeff	Leakance	Estimation Err.
3734.825	0.000002038198		0.03
Aquifer	Fit Method	Jacob Method	
CONFINED			

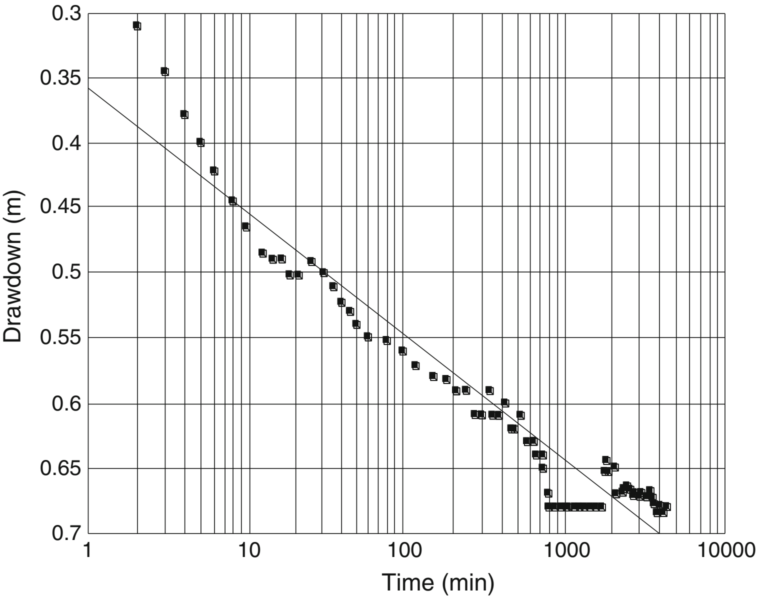

Fig. 6.5 Pumping test output data at Edilpur, Burdwan well site E1

6.5.4 Determination of Safe Yield of Collector Well

Since our objective is to draw 20 MLD water in the first phase of the project, a collector well of 7 m inner diameter is being provided to comfortably house the pumping machinery needed to deliver the 40 MLD water. The outer diameter of caisson will be 8 m with thickness of caisson being 50 cm.

The maximum length (L) of each strainer has been limited to 30 m along with 5-m blind pipe considering the efficiency of the available jack machinery.

Well Ident.	Description
E2	Edilpur, Burdwan

Distance (m)	Avg. Pumping Rate	Duration (min)	initial Sat Thickness
50.0	21.34523 m^3/ day	4320.000	

RESULTS			
Transmissivity (m^2/day)	Storage Coeff.	Leakance	Estimation Err.
3725.350	0.00001905691		0.02
Aquifer	Fit Method	Jacob Method	
CONFINED			

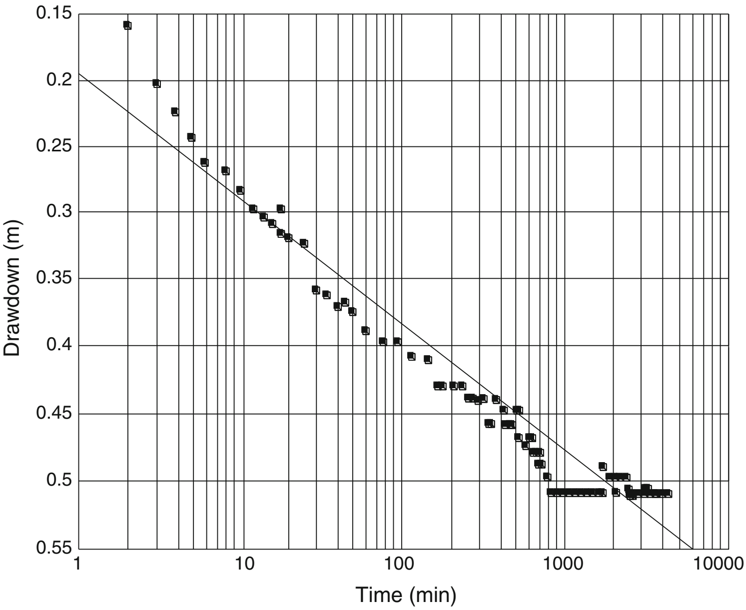

Fig. 6.6 Pumping test output data at Edilpur, Burdwan well site E2

The effective radius (r_e) of the collector well is given by

$$r_e = 0.25(L + r_c) \tag{6.21}$$

where r_c is the radius of collector well caisson.

Hence,

$$\begin{aligned} r_e &= 0.25(35 + 4) \\ &= 9.75 \text{ m} \end{aligned} \tag{6.22}$$

Well Ident.	Description
W1	Edilpur, Bardwan

Distance(m)	Avg. Pumpng Rate	Duration (min)	Initial Sat Thickness
20.00	21.34523m^3/day	4320.00	

RESULTS			
Transmissivity(m^2/day)	Storage Coeff	Leakance	Estimation Err.
3298.218	0.000001026130		0.02
Aquifer	Fit Method	Jacob Method	
CONFINED			

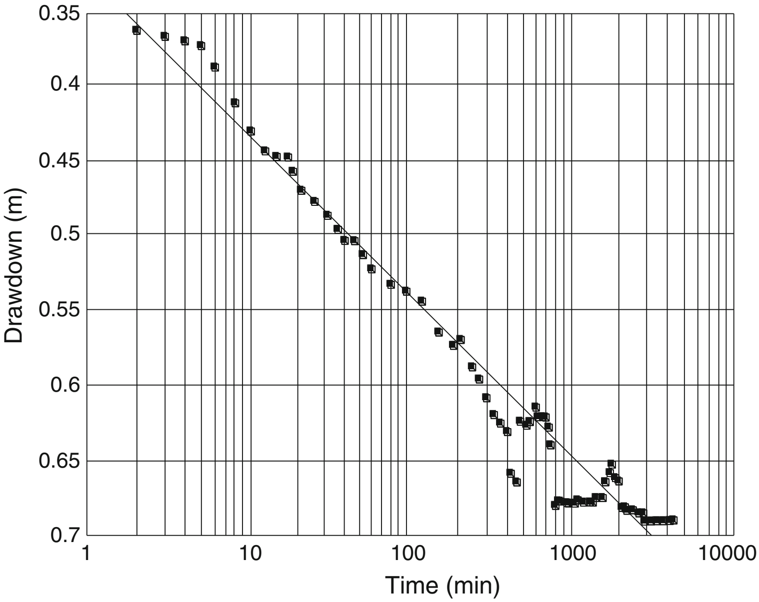

Fig. 6.7 Pumping test output data at Edilpur, Burdwan well site W1

The yield from the collector well will be

$$Q = \frac{2.72T' s_{\mathrm{w}}}{\log^{10}\left(\frac{R}{r_{\mathrm{e}}}\right)} \tag{6.23}$$

$$= \frac{2.72 \times 3250 \times 3.4}{\log(300/9.75)} \tag{6.24}$$

$$= 20197 \text{ m}^3 \text{ /d} \cong 20 \text{ MLD}$$

Well Ident.	Description
S2	Edilpur, Bardwan

Distance(m)	Avg. Pumpng Rate	Duration (min)	Initial Sat Thickness
20.00	21.34523m^3/day	4320.00	

RESULTS			
Transmissivity(m^2/day)	Storage Coeff	Leakance	Estimation Err.
3339.115	0.000008127753		0.03
Aquifer	Fit Method	Jacob Method	
CONFINED			

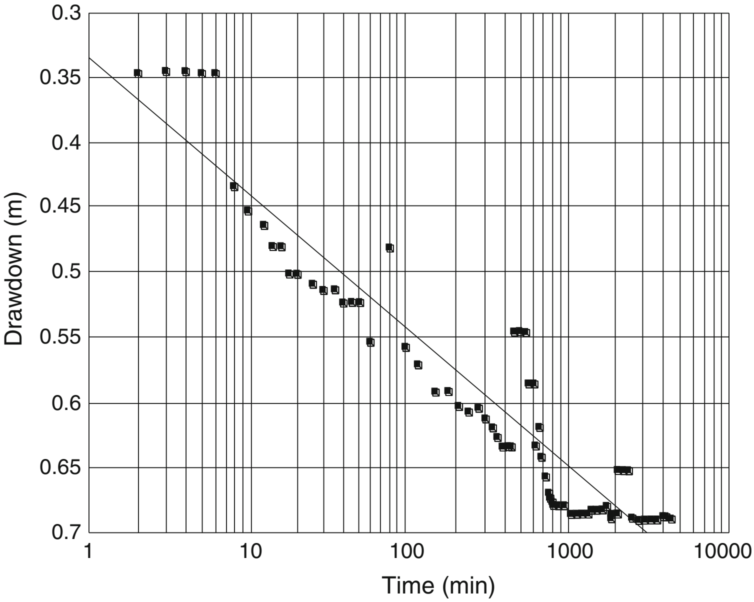

Fig. 6.8 Pumping test output data at Edilpur, Burdwan well site S2

If allowable drawdown was increased to 6.8 m, the safe yield from the collector well can be increased to 40 MLD.

Hence, it is recommended that in the first phase, the pump machinery (having rating of 1100–1600 m^3/h, target rating of 850–1250 m^3/h with 80 % efficiency) be provided such that the drawdown after 24-h pumping will be maintained at 3.4 m or so, for 20 MLD water supply. In the final phase, one more pump machinery may be lowered suitable for additional 20 MLD pumping. The operation has to limit the drawdown to 6.8 m in 24 h. It is advisable that in no case, i.e. even during "worst-case" conditions during the summers, the drawdown be permitted to exceed 10 m.

6.5.5 Characterization of Aquifer Material

The confined aquifer planned for tapping water consists of two distinct layers—first of coarse sand and second of coarse sand mixed with gravels throughout the areal extent of 50 m diameter as determined by bore logs. In order to get engineering data of aquifer material required for the design of collector well, the grain size distribution analyses were performed for the soil samples collected from the aquifer at main pumping well as well as at 4 observation wells situated at a radial distance of 50 m from the pumping well.

In order to provide more effective head over the horizontal strainers, the strainers will be placed at a depth corresponding to two-third that of the aquifer. Hence, the strainers will be provided in the course sand with gravel layer, and as such, the critical design parameter corresponding to this layer shall be utilized for the design of strainer pipes. The grain sizes are varying from 0.25 to 0.48 mm. The effective size (ES) is estimated as 0.25 mm and uniformity coefficient (UC) as 3.11.

6.6 Design of Collector Well

The collector well will be designed for a capacity of 20 MLD. The pumping shall be done for 24 h (3 shifts of 8 h each). Let the horizontal strainers 30 m length (L_s) having 250 mm diameter (D) be used (Fig. 6.9), (Bandopadhyay et al. 2000).

The design yield (Q) will be given by

$$Q = n\pi DLpV \tag{6.25}$$

where n is the number of horizontal strainers or laterals, p is open per cent area of strainers (usually kept as 15–18 %), and V_e is entrance velocity through strainer slots (not to exceed 0.6 m/min). Here, Q is 20 MLD, i.e. 0.231 m^3 s.

Let us assume 16 % open area of the strainer pipe, 40 % clogging of the slots of each strainer and entrance velocity of 5 mm/s. The number of strainers required to provide the design yield of 0.231 m^3/s is given by

$$\begin{aligned} n &= \frac{Q}{\pi DL_s pV_e} \\ &= \frac{0.231}{\pi \times 0.25 \times 30 \times (0.60 \times 0.16) \times 0.005} \\ &\cong 20 \end{aligned} \tag{6.26}$$

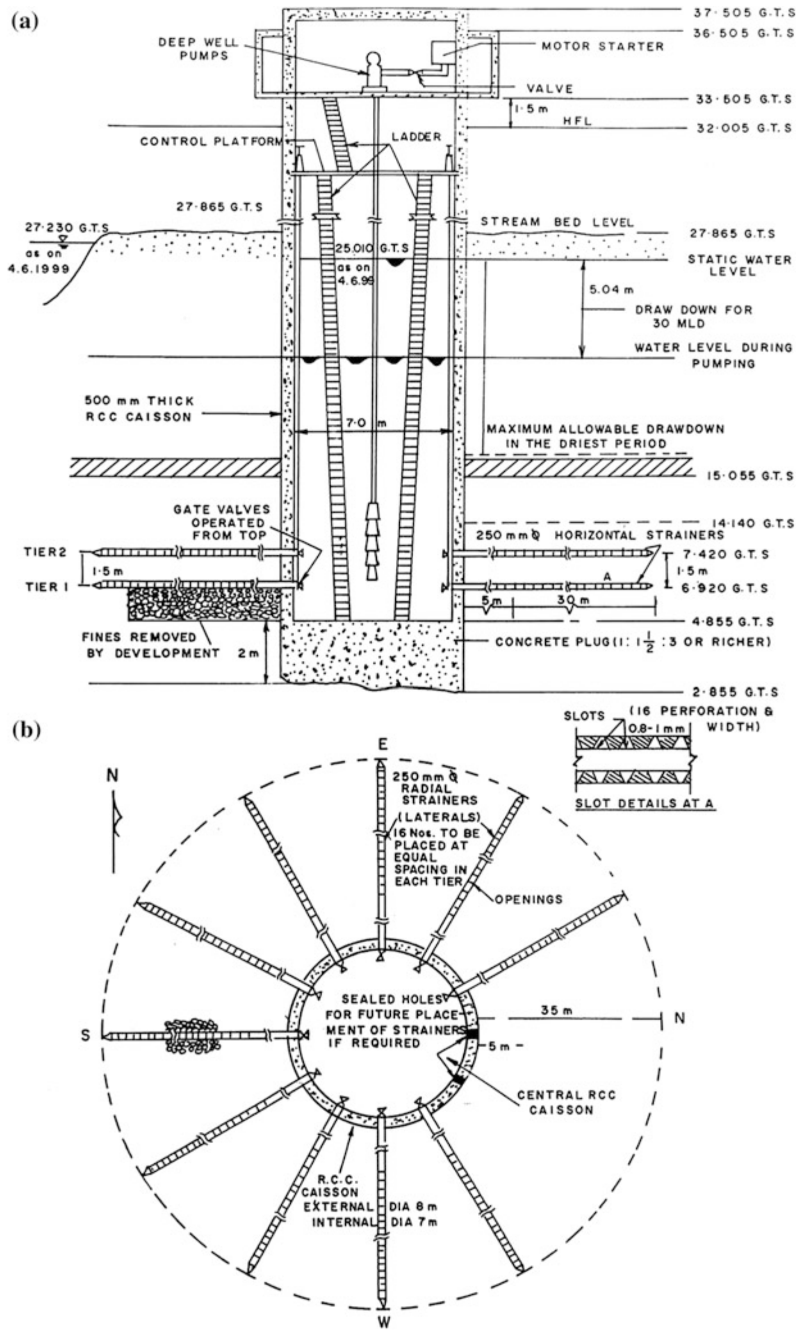

Fig. 6.9 **a** Sectional elevation and **b** plan showing position of strainers

These 20 nos. of 250 mm dia strainers will be spaced equally around the circumference of the caisson in single tier. Let the centre-to-centre distance between the strainers be 1 m, and then, the circumferential length required will be

$$= (n - 1) \times c/c \text{ distance}$$
$$= (20 - l) \times l = 19 \text{ m}$$

So required internal diameter of the caisson is

$$\frac{19}{\pi} = 6.05\,\text{m} \tag{6.27}$$

To facilitate lowering and placing of pump machinery, an internal diameter of 8 m of the RCC caisson has been recommended here. The strainers may also be provided as 17 nos. of 300 mm dia or 13nos. of 400 mm dia or 10 nos. of 500 mm dia.

6.6.1 Design on the Basis of 16-h Pumping

It is usual practice to pump required supply by pumping only for 16 h (2 shifts of 8 h each); hence, the design has been revised to accommodate for the same purpose. Now, the collector well has to supply 20 MLD water in 16 h only at the pumping rate of 0.347 m^3/s. Assuming same design parameters as before, the number of 250 mm dia strainers required to deliver the target flow rate is as follows (Eq. 6.26):

$$n = \frac{0.347}{\pi \times 0.25 \times 30 \times (0.60 \times 0.16) \times 0.005} = 32$$

The internal diameter of well caisson will be kept as 7 m and external as 8 m. Sixteen strainers of 250 mm dia shall be placed at an equal distance (about 1.465 m centre to centre) along the internal wall of the caisson in the first tier. The second tier consisting of another 16 strainers shall be placed at a distance of 1–1.5 m below the central line of upper tier.

The strainers may also be provided as 26 nos. of 300 mm dia (in two tiers) or 22 nos. of 350 mm dia (in two tiers) or 20 nos. of 400 mm dia (in single tier).

6.6.1.1 Check for Drawdown

The expected drawdown in the collector well for a pumping rate of 0.347 m^3/s for 16 h will be

$$s = \frac{0.347 \times \log(300/9.75)}{2.72 \times 3250} = 5.04 \text{ m} \tag{6.28}$$

6.6.1.2 Specification of Strainers

Since ES for aquifer soil is 0.25 mm and UC is 3.11 > 2, i.e. well graded, the artificial gravel packing can be avoided. However, natural development of the strainers as per standard practice is strongly recommended.

The width of slots on the strainers may be kept at d_{40}–d_{70}, i.e. 0.4–1 mm, say 0.8 mm as obtained from sand analysis. Hence, slot size may be kept as 0.8–1 mm with the perforated area of the strainers around 16 %.

The design of the radial collector well is shown in Fig. 6.9a, b (Bandopadhyay et al. 2000).

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Chapter 7
Groundwater Quality and Contamination

Abstract Besides quantity of water, quality is very much important for human use. Beyond the permissible limit, the water is considered as polluted. Direct pollutions are bacterial, organic, heavy metal, seepage, discharge of salt and chemical. Indirect pollutions are nitrogen monoxide in atmosphere and fluoride and arsenic pollution in the water in different parts of India. Groundwater is used for domestic, municipal and other purposes. The groundwater within the dug wells may be polluted with the contaminants from shallow depths. Hence, hand pump water from deeper depths is preferred for drinking purposes. Nowadays, use of groundwater is increasing day by day due to high carrying cost of surface water. In industry, also deep tube well groundwater is preferred due to its purity. The quality of water is measured by the amount of TDS (total dissolved solids). This amount must be controlled by different treatments depending upon the use. Groundwater may be contaminated by different sources, i.e. municipal and domestic sources, agriculture sources and industrial sources. It is very difficult to purify the polluted water; hence, remedial measures must be taken to prevent the contamination. For example, pollution may be restricted by selecting proper dumping site which is underlain by impermeable formation.

Keywords Quality · Permissible · Chemical · TDS · Pollution · Contamination · Arsenic and fluoride

7.1 Introduction

Most of the total 1.4 billion km^3 of water available on earth is sea water. Of this, about 2.5 % is freshwater mostly contained in ice caps and glaciers. Thirty per cent of the freshwater is stored as groundwater. Earth receives 1, 10,000 km^3 of precipitation over the land masses (rest on sea) of which 39,000 km^3 forms the surface and subsurface run-off. About one-third of this, i.e. 14,000 km^3, seeps into the ground as subsurface run-off and becomes groundwater.

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Springer Hydrogeology, DOI 10.1007/978-981-10-1148-1_7

According to the available global water supply data, there should not be any lack of freshwater supply worldwide. However, regional shortage cannot be avoided due to special and temporal variations in precipitation reducing potential usable water supply. This shortage is of seasonal, local and regional nature.

In the following sections, quality of groundwater aspects will be outlined followed by groundwater pollution. Besides quantity of water, quality is very important from human use point of view. Beyond a certain degree of pollution, water becomes unusable. As a result, the supply of usable water is reduced. There may be several types of direct pollution, namely bacterial, organic, heavy metal, seepage and discharge of salt and chemicals. There is some amount of atmospheric pollution (such as nitrogen monoxide), which enters the water through precipitation. In some parts of India, fluoride pollution has been significant. Arsenic pollution has reached a dangerous level in eastern India (W. Bengal state) and in Bangladesh.

Arsenic is one of the big four metals of environment concern along with lead, mercury and cadmium. Initially, arsenic has been notorious as a preferred poison in homicides. The arsenic level permissible for drinking water on international standard ranges from 0.04 to 0.05 ppm. It has been observed that the health risk of skin cancer is high compared to other contaminants.

7.2 Dissolved Salts and Salinity

The concentration of dissolved salts within groundwater is a measure of the quality of water. Depending on the percentage of the material, the water may be considered for drinking, industrial and agricultural purposes. The concentration of dissolved matter given by the total weight of the material on evaporation to dryness is known as total dissolved salts and is expressed in ppm (parts per million or mg/l). The total dissolved salt of groundwater may range from 20 ppm (freshwater) to 1000 K ppm for seawater and desert brine. Groundwater with a total dissolved salt of less than 1000 ppm can be assumed to be fresh, while total dissolved salt up to 500 ppm is good enough for drinking.

The dissolved mineral material in the water is derived from the soils and rocks, and it flows through besides a little amount of carbon dioxide dissolved in the atmosphere.

7.3 Groundwater Utilization

Groundwater is used for domestic, municipal, agricultural, industrial and other purposes. Groundwater is preferred compared to surface water because of its convenient availability close to the point of use and quality needing no treatment for various uses. We may classify the utilization of groundwater under the following heads.

(i) Domestic,
(ii) Municipal,

(iii) Agricultural,
(iv) Industrial and
(v) Nature and environment.

From the available statistics, it can be stated that approximately seventy per cent of the exploited water, worldwide, is used for agricultural, mainly irrigation, purposes. While industrial water use is estimated roughly as twenty-four per cent worldwide, the rest is used for other purposes (domestic and municipal) including nature and environment protection.

Accordingly, the conventional renewable groundwater sources are outlined as follows.

7.3.1 Groundwater for Drinking (Domestic and Municipal)

In the choice of the type of well for a particular supply, the problem will depend on the quantity of required water besides economic aspects and existing hydrogeological situation. For domestic purposes, the quantity required is usually low, normally available from shallow bored well and mainly dug wells with depth varying from a few metres to several tens of metres dependant on geological conditions. In this case, groundwater is available through open holes, mainly of circular and sometimes square or rectangular cross section. Yield from shallow dug wells may be high even through thin aquifer due to large cross section available for inflow. Sometimes, dug-cum-bore wells are used for increased yield. For domestic supply, therefore, contaminants from shallow depths may pollute the groundwater within dug wells, and shallow bored wells fitted with hand pump are commonly preferred if groundwater is available.

For municipal supply, large quantity of groundwater is needed which cannot be obtained from shallow dug or bored wells. Shallow large-diameter (200 mm) boreholes sometimes, under favourable hydrogeological conditions, give prolific sustained supply with a perennial recharge from a potential source.

Other sources of large-scale municipal supply are as follows: collector well and open large-diameter well with infiltration galleries. Besides tube wells, several hundred metres deep and of comparatively larger diameter (up to 200 mm) intersecting several porous and permeable zones within impermeable clays form the source of sustained large-scale supply for municipalities.

7.3.2 Groundwater for Irrigation (Agriculture)

Irrigation of agricultural land has long been carried out with the use of surface water, major part of it coming from dams and canals constructed throughout the world. Construction of more possible dams to make up the deficit faced globally does not boost the surface water sufficiently. Such a move would increase global surface water for irrigation and other purposes by ten per cent only but at a highly prohibitive cost.

Accordingly, there has been a gradual increase in the use of groundwater. Without population and pollution control, the scarcity of groundwater will be alarming with time with water tables falling in the major food-producing regions.

Irrigation water from underground is obtained through shallow tube wells and deep tube wells drilled through the sediments. The yield from the production well and quality of groundwater must be known before its utilization for irrigation purpose.

7.3.3 Groundwater for Industry

Normally, good quality deep tube well water is preferred for industrial purposes as both bad quality groundwater and surface water may need treatment for some elements, not desirable for corresponding industrial point of view.

Groundwater requirement will vary from industry to industry and is expected to be maximum at par with municipal supply (Sect. 7.3.1) with similar sources used for supply. Some industries arranged in the order of decreasing requirement are as follows: oil refineries, paper manufacturing, metal working plants, chemical manufacturing, air conditioning and refrigeration (Todd 1995).

7.3.4 Groundwater for Protection of Environment

Groundwater requirement for protection of the nature and the environment is comparatively low. Environment is protected mainly by the subsoil water. Depletion in naturally existing water table may have damaging effect on the greens and the plants causing gradual worsening of the soothing environmental conditions.

7.4 Groundwater Quality and Control

Quality of groundwater is controlled largely by its physical and chemical properties. Other quality control parameters are as follows: the presence of bio-organisms, radioactive isotopes and toxic elements such as arsenic. Detailed quality criteria will, however, depend on the type of uses such as drinking, irrigation and industrial.

The source of dissolved substances, mainly salts, involves dissolution of naturally occurring minerals and their salts within the earth through percolating water. The typical cations such as sodium, calcium, magnesium and iron and anions such as fluoride, chloride, sulphate and bicarbonate are formed through chemical reaction and sediment leaching as part of the hydrologic cycle. The total amount of the above substances is quantified by the parameter called TDS. While freshwater may have a maximum limit of 1500 ppm, drinking may have a recommended maximum limit of 500 ppm TDS. Higher TDS for irrigation is allowed depending on the nature of the crops. For industry, certain elements are detrimental depending on the type of industry and treatment processes are to be adopted accordingly.

7.5 Sources of Groundwater Contamination

Groundwater pollution means the presence of impurities in it making the water detrimental to its use for different purposes. Contaminants may be natural or artificial (human-induced) categorized as follows:

(i) Physical (turbidity, colour, etc), aesthetically displeasing;
(ii) Pathogenic (micro-organisms), which transmits diseases;
(iii) Salts (mainly sodium chloride);
(iv) Toxic (heavy metals, pesticides, etc).

The toxic metals include arsenic, cadmium, chromium, cobalt, copper and lead. Besides, compounds of mercury may produce acute poisoning. Arsenic occurs naturally as compound of sulphur, copper, cobalt, lead, zinc, etc. Arsenic concentration in groundwater more than the permissible limit (0.01 ppm as per WHO guidelines) has played havoc in several parts of the world and particularly in India and Bangladesh (to be outlined in the case study in Sect. 7.7). Prolonged use of arsenic-contaminated groundwater causes chronic poisoning such as general muscular weakness, loss of appetite and nausea, skin diseases, neurological disorders and possibly malignant tumours.

The principal sources and causes of groundwater contamination are given in the following sections.

7.5.1 Municipal and Domestic Sources

Leakage of sewage from improperly designed municipal sanitary sewers is the source of groundwater contamination, particularly from old sewers. Several other types of damages caused to the sewers cause flow of sewage into the adjacent formations.

Wastewater from urban domestic uses, storm runoff, etc., a highly variable mix, may cause pollution. Septic tank, tile drains and seepage pits are potential sources of contamination to groundwater. Municipal dumps and sanitary landfills located at badly selected ground may lead to groundwater contamination. Such wastewater introduces bacteria, viruses and inorganic and organic chemicals.

7.5.2 Agricultural Sources

Agricultural wastes left by the crop residues at the end of the cropping season gradually create a source of pollution through percolating water.

The wastes created by animals, confined in large number within smaller areas, leave lot of manure. This large quantity of manure carried away by storm runoff from highly concentrated pollutants reach surface and subsurface waters. Such wastes may carry salts, organic matters, bacteria and nitrates. Nitrate nitrogen is the most important pollutant here.

Application of fertilizers for agricultural purposes containing nitrogen, phosphorous and potassium leads to nitrogen pollution mainly as others are easily absorbed in the soil.

Pesticides used for agricultural purposes in controlling pests may lead to pollution of the water table as pesticides contain detrimental chemicals.

Irrigation return flows are highly saline in nature. This drains into the nearby areas causing contamination.

7.5.3 Industrial Sources

The nature of effluents from different industrial plants will vary with the type of industry and the type of use. Quality of the wastewater will be controlled by the use of water for various purposes within the plant. The effluents discharged into pits, ponds or lagoons migrate gradually down into the water table.

Leaking tanks and pipelines used for storage and transmission underground of petroleum and petroleum products leads to contamination at water-table level and then migrates laterally with groundwater flow. Metallic wastes in plating industry contain cadmium and hexavalent chromium which seep into the water table causing contamination of groundwater.

Different mines play important roles in polluting the groundwater. Coal, phosphate and uranium mines are major sources, next being the ores for extraction of iron, copper, zinc and lead. Oil field brines are highly mineralized contaminants from subsurface disposal of the brine due to various faults within.

7.6 Remedial Measures

The groundwater reserves throughout the world are gradually being contaminated due to discriminatory interference from the mankind through urbanization, industrialization and agricultural irrigation. It should be well remembered that once groundwater is contaminated, cleaning process becomes more or less impossible and such water is seriously hazardous to health. Thus, remedial measures may only contain pollution but cannot stop pollution.

In urbanization pollution such as the one caused by municipal dumps and sanitary landfills, pollution may be restricted by proper choice of dumping site underlain by impermeable formation and a properly constricted sanitary land fill. For septic tank-related effluent discharge and subsequent contamination, extreme care should be taken in locating septic tanks.

The liquid wastes available in industrial processes being hazardous and toxic are usually disposed in deep injection wells drilled up to aquifers with saline water or in undesirable deep porous formations to avoid any use.

Pollutants in groundwater may be reduced or partly removed with time and distance travelled through filtration, chemical processes, microbiological decomposition and dilution. It should be noted that while surface water can be reclaimed, it is difficult to control groundwater contamination because it may persist underground for years. The contaminants are to be controlled at the source if located.

7.7 Arsenic Contamination and a Case Study

7.7.1 Arsenic Contamination in Groundwater

Arsenic is a natural part of the earth's crust and may be found in water flowing through arsenic-rich rocks. Arsenic is a toxic element, and arsenic trioxide being odourless and tasteless has often been used as a poison. Therefore, drinking arsenic-rich water over a long period is unsafe. The inorganic arsenic of higher toxicity found in groundwater is more hazardous compared to organic arsenic found in sea fish, for example.

Arsenic, widely distributed in the earth's crust, is introduced into water through dissolution of minerals and ores, from industrial effluents and from atmospheric deposition. Hyperpigmentation, depigmentation, keratosis and peripheral vascular disorders are commonly reported symptoms of chronic arsenic exposure. Skin lesions generally appear after a minimum exposure of five years. There is no proven technology as yet for removal of arsenic at water collection points, e.g. wells. Arsenic is sometimes reduced if the water is treated for iron and manganese removal.

WHO guidelines for drinking water quality states that inorganic arsenic may be documented as human carcinogen. The safe limit for arsenic in groundwater is accepted as 0.01–0.05 ppm as the national standard may vary country-wise.

7.7.2 A Case Study

The countries in the world wherefrom arsenic contamination in groundwater has been reported are as follows: Argentina, Bangladesh, China, Chile, Ghana, Hungary, India, Mexico, Thailand and USA. Seriously affected are parts of the countries Bangladesh and India (West Bengal, adjacent to Bangladesh). In Bangladesh, the contamination of groundwater is of geological origin, the processes involved being pyrite oxidation and oxy-hydroxide reduction.

7.7.2.1 Groundwater Contamination in India and Bangladesh

Arsenic toxicity in groundwater around southern West Bengal (India), and southern and eastern parts of Bangladesh, is an alarming environmental problem (Acharya et al. 2000). Here, arsenic concentration in groundwater exceeds the permissible limit of 0.05 ppm. In Bengal basin, the area affected by arsenic is mainly located in the delta of Ganges, Brahmaputra and Meghna rivers which suggests multiple natural sources for the arsenic. The cause of arsenic is either natural or anthropogenic accelerated by intense exploitation of groundwater, application of fertilizers and pesticides.

7.7.2.2 The Geological Set-up

The arsenic-affected area in West Bengal (India) and Bangladesh was initially confined to the lower flood–delta plains of the Ganges River, downstream of the Rajmahal Hills (R) shown in Fig. 7.1. The Gangetic alluvial tract upstream of the Rajmahal Hills is generally free of arsenic toxicity. The adjacent part of the Ganges delta in Bangladesh is equally affected in the Bengal basin. It is recognized that arsenic toxicity in Bangladesh extends up to Sylhet basin (Fig. 7.2) and flood–delta plains of the Meghna River in eastern and southern Bangladesh (Fig. 7.1). A strong correlation is observed between arsenic-affected area and the geomorphology and quaternary geology of the Bengal basin (Figs. 7.1 and 7.2). The tectonics of the Bengal basin is revealed by the presence of several normal faults that were active during Quaternary (Fig. 7.2). In Bangladesh, the older oxidized residual clay and sediments beneath the Barind (B, Fig. 7.2) and the Madhupur uplands to the north are free from arsenic problems, whereas the lower plains of the Ganges delta are affected (Acharya et al. 2000).

The floodplain deposits of the Brahmaputra–Jamuna are unaffected. However, the Sylhet basin and Meghna floodplains are affected (Fig. 7.2). The oxidized Pleistocene sediments from the lalmai horst block are free of arsenic problem. It is observed that the arsenic-affected sediments in the Bengal basin are controlled largely by geomorphology and Quaternary stratigraphy.

7.7.2.3 Quaternary Stratigraphy and the Aquifers

The presence of the youngest Toba-ash bed marker at the basal parts of the Quaternary profile has been recorded slightly to the west of the Bengal basin

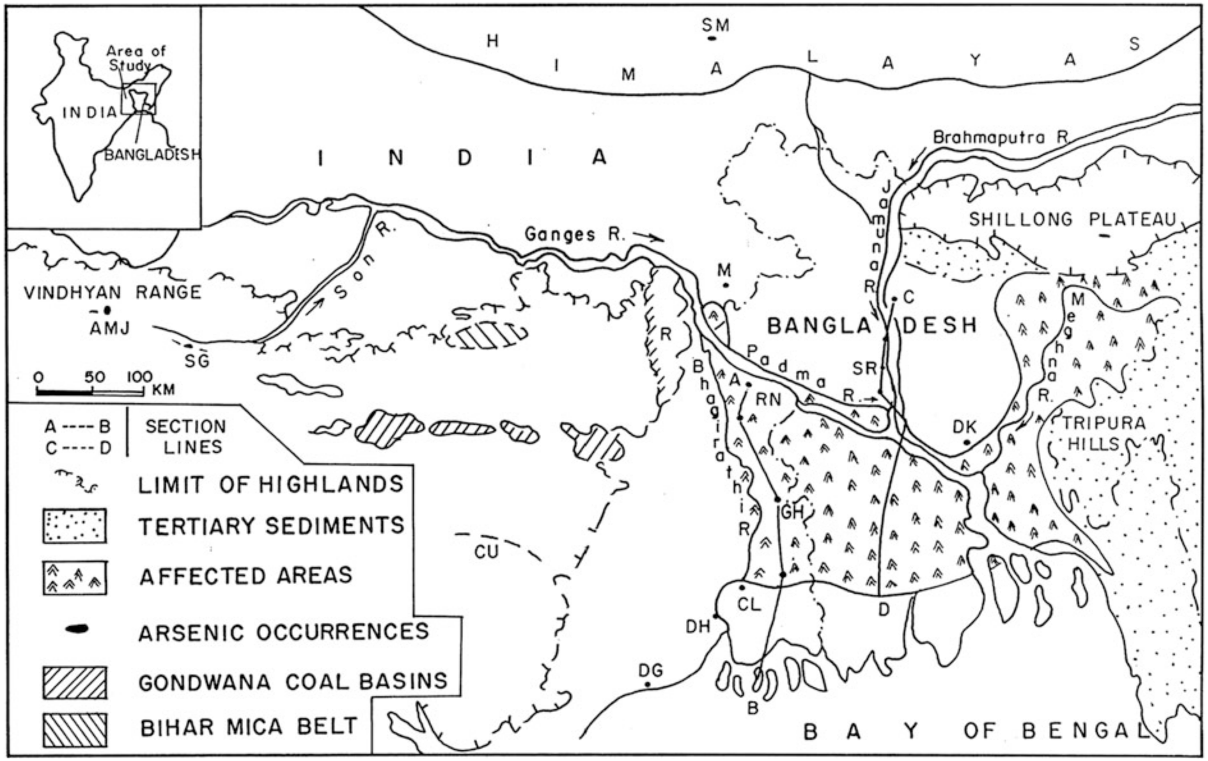

Fig. 7.1 Map of arsenic-affected areas in part of Bengal basin and potential surface. *AMJ* Amjhore pyrite mine, *CL* Calcutta, *CU* Copper belt Bihar, *DH* Diamond Harbour, *DG* Digha, *DK* Dhaka, *GH* Ghetugachi, *M* Malda, *R* Rajmahal Hills, *RN* Raninagar, *SG* Son Valley gold belt, *SM* Samthar, *SR* Sirajganj

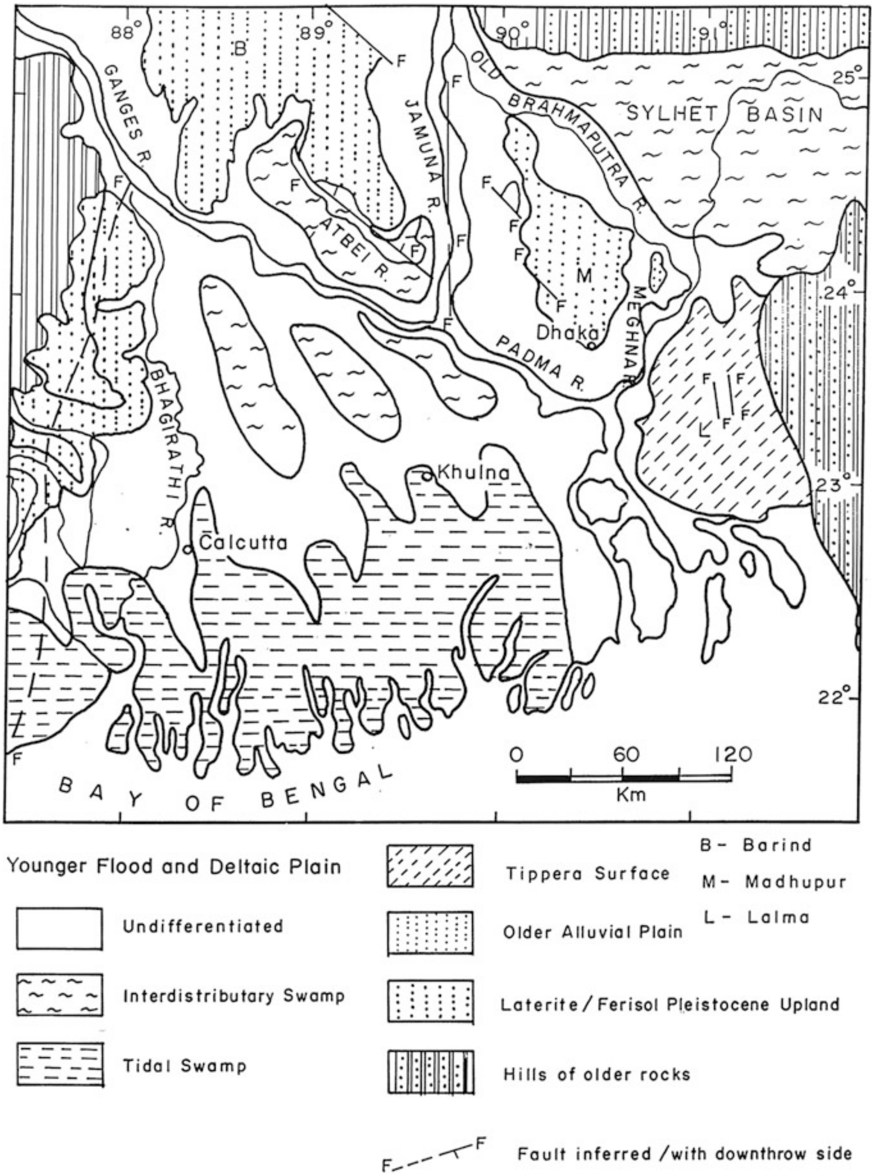

Fig. 7.2 Arsenic toxicity in Bangladesh extends up to Sylhet basin

margin. The Upper Pliestocene–Early Holocene Toba-ash-bearing unit is mainly represented by coarse alluvium that often contains profuse laterite pisolite clasts and is associated with calcretes. This Toba-ash-bearing basal Quaternary unit is correlated with the younger laterite topped unit to the western margin of Bengal basin.

Thus, the laterite plain of West Bengal may be assigned to Pliestocene or Early Holocene age (Fig. 7.2). Figure 7.3a shows (Acharya et al. 2000) the generalized lithology inferred from groundwater drilling and heavy mineral studies. The subsurface sediments beneath the younger delta plain from northern and southern arsenic-affected districts in West Bengal have been tentatively classified into three broad zones (I, II and III in Fig. 7.3a) according to arsenic concentration. Figure 7.3b represents Brahmaputra–Jamuna braided river flood plain and southern parts of the Ganges delta in Bangladesh. This compares well with Quaternary section of the Bhagirathi–Ganges delta plain in West Bengal (Fig. 7.3a). The middle units (unit II in Fig. 7.3a and unit 2 in Fig. 7.3b) containing arsenic-bearing aquifers from West Bengal and Bangladesh can also be correlated.

7.7.2.4 Source of Arsenic in Groundwater

The regional extent of arsenic toxic zone in West Bengal (India) and Bangladesh indicates multiple natural sources of arsenic contamination. However, Brahmaputra–Jamuna and Brahmaputra flood plains in Bangladesh remain unaffected from the contamination.

Although the specific source of arsenic contamination in the Ganges delta is yet to be identified, the likely sources are as follows: (i) the Gondwana coal seams in Rajmahal basins (upto 200 ppm), (ii) pyrites with pegmatites in mica belt of Bihar and (iii) the gold belt of the Son Valley (arsenic upto 1000 ppm) along with other minor sources.

The arsenic toxicity in groundwater in Bengal basin is caused by its natural setting and accelerated by recent anthropogenic activities.

7.7.2.5 Mobilization of Arsenic in Groundwater

Movement of arsenic depends on reducing conditions created by organic-rich sediments, and the presence of poorly crystallized ferric oxide reacts with pyrites-releasing iron and additional arsenic. Dissolved iron content is, therefore, a measure of the degree of reduction in groundwater. The dissolved iron in groundwater in the Ganges basin upstream is low (1 ppm) compared to that in the south West Bengal (36 ppm) downstream. This indicates that not much of iron and arsenic has been mobilized upstream compared to south Bengal basin.

The recent increase in arsenic contamination in groundwater is linked to excessive groundwater extraction for irrigation, the application of phosphate fertilizers and use of pesticides.

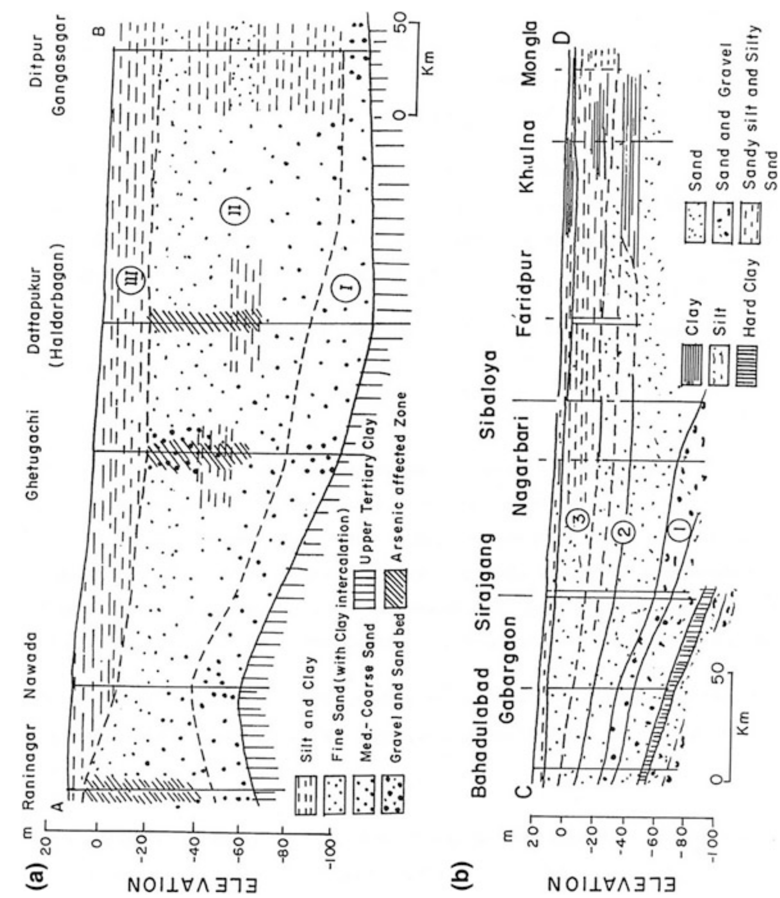

Fig. 7.3 Lithology inferred from groundwater drilling and heavy mineral studies

7.7.2.6 Concluding Remarks

High arsenic contamination of more than 0.05 ppm in West Bengal is observed mainly on both the sides of the Bhagirathi River occurring generally within the depth span 20–100 m below ground level. Arsenic-rich groundwater is found to occur by and large within the upper delta plain of meander belt of the Bengal basin. Changes in pH, oxidation–reduction potential and aqueous chemistry may have mobilized the contaminant arsenic species already present in the sediments. The likely mechanism is leaching of arsenic into groundwater influenced by a number of interacting factors such as groundwater withdrawal, percolation of oxygenated water through soil, properties of iron-oxide present in the soil, application of fertilizer containing phosphate and microbial reactions within the soil. Groundwater withdrawal for irrigation purposes is assumed to be the primary cause.

In Bangladesh, arsenic contamination is derived from the strata underground, through the processes of pyrite oxidation and oxy-hydroxide reduction. With pumping, air or water with dissolved oxygen penetrates into the ground and helps in decomposition of the sulphide-releasing arsenic. In the other process, arsenic is naturally transported and absorbed on to fine-grained iron or manganese oxy-hydroxide, which slowly breaks down.

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Chapter 8
Groundwater Legislation and Management

Abstract During past two decades, the water level in several parts of the country has been falling down rapidly due to the increase in exploration. It is also calculated that in 2050 AD, most of the river basins shall become water deficient. To restrict the declining trend in groundwater level due to random drilling without planning and heavy withdrawal efforts made by Ministry of Water Resources for enactment of suitable legislation by States/UTs to control and regulate the development of groundwater in their respective areas. Hence, Ministry created Central Ground Water Authority for dealing with all drillers and other agencies that are planning for drilling. In these rules, there are certain areas which are restricted for drilling for a particular depth, some areas are restricted for deeper depth, and some areas are restricted not for drilling. Also some places are decided free for drilling as there is no depletion of water. The authority is also to look after the pollution aspects with certain Act. Beside the regulations, these legislations are necessary for efficient management of pure groundwater.

Keywords Drilling · Enactment · Decline · Regulation · Pollution · Management and development

8.1 Introduction

Water occupying the pores and interstices within a geological formation in the zone of saturation is commonly referred to as groundwater. A porous and permeable formation which holds and transmits an appreciable quantity of water under normal field conditions is known as an aquifer (Todd 1995). Groundwater becomes a useful resource when water yield from a well or spring is perennial or persists for a large part of the year and is available in a quantity and quality commensurate to the desired use. Groundwater is replenishable but not inexhaustible. Groundwater resource management is vital for overall human survival. Proper well design, its optimum yield and well spacing parameters should be properly assessed for appropriate groundwater management.

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Springer Hydrogeology, DOI 10.1007/978-981-10-1148-1_8

In our country, plenty of water is available as groundwater but per capita availability is getting decreased due to degradation in its quality through pollution processes and increase in demand. Due to unplanned and uncontrolled withdrawal of groundwater, it is estimated that by 2050 AD, most of the river basins in India shall become water deficient (Chaturvedi 2000). Further, random drilling by individuals without any legal obligations calls for government control through legislation of the Parliament.

8.2 Legal Aspects of Groundwater

Water policy is an important part of water supply and demand managements although no restriction is welcome by the people as water is treated to be a free natural asset like air. However, water policy reforms through legislation are necessary for an equitable distribution of quality water for domestic use particularly due to deficiency in supply against demand. The scale of development and water shortage and intensity of agricultural production and industrial reduction are the factors influencing water policy reforms, and key elements are as follows:

(i) legal and social safeguarding of water rights;
(ii) management of the irrigation systems by user cooperative;
(iii) creation of price incentives for saving water;
(iv) environmental safeguards; and
(v) control on subsidies on water use, particularly in agricultural sector.

Subsidies on irrigated agriculture are the largest single item on agricultural budget in many countries. Statistics available shows that eighty per cent of public spending in Mexico, over fifty per cent in China, Pakistan and Indonesia and thirty per cent in India are spent on irrigation. Lowering of the water table is another serious problem in irrigated agriculture due to overdraft at a rate higher than the recharge. Legislations are needed to restrict pollution of groundwater from industrial effluents, poorly treated sewage and effluents, seepage of agricultural chemicals and run-off from mining wastes.

Strategies for sustainable groundwater management need the framework conditions for effective use of water. Reform of existing water policy through legislation is of primary importance for a sustainable supply.

8.3 Groundwater Legislation

Groundwater overdraft control and groundwater pollution prevention are the main aspects of consideration in groundwater legislations. The legislations are necessary for proper regulation, control and development and efficient management of groundwater.

8.3.1 Global Scenario in Legislation

Unrestricted development and exploitation of groundwater may gradually lead to lowering of the phreatic water levels, yield of wells, change in quality of water, intrusion of saline water and so on. In the absence of any groundwater law, there is no machinery to protect from harms due to overdraft and to provide equitable distribution. Legislation may stop random drilling and pumping and thereby well interference. However, depending on the regional factors such as degree of water shortage and quantum of pollution, groundwater regulatory legislations vary country-wise.

Some salient points of the basic doctrines of the groundwater law applied in various parts of the world are discussed in various literatures such as Karanth (1995) and Planning Commission (2007). It may, however, be noted that some States even in USA do not regulate or administer groundwater use at all, while others do not control withdrawal. Some States bring critically overdrawn basins under regulatory control. In England and USA, the groundwater laws cover a wide spectrum of water rights (Karanth 1995).

For the English, the absolute ownership of groundwater below the land rests with the owner of the land without any liability for harm to neighbouring property owners. This common law doctrine may meet most agricultural demands in a temperate country with several streams around. Such a system which permits full exploitation of land and water resources may not be suitable in countries with limited groundwater resources.

Under American system, reasonable use rule permits the owner to use the underground water only for the owner's land around. Transportation outside his land may cause legal action for the harm to neighbouring owner. The landowner has a restrictive vested right (correlative rights) and has to share with other owners proportionately during shortage of water. Similar other rights are enforced under American doctrine in the event of water scarcity and adverse use. The State of Colorado decommissioned irrigation wells by force, and Idaho purchased water rights from irrigators and closed wells where pumping from increased depths became expensive. In Arizona, over-exploitation and falling water levels are addressed by legislation that mandates balancing abstraction with recharge (Planning Commission 2007).

In Oman, groundwater regulatory measures include obligatory registration of all wells, introduction of well permits, prohibition of wells at less than 3.5 km from the mother well of a "*falaj*" (water management system to provide reliable supply of water to human settlements and for irrigation in hot, arid and semi-arid climates), filling up of illegally constructed wells, confiscation of drilling contractor's equipment involved in illegal drilling, a national well inventory, well metering, well-field protection zoning, water treatment, leakage control, improving irrigation techniques and public awareness campaigns for water conservation (Planning Commission 2007).

Water Act (1985) in Spain bestowed ownership rights upon the State. River basin management agencies were given a role in managing groundwater. They were also vested with the power to grant permits for groundwater use that started after 1985. It also gave authority to the river basin agencies to declare an aquifer as over-exploited and, once it was so declared, to formulate an aquifer management plan for recovery of the aquifer. Some features of such a plan were the reduction in volume of withdrawals or rejection of new applications for wells. In addition, all users of the aquifer were required to organise themselves into groundwater user associations in order to encourage user participation (Planning Commission 2007).

By the law of the Nation's Waters of 1992, water was declared as a national property in Mexico and it became mandatory for existing users to legitimizing their rights through procuring water concessions. The National Water Commission (NWA) was entrusted with the responsibility of registering water user associations and sets up a regulatory structure to enforce and monitor their concessions granted and also to collect a volumetric fee from all users, except small-scale irrigators (Planning Commission 2007).

8.3.2 Indian Scenario in Legislation, Regulation and Control

There is no comprehensive legislation in India on groundwater extraction and particularly over-exploitation. In the constitution of India, there is no specific mention of groundwater but only water. Groundwater is an invisible resource whose withdrawal may be made through a point on the land surface owned by an individual or community (Chaturvedi 2000).

Some points in Indian Constitution are important in this regard:

Water is included in List II (State list) at entry 17 which States Water, that is to say, water supplies, irrigation and canals, drainage and embankments, water storage and water power are subject to provision of entry 56 of List I (Union list). Entry 56 of List I States Regulation and development of Interstate River valleys to the extent to which such regulation and development under the control of the Union is declared by Parliament by-law to be expedient in the public interest.

It is beyond doubt that water is a State subject and Union (Central Govt.) may only enact a law through Parliament under article 262 of the Constitution. State Governments, however, may enact laws to regulate withdrawal and supply of the groundwater through entry 20 of List III (Concurrent list, Union + State) where the economic and social planning is included and, therefore, indirectly the water resources (Chaturvedi 2000). According to entry 17 of List II, States are empowered to enact laws to control and regulate groundwater exploitation.

Groundwater is a major source of drinking water in both urban and rural India. It is an important source of water for agricultural and industrial sector. Till recently, it had been considered a dependable source of uncontaminated water. At present, more than 85 % of the water supplies for domestic use in rural areas, 50 % of water for urban and industrial areas and 55 % of irrigation water requirement are being met from groundwater. The demand for water has increased over the years, and this has led to water scarcity in many parts of the world. During the past two decades, the water level in several parts of the country has been falling rapidly due to an increase in extraction. The number of wells drilled for irrigation has rapidly and indiscriminately increased. India's rapidly rising population and changing lifestyles has also increased the domestic need for water. The water requirement for industry also shows an overall increase. Intense competition among users—agriculture, industry and domestic sectors—is driving the groundwater table lower. The reasons for this trend can be attributed to enhanced pumpage and over-exploitation. The number of groundwater abstraction structures has increased from less than 4 million during 1951 to more than 17 million by the end of the century. With the growth of abstraction structures, there has been an increase in irrigation potential created by groundwater from 6.5 to 45 m ha during the same period.

In order to arrest the declining trend and to avoid indiscriminatory withdrawal of groundwater, the Government of India has circulated a Model Bill to the States/Union Territories (UTs) as early as 1970 to help them bring out suitable legislation on the lines of the Model Bill to regulate and control the development of groundwater, in their respective areas. The Model Bill was revised and recirculated in 1992, 1996 and finally in February 2005.

The efforts made by Ministry of Water Resources for the enactment of suitable legislation by States/UTs to control the development and management of groundwater are as follows:

- Water being a State subject, it is primarily the responsibility of the concerned State Governments to make suitable legislation to regulate utilization of groundwater.
- With a view to protect groundwater regime and taking safeguard measures against hazards of over-exploitation and to ensure equitable distribution of this vital and limited resources, the Central Government circulated a Model Bill to regulate and control the development of groundwater to all States/UTs in 1970.
- The Model Bill was recirculated in 1992 and again in 1996 for adoption.
- Planning Commission desired that the focus of the Model Bill should be shifted from mere regulation to groundwater development and regulation.
- Accordingly revised Model Bill, 2005, to "**Regulate and Control the Development and Management of Ground Water**" has been again circulated on 28 February 2005.
- So far 10 States/UTs have adopted and implemented the groundwater legislation on the lines of Model Bill.
- 20 other States/UTs have also initiated action in this direction.

In the revised Model Bill circulated in 2005, a new chapter on "Rain Water Harvesting for Recharge to Groundwater" has been introduced, which provides for:

(a) Identification of recharge worthy areas, issuance of necessary guidelines for adoption of rainwater harvesting for groundwater recharge in these areas and issuance of direction by the Authority to the concerned department to include rainwater harvesting in all development schemes falling under notified areas.
(b) Imposition of stipulated conditions by the Municipal Corporation or any other local Authority for providing rooftop rainwater harvesting structures in the building plan in an area of 100 m^2 or more, while according approval for construction.
(c) Promotion of rainwater harvesting and artificial recharge by the Authority through Mass Awareness and Training Programmes.

The Model Bill stipulates:

(a) Establishing of State Ground Water Authorities to frame policies for administration of the legislation;
(b) Empowering the State/Union Territory Government to control and/or regulate the abstraction of groundwater; and
(c) Requiring users of groundwater to seek permission from the State Ground Water Authority to sink a well in the notified area.

The objective of the legislation is to regulate and control the development of groundwater. With a view to bring equity in the distribution of the resource, the “Small” and “Marginal” farmers have been exempted.

The position of enactment of legislation on control and development of groundwater resources in various States/UT as on 04 July 2007 is detailed below: (Tables 8.1, 8.2 and 8.3).

8.3.2.1 Indian Supreme Court Case, 1996

Development took place in this direction due to a Court case between environmentalist Mr. M.C. Mehta Versus Union of India (dated 18 March 1996), regarding water table depletion by 4–8 m in the National Capital Territory (New Delhi).

Supreme Court passed an order on 21 November 1996 for the purpose of controlling/regulating the groundwater resources and constituting an Authority under section 3(3) of the Environment (Protection) Act 1986.

This Court passed orders again on 5 December 1996 (notified on 14 January 1997) directing to constitute a Central Ground Water Authority (CGWA) under subsection 3 of section 3 of the Environment (Protection) Act 1986. Accordingly, the function of CGWA has been given to Central Ground Water Board (CGWB) to collaborate and coordinate with the State Authority in the regulation and control of groundwater.

Table 8.1 States/UTs where legislation enacted and being implemented

Sl. no.	States/UTs	Status of implementation of enactment of legislation
1.	Andhra Pradesh	Andhra Pradesh Water, Land and Trees Act 2002 covering whole State has been enacted with effect from 19 April 2002
2.	Goa	The “Goa Ground Water Regulation Act 2002” has already been enacted by the State legislature on 25 January 2002 and comes into force on 17 March 2003
3.	Tamil Nadu	The State Government of Tamil Nadu has passed an Act “Tamil Nadu Ground Water (Development and Management) Act 2003” on 04 March 2003 which includes provision for setting up Tamil Nadu Ground Water Authority to regulate and control water development in the State of Tamil Nadu. Framing of rules and constitution of State Ground Water Authority is under consideration of State Govt. New provisions of the Model Bill, 2005, circulated by Ministry of Water Resources (MoWR) would be incorporated at appropriate time
4.	Lakshadweep	Lakshadweep Ground Water (Development & Control) Regulation, 2001, has been enacted with effect from 01 November 2001
5.	Kerala	The “Kerala Ground water (Control and Regulation) Act 1997” has since been passed by the State Legislative Assembly
6.	Pondicherry	Pondicherry Ground Water (Control & Regulation) Act 2002 to regulate and control the development of groundwater has been notified in the Gazette of Pondicherry vide No. 6 dated 04 March 2003 which came into effect from 02 February 2005
7.	West Bengal	“West Bengal Ground Water Resources (Management, Control and Regulation) Act 2005” came into effect on 15 September 2005. Rules under the Act have also been framed by the State Govt.
8.	Himachal Pradesh	The State Government has enacted “Himachal Pradesh Ground Water (Regulation and Control of Development and Management) Act 2005” (Act No. 31 of 2005) in the State of Himachal Pradesh which has also been notified on 28 October 2005. The rules under this Act are being finalized
9.	Bihar	The State Government has enacted “The Bihar Ground Water (Regulation and Control of Development and Management) Act 2006” which was notified on 29 January 2007
10.	Chandigarh	In UT of Chandigarh, by-law requiring permission of Chandigarh Administration for withdrawal of groundwater in capital project areas exists. It was informed by Administrator of UT of Chandigarh vide letter No. PS/ADMR-06/578, dated 22 August 2006 that all projects will incorporate provision for rainwater harvesting. 5 additional water bodies have been planned to help recharge groundwater resources

8.3.2.2 Constitution of CGWA

The Central Government, in terms of directions of Hon’ble Supreme Court of India under order dated 10 December 1996, in I.A. No. 32 of CWP No. 4677 of 1985, constituted the CGWA. The Court under its order dated 10 December 1996 directed as under:

Table 8.2 States/UTs which have initiated action for preparing legislation

Sl. no.	States/UTs	Status of implementation of enactment of legislation
1.	Maharashtra	The State Government informed vide d. o. letter No. APANA-1006/C.R. 2005/PAPU-15 dated 04 October 2006 that the Maharashtra Water Resources Regulatory Authority Act was enacted in May 2005 and the State Government is considering amending this Act to incorporate the provision included in the Model Bill circulated by this Ministry. A reminder from Minister, Water Resources, has been sent to the Chief Minister on 28 June 2007
2.	Gujarat	The State Government informed vide letter No. GWR/2005/104-3 (81)-146 dated 27 April 2005 that the draft bill is under the process of finalization and suitable legislation will be enacted soon. A reminder from Minister, Water Resources, has been sent to the Chief Minister on 28 June 2007
3.	Assam	"The Assam Ground Water Bill" has been prepared by the Government of Assam to regulate and control the development of groundwater, which has been referred to Law Department for vetting. Necessary action is being taken for finalization
4.	Haryana	The State Government informed vide letter No. CMM/2006/1549 dated 27 November .2006 that the draft legislation in this regard is in the process of finalization. A reminder from Minister, Water Resources, has been sent to the Chief Minister on 28 June 2007
5.	Jammu & Kashmir	The State Government informed vide letter No. PS/S/PHE/GWB/04 dated 24 November 2005 that the draft Bill for the State has been prepared and sent for obtaining comments of Central Ground Water Board/Ministry of Water Resources. This CGWB informed the J&K Government vide its letter No. 22-2/CGWA/Model Bill/2002-13, dated 6 January 2006 to take into consideration the provisions under the Environment (Protection) Act 2005 while finalizing the State Legislation. A reminder from Minister, Water Resources, has been sent to the Chief Minister on 27 June 2007
6.	Karnataka	The State Government informed vide letter No. MID 36 2003, dated 23 May 2007 that approval of State Cabinet has already been obtained for enactment of the Bill which will be introduced in the State Legislation for approval. A reminder from Minister, Water Resources, has been sent to the Chief Minister on 28 June 2007
7.	Mizoram	Preparation of draft Bill for regulating groundwater with reference to Model Bill for the State is under process in Public Health Engineering Department (PHED). The concerned authority has been instructed to take necessary action
8.	Orissa	The State Government informed vide letter No. 1622/27/WR dated 24 May 2007 that draft Bill to regulate exploitation of groundwater is being finalized for obtaining approval of the Cabinet. A reminder from Minister, Water Resources, has been sent to the Chief Minister on 28 June 2007

(continued)

Table 8.2 (continued)

Sl. no.	States/UTs	Status of implementation of enactment of legislation
9.	Rajasthan	The State Government informed vide letter No. P.14(11)GW/2006, dated 4 May 2007 that the "Rajasthan Ground Water & Management Bill 2006" was presented in Rajasthan Vidhan Sabha on 7 April 2006 and was referred to the Select Committee for examination. A reminder from Minister, Water Resources, has been sent to the Chief Minister on 28 June 2007
10.	Uttar Pradesh	The State Government informed vide letter No. 34/401/62-1-06-17/GW/94 dated 13 December 2006 that after obtaining approval of Planning & Finance Departments, action is being taken to approve the draft Bill. A reminder from Minister, Water Resources, has been sent to the Chief Minister on 28 June 2007
11.	Daman & Diu	The UT Administration informed vide letter No. SE/PWD/DMN/TB/F-149(A)/07-08/130 dated 15 April 2007 that the draft Model Bill to regulate and control the development and management of ground water has been sent to Ministry of Home Affairs, Government of India for obtaining concurrence from the Parliament. A reminder from Minister, Water Resources, has been sent to the Administrator on 28 June 2007
12.	Dadra & Nagar Haveli	The UT Administration informed vide **D.O. No. SE/PWD/DMN/F-163/06-07/620 dated 20 October 2006** that the UT Administration has started the process to regulate the over-exploitation of groundwater by drafting regulation based on Model Bill. **A reminder** from Minister, Water Resources, has been **sent to the Administrator on 28 June 2007**
13.	NCT Delhi	The NCT of Delhi Administration informed vide **letter No. 16 (332)/UD/W/Vol.I/2002/19353 dated 16 March 2006** that the Delhi Water Board (Amendment) Bill 2005 had been placed before the Assembly after which it was referred to a Select Committee of the Assembly. The Select Committee has since rejected the amendment Bill, and the report was adopted by the Assembly on 06 March 2006. **A reminder** from Minister, Water Resources, has been **sent to the Chief Minister on 28 June 2007**
14.	Jharkhand	Enactment of legislation for regulating the extraction and use of groundwater on the lines of the Model Bill circulated by this Ministry is under active consideration of the State Government. Model Draft Bill for the legislation has already been formulated and is likely to be finalized shortly
15.	Meghalaya	The State Government informed vide d. o. letter No. PHE.13/98/181 dated 08 September 2006 that a Committee has been set up to examine the Model Bill. Action taken on the basis on the Committee's recommendation will be intimated in due course. A reminder from Minister, Water Resources, has been sent to the Chief Minister on 28 June 2007
16.	Madhya Pradesh	The State Government informed vide d. o. letter No. 1210/CMO/2006 dated 04 September 2006 that suitable legislation on the lines of Model Bill is under consideration of the State Governments. A reminder from Minister, Water Resources, has been sent to the Chief Minister on 28 June 2007

(continued)

Table 8.2 (continued)

Sl. no.	States/UTs	Status of implementation of enactment of legislation
17.	Uttarakhand	The State Government informed vide d. o. letter No. 621/2-06-14 (01)/04 dated 07 September 2006 that the Bill has been prepared on the lines of Model Bill in consultation with Regional Office of CGWB. Necessary action for approval of the State Cabinet is being taken before the Bill is introduced in the Assembly. A reminder from Minister, Water Resources, has been sent to the Chief Minister on 28 June 2007
18.	Andaman & Nicobar	The UT Administration informed vide letter No. WS/5-1/CE/2007/3286 dated 26 June 2007 that steps have been initiated for enactment of the legislation for groundwater management
19.	Chhattisgarh	The State Government informed vide d. o. letter No. 1716/CMS/2006 dated 12 September 2006 that the groundwater bill is under consideration of the State Government. A reminder from Minister, Water Resources, has been sent to the Chief Minister on 28 June 2007

Table 8.3 States/UTs which feel it not necessary to enact legislation

Sl. no.	States/UTs	Status of implementation of enactment of legislation
1.	Nagaland	In view of very low development of groundwater, State Government feels that the groundwater regulation and management law may be deferred at present. However, now the State has informed that the matter is being examined for necessary follow-up action
2.	Sikkim	In view of very low development of groundwater, State Government feels it not necessary to enact any law at present
3.	Tripura	In view of very low development of groundwater, State Government feels it not necessary to enact any law at present. However, the State Govt. would introduce the Bill in future when stage of development approaches 70 %
4.	Manipur	There is no over-exploitation of groundwater resources in the State. As such, at present, there is no need for such legislation in the State
5.	Arunachal Pradesh	In view of very low development of groundwater, the State has not enacted any legislation for regulation of groundwater

- The Central Government in the Ministry of Environment and Forests shall constitute the CGWB as an Authority under section 3(3) of the Act.
- The Authority so constituted shall exercise all the powers under the Act necessary for the purpose of regulation and control of groundwater management and development.
- The Central Government shall confer on the Authority the power to give directions under section 5 of the Act and also powers to take such measures or pass any orders in respect of all the matters referred to in subsection 2 of section (3) of the Act.

- The Board having been constituted an Authority under section 3(3) of the Act, it can resort to the penal provisions contained in sections 15 to 21 of the Act.
- The main object for the constitution of the Board as an Authority is the urgent need for regulating the indiscriminate boring and withdrawal of underground water in the country.
- The Authority so constituted shall apply its mind to this urgent aspect of the matter and shall issue necessary regulatory directions with a view to preserve and protect the underground water.
- The Central Government in the Ministry of Environment and Forests shall issue the necessary notification under section 3(3) of the Act as directed, before 15 January 1997.

Accordingly, the Central Government in the Ministry of Environment and Forests has issued the notification constituting the CGWB as an Authority for the purposes of regulation and control of Ground Water Management and Development. The CGWA was initially constituted for one year vide S.O. 38(E) dated 14 January 1997. The term of Authority was extended for five years vide S.O. 40(E) dated 13 January 1998. The Authority was made a permanent body vide S.O. 1024(E) dated 6 November 2000.

8.3.2.3 Powers and Functions of CGWA

The Authority has to exercise the following powers and perform the following functions namely:

I. Exercise of powers under section 5 of the Environment (Protection) Act 1986 for issuing directions and taking such measures in respect of all the matters referred to in subsection (2) of section 3 of the said Act.
II. To resort to penal provisions contained in sections 15 to 21 of the said Act.
III. To regulate and control management and development of groundwater in the country and to issue necessary regulatory directions for the purpose.
IV. Exercise of powers under section 4 of the Environment (Protection) Act 1986 for the appointment of officers.

8.3.2.4 Constitution of CGWA

As per the Central Government's notification issued under S.O. 38(E) dated 14 January 1997 read with S.O. 1024(E) dated 6 November 2000, the composition of the Authority is as under:

1. Chairman, CGWB	Chairman
2. Member (SAM), CGWB	Member
3. Member (ED&MM), CGWB	Member
4. Member (SML), CGWB	Member
5. Member (T&TT), CGWB	Member
6. Joint Secretary (Admn.), MoWR	Member
7. Joint Secretary & Financial Advisor, MOWR	Member
8. Joint Secretary (I.A.) MoEF, Paryavaran Bhavan	Member
9. Chief Engineer, IMO(WP&P), CWC	Member
10. General Manager (Exploration), ONGC	Member

The Authority may invite from time to time the following as special invitees as and when required for the Authority meetings

1. The Joint Secretary (Soil and Water Conservation), Dept. of agriculture and Cooperation.
2. The Joint Secretary (Water Supply), Ministry of Urban Development.
3. The Joint Secretary, (Department of Drinking Water Supply), Ministry of Rural Development.
4. Director, National Institute of Hydrology, Roorkee.
5. Director, National Geophysical Research Institute, Hyderabad.

The CGWA has been sanctioned 10 posts. Since the strength is not sufficient, officer and staff from CGWB have been deployed to carry out its functions.

CGWA was constituted vide notification no. S.O. 38(E) dated 14 January 1997, with mandate to regulate and control the development of groundwater and management in the country under the Environment (Protection) Act 1986.

8.4 The Present Scenario

The Union Government has circulated a Model Bill to the States and Union Territories to enable them to enact suitable legislation for regulation and control of groundwater development. After constituting the CGWA, all the States and Union Territories are required to constitute similar Authorities with functions in the State as the Central Authority. The mandate of the Authority shall include the following:

(i) To deploy river basins as the basis for regional planning for sustainable water resource management.
(ii) To prepare medium and long-term national land use including agricultural practices.
(iii) To assess the present irrigation practices and cropping pattern to encourage judicious use of water resources.

(iv) To keep groundwater levels and quality under review and surface water quantity and quality under review.
(v) To ensure maintenance of minimum flows in the rivers.
(vi) To ensure techno-economic feasibility and to implement programmes on reuse of appropriately treated sewage for agriculture, social forestry and non-consumptive public uses.
(vii) To protect, conserve and augment traditionally retaining structures.
(viii) To protect, conserve and augment natural and man-made wetlands in the country.
(ix) To promote rainwater harvesting in human settlement practices and so on.

Although necessary legislation has been made, it is very difficult to implement it. There has to be a radical change in our attitude as water of desired quantity and acceptable quality may not be available. By conservative estimates, India would face acute shortage of freshwater in 2050 AD.

8.5 Groundwater Pollution Control in India

The prevention and control of pollution of groundwater in India is governed by the Water (Prevention and Control of Pollution) Act 1974. According to the Act, pollution includes contamination of water and alteration of physical, chemical and biological properties of water discharge of sewage, trade effluent or any liquid, gaseous and solid substance into water, rendering it harmful or injurious to public health or safely. It also includes contamination of water, rendering it harmful to domestic, commercial, industrial and agricultural or other legitimate uses or to the life and health of animals or aquatic organisms (Karanth 1995). This also restricts the release of pollutants into streams or subsurface water body.

Under the Act, a Central Pollution Control Board was constituted. This provides for constitution of Pollution Control Boards for various States. While the Central Board is advisory in nature, State Pollution Boards have regulatory function of inspection of effluents, plants and works. They have the power to enforce the provisions in the Act and impose penalties.

8.5.1 Contamination Problems

Contamination of water with harmful and pathogenic substances is a well-known problem in developed industrial countries. In developing countries also, contamination is observed with sharp upward trend. The controlling factors include untreated and inadequately treated water from settlements and industrial waste and diffuse contamination from agriculture.

In India, for example, only eight out of 3119 cities are equipped with wastewater treatment plants (Wolff 1999). The Yamuna River flowing through capital New Delhi is contaminated with 0.2 million m^3 of untreated wastewater every day. This leads to a 3200-fold increases in the coliform organism content in the river water within New Delhi.

Contamination of water from industrial effluents, seepage of agricultural chemicals and run-off of mining wastes are a growing problem around the world. The main contaminants found in water include detergents (soap and solvents), all kinds of biocides, petroleum and other derivatives, toxic metals, radioactive wastes, fertilizers and plant nutrients, oxygen-depleting compounds and vectors of diseases such as hepatitis, typhoid fever, cholera and dysentery. As reported in Newspaper (Ananda Bazar Patrika dated 11 February, 2002, Page 5), several people have died in the district of 24 Parganas (West Bengal) near Calcutta due to arsenogenic cancer derived from arsenic contaminated tube well water.

Because of water scarcity, contaminated water is often used for irrigation, creating significant risks for human health and well-being. Contamination of arsenic through tube well irrigation has taken place in fruits and vegetables in parts of West Bengal (India) and Bangladesh. Studies on this aspect are being undertaken now on global basis.

8.6 Groundwater Development and Management

Unplanned use of groundwater through random drilling and unlimited pumping causes gradual depletion in water table. This depletion is reduced through recharge ultimately bringing back the original water table. However, if lowering continues, it must be arrested with what is known as the concept of groundwater management. This approach of planning for the aquifer to yield water at economical cost, in adequate quantity and of suitable quality is called aquifer management system.

Groundwater management is classified into (i) technical management, dealing with technical consideration and methods, and (ii) overall integrated management, dealing with the wider aspects of groundwater and its integration with other sources of water, e.g. precipitation surface run-off and desalinated water, and extends to policy, legal, socio-economic as well as financing and economic aspects of management (Karanth 1995). Wolff (1999) classified management into two strategies, namely supply management and demand management. Supply management deals with identification, exploitation and utilization of unexplored water resources, as well as optimization of operations, maintenance of water supply plants and reallocation of water resources among various consumer and user sections. Demand management deals with special incentives for water-saving mechanism and economic and efficient use of water as a resource.

8.6.1 Groundwater Resource Development

Management of groundwater is not feasible unless a complete assessment of the system is made. Safe yield indicates the quantum of water that can be extracted without disturbing the hydrological equilibrium. Optimum yield takes into account the factors such as economics, water quality, pollution control and water rights. In order to assess development potential of an aquifer, one must know (i) geometry of the reservoir defining dimensions and boundaries, (ii) conditions at the boundaries indicating source of recharge, (iii) lithology and aquifer characteristics, (iv) hydrodynamic conditions, (v) order of magnitude of the reserves, (vi) average natural recharge and discharge and (vii) quality of water (Karanth 1995).

For the evaluation of the above parameters, rigorous hydrological studies, geophysical investigations, assessment of aquifer parameters, evaluation of well hydraulics and water quality testing are the required prerequisites for scientific management of groundwater resources (Maitra and Ghose 1992) given in the flow chart (Fig. 8.1).

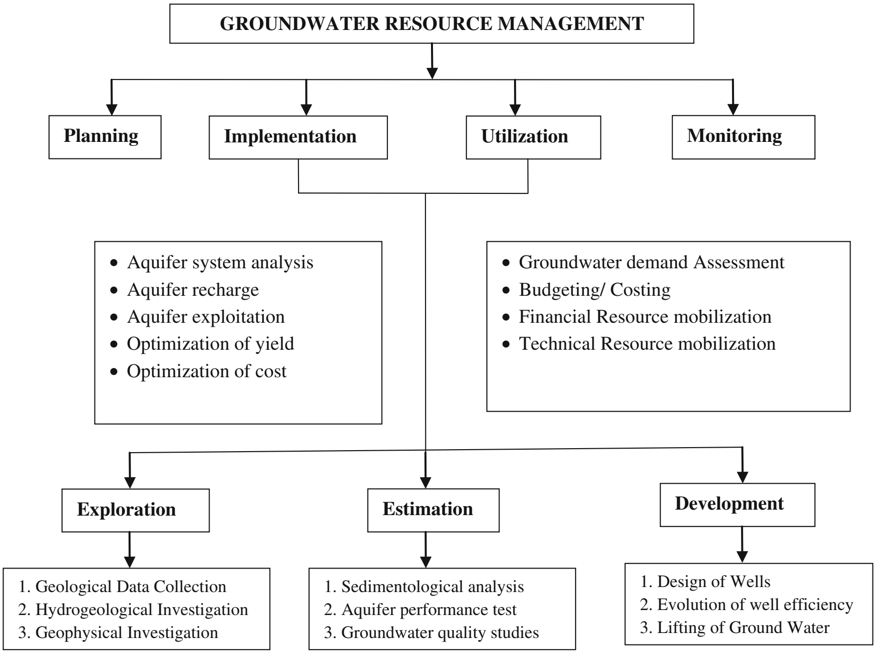

Fig. 8.1 Block diagram outlining groundwater management approach

8.7 Groundwater Resource Management

The term "technical groundwater management" mentioned earlier normally comes in the developmental stage, while "integrated groundwater management" goes beyond into policy, organizational and financial matters and, more broadly, the consideration in totality of water resources. Optimum economic development of water resources in an area requires an integrated approach.

Management of a groundwater body (say, basin) or underground reservoir is to obtain the maximum quantity of water to meet predetermined quality requirements at least cost. However, interference between wells while extracting water must be taken care of in planning and management. Since groundwater is a renewable energy, one may expect unlimited supply. This is possible only when withdrawal is balanced with the recharge of groundwater from the surface. Continued development and exploitation need a "management plan" to stop depletion of groundwater resource.

The groundwater resource is known to be vast but limited. Increase in population, the demand for domestic, industrial and agricultural use of water throughout the world is gradually growing. A lack of management may ultimately be catastrophic. The management objective, therefore, consists of providing an economic and sustainable water supply to meet the growing demand from the underground water resource of which a small portion is perennially renewable (Todd 1995).

We have somewhat fixed groundwater resource already developed, and more sources are being developed without control while demand is growing particularly in the field of agri-irrigation. Two strategies to help meet the above noted challenges are supply management and demand management.

8.7.1 Groundwater Supply Management

The sharp increase in the cost of building allied infrastructure for surface water, resistance from people regarding settlement of the affected and fall of food grain price in the international market, all put together, have a negative effect on the economic viability of new irrigation projects based on surface water.

Political decision-makers, influenced by critical public, and subsequent delayed planning and implementation worsen the crisis in regions of scarce water.

The present new demand for water should be met from carefully selected, economically efficient new water sources through impoundment of surface water and sustainable exploitation of groundwater resources besides the development of non-traditional sources.

Since the management of water resources through construction of dams is expensive and insufficient, exploitation of groundwater is necessary. When renewable groundwater is exhausted, recourse is taken to exploiting non-conventional water resources (reprocessing human and industrial wastewater, desalination of sea and brackish water, for example). Non-conventional water is extremely expensive and uneconomic particularly for agricultural purpose.

Maintaining the balance between supply and demand by supply management does not need new water resources but improved management of available water resources. The shortage of water is often the consequence of inadequate operation and maintenance planning. The shortage may be overcome by proper planning and its application, i.e. proper management.

Management of critical shortage is done, these days, if feasible, through reallocation from one user sector to another. By transferring a small part of the water used in agriculture, water supply for the other sectors may be improved significantly. In Morocco, for example, by transferring only five per cent of water used in agriculture, water supply for community drinking and general purpose of water could be doubled. But whether such reallocation is socially, politically, economically and technically feasible would have to be examined case-wise. Only few countries have so far considered this measure although such a measure is inevitable. Further, the politicians controlled by critical public are afraid of such reallocation, particularly in arid and semi-arid region as it restricts development through irrigation and causes migration from rural to urban centres.

8.7.2 Groundwater Demand Management

With rising demand, an attempt has been made to maintain the balance between supply and demand by exploiting new water resources. By water shortage and drastically increased supply costs and usually inefficient water use, the pressure now is for a greater orientation to demand management. More efficient use of water leads to economic treatment of water as a resource, less environment impact and thus creation of preconditions for sustainable development.

Under demand management, the direct measure is to control water use and indirect measure may be to enforce change in behaviour on the part of users (introduction of market mechanism, financial incentives, programme of raising public awareness, etc.)

Due to losses in all consumption sectors, an increase in the efficiency of water use is the most effective measure in demand management. Improved efficiency level normally leads to water saving, but for water-saving devices, capital expenditure increases substantially. In drip irrigation, for example, a saving of fifty per cent water is possible, but investment is several times more than the flood irrigation.

Another possibility of demand management may be the regulatory measures, if carried out in practice. These include restrictions on the quantity of water used, prohibition on specific uses, water supply on a rotation basis, change in crop pattern, rotation of crops and regulation of groundwater extraction. Also financial incentives on the basis of "user pays" and "polluters pays" principles, which may be difficult in practice for demand management, may be introduced.

8.8 Groundwater Management Scenario in India

As per estimates jointly carried out by CGWB and concerned State agencies, the total annual replenishable groundwater potential in the country is about 433 billion m^3. Keeping 34 bcm for natural discharge, the net annual ground water availability is estimated as 399 bcm. Ground water draft as on March 2004 for all uses is estimated as 231 bcm per year. The stage of ground water development is 58 % (Chatterjee et al. 2009). Development of groundwater for irrigation has been mainly through dug wells and tube wells. Out of 5723 assessment units (Blocks/Mandals/Talukas) in the country, 839 units in various States have been categorized as “over-exploited”, i.e. the annual groundwater extraction exceeds the net annual groundwater availability and significant decline in long-term groundwater level trend has been observed in either premonsoon or post-monsoon or both. In addition, 226 units are “critical”, i.e. the stage of groundwater development is above 90 % and within 100 % of net annual groundwater availability and significant decline is observed in the long-term water level trend in both premonsoon and post-monsoon periods. There are 550 semi-critical units, where the stage of groundwater development is between 70 and 100 % and significant decline in long-term water level trend has been recorded in either premonsoon or post-monsoon (Chatterjee et al. 2009). State-wise groundwater resources and categorization of assessment units are given in Table 8.4.

There is large scope for exploitation of untapped resource. There is a tendency to withdraw groundwater more than the yearly replenishable quantity, causing mining of groundwater. The annual requirement of freshwater from various sectors will be about 1050 billion m^3 by 2025 AD. The deficiency is to be made up by additional supply through exploration of additional groundwater resource in one hand and better management of available resource on the other.

8.8.1 Groundwater Development in India

Most of the rural drinking water and about 50 % of the irrigation water come from underground. Clean and safe groundwater, once easily available, is now becoming a rare commodity due to over withdrawal, contamination, poor sanitation or salt water intrusion.

Overdraft of groundwater lowers the water level and changes flow paths bringing pollutants into uncontaminated zones. In rural and urban groundwater supply, excess fluoride and arsenic have already caused a matter of serious concern. Arsenic in the State of West Bengal on both the banks of river Bhagirathi is playing havoc through tube well water used for drinking and irrigation. Subsidies in water supply, both domestic and agricultural, have not been able to motivate users in groundwater conservation. In irrigation sector, groundwater is developed and managed by the people; a participatory irrigation management emerges as an issue

Table 8.4 State-wise groundwater resource availability, utilization and categorization of assessment units in India (in bcm)

Sl. No.	States/union territories	Annual replenish-able groundwater resources	Natural discharge during non-monsoon season	Net annual groundwater availability	Annual groundwater draft	Stage of groundwater development (%)	Categorization of assessment areas (numbers)	
							Over-exploited	Critical
1	2	3	4	5	6	7	8	9
States								
1	Andhra Pradesh	36.50	3.55	32.95	14.90	45	219	77
2	Arunachal Pradesh	2.56	0.26	2.30	0.0008	0.04	0	0
3	Assam	27.23	2.34	24.89	5.44	22	0	0
4	Bihar	29.19	1.77	27.42	10.77	39	0	0
5	Chattisgarh	14.93	1.25	13.68	2.80	20	0	0
6	Delhi	0.30	0.02	0.28	0.48	170	7	0
7	Goa	0.28	0.02	0.27	0.07	27	0	0
8	Gujarat	15.81	0.79	15.02	11.49	76	31	12
9	Haryana	9.31	0.68	8.63	9.45	109	55	11
10	Himachal Pradesh	0.43	0.04	0.39	0.12	30	0	0
11	Jammu & Kashmir	2.70	0.27	2.43	0.33	14	0	0
12	Jharkhand	5.58	0.33	5.25	1.09	21	0	0
13	Karnataka	15.93	0.63	15.30	10.71	70	65	3
14	Kerala	6.84	0.61	6.23	2.92	47	5	15
15	Madhya Pradesh	37.19	1.86	35.33	17.12	48	24	5

(continued)

Table 8.4 (continued)

Sl. No.	States/union territories	Annual replenish-able groundwater resources	Natural discharge during non-monsoon season	Net annual groundwater availability	Annual groundwater draft	Stage of groundwater development (%)	Categorization of assessment areas (numbers)	
							Over-exploited	Critical
16	Maharashtra	32.96	1.75	31.21	15.09	48	7	1
17	Manipur	0.38	0.04	0.34	0.002	0.65	0	0
18	Meghalaya	1.15	0.12	1.04	0.002	0.18	0	0
19	Mizoram	0.04	0.004	0.04	0.0004	0.90	0	0
20	Nagaland	0.36	0.04	0.32	0.009	3	0	0
21	Orissa	23.09	2.08	21.01	3.85	18	0	0
22	Punjab	23.78	2.33	21.44	31.16	145	103	5
23	Rajasthan	11.56	1.18	10.38	12.99	125	140	50
24	Sikkim	0.08	0.00	0.08	0.01	16	0	0
25	Tamil Nadu	23.07	2.31	20.76	17.65	85	142	33
26	Tripura	2.19	0.22	1.97	0.17	9	0	0
27	Uttar Pradesh	76.35	6.17	70.18	48.78	70	37	13
28	Uttaranchal	2.27	0.17	2.10	1.39	66	2	0
29	West Bengal	30.36	2.90	27.46	11.65	42	0	1
	Total States	**432.42**	**33.73**	**398.70**	**230.44**	**58**	**837**	**226**
Union Territories								
1	Andaman & Nicobar	0.330	0.005	0.320	0.010	4	0	0
2	Chandigarh	0.023	0.002	0.020	0.000	0	0	0

(continued)

Table 8.4 (continued)

Sl. No.	States/union territories	Annual replenish-able groundwater resources	Natural discharge during non-monsoon season	Net annual groundwater availability	Annual groundwater draft	Stage of groundwater development (%)	Categorization of assessment areas (numbers)	
							Over-exploited	Critical
3	Dadara & Nagar Haveli	0.063	0.003	0.060	0.009	14	0	0
4	Daman & Diu	0.009	0.0004	0.008	0.009	107	1	0
5	Lakshdweep	0.012	0.009	0.004	0.002	63	0	0
6	Pondicherry	0.160	0.016	0.144	0.151	105	1	0
	Total Uts	**0.597**	**0.036**	**0.556**	**0.181**	**33**	2	0
	Grand Total	**433.02**	**33.77**	**399.25**	**230.62**	**58**	**839**	**226**

Source CGWB, Chatterjee et al. (2009)

in groundwater development. The problem of rising water table and subsequent waterlogging needs be tackled.

8.8.2 Improvement of Groundwater Development Constraints

The constraint in groundwater development locally or regionally calls for an integrated water resource management approach. Accordingly, water quality standards should be set for Indian conditions. On the legislation side, CGWA should declare problematic areas under section 3(3) of Environment (Protection) Act 1986 as notified area for the regulation of groundwater extraction without prior specific approval of the authority. Pollution control, legally controlled extraction and subsurface waste disposal restriction for groundwater may be some way, among others, measures for a probable sustainable availability of groundwater resources in India.

8.8.3 Groundwater Development Strategies

The people of the country now concerned about sustainable environmentally sound groundwater resource development. This will depend on the understanding of the processes in the aquifer system, quantitative and qualitative monitoring of the resource and the interaction with the land and surface water development. The key strategies for sustainable supply are as follows (Sinha Ray 2000).

1. Long-term conservation of groundwater resources;
2. Protection of groundwater from significant degradations; and
3. Consideration of environmental impact of groundwater

The important operational management strategies are as follows:

1. Groundwater resource availability and its vulnerability should be well understood and used in practice;
2. Resource managers and decision-makers should recognize groundwater as crucial component of water resources and the environment; and
3. Knowledge of groundwater system and the environment should be transferred to the groundwater users.

Thus, there should be excellent management institutions which possess the capability and expertise in cost-effective data collection and evaluation scheme. Secondly, effective control on groundwater exploitation and protection of groundwater quality should be enforced. Policies and land use planning are only effective when regulatory measures are implemented through by-laws. Thirdly, the community using groundwater should be provided with knowledge and information on the groundwater system and its interaction with the environments.

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