

The purpose of most hydrogeological investigations is to locate potential sites for development of adequate quantity of reasonably good quality groundwater for a particular use: domestic, irrigation or industrial etc. The quantity and quality criteria would depend on the local needs and the socio-economic conditions of the people. Alternative possible sources of water supply, e.g. import of surface water or groundwater from adjoining areas may also be considered. Further, hydrogeological investigations in fractured rocks are also taken up for the selection of suitable sites for waste disposal including radioactive waste, tapping of geothermal power and in several other geotechnical problems, viz. tunnelling, mining, hill slope stability etc. These include geological, geomorphological, geohydrological studies given in this chapter. Besides, remote sensing and geophysical studies are described in Chaps. 4 and 5, hydraulic properties and methods of aquifer characterisation are discussed in Chaps. 8–9, and tracer techniques are described in Chap. 10.

3.1 Geological Investigations

Geological investigations include surface mapping of different lithological units and their structural and geomorphological features on a scale of about 1:20 000–1:200 000. Aerial photographs and satellite images are preferred as base maps for geological and geomorphological mapping.

In this text, from a hydrogeological point of view, the various rock types are broadly classified into four groups (Table 3.1). Their detailed hydrogeological characters are described in Chaps. 13–16.

In fractured rocks, special emphasis has to be provided for mapping of lineaments, fractures and other

rock discontinuities (Chap. 2). Field mapping should also include information about the orientation and density of fractures, although their subsurface distribution may be different which can be deciphered from subsurface investigations (Chap. 5).

Data about the thickness and composition of the weathered zone (regolith) is particularly important especially in crystalline rocks (Chap. 13). In volcanic rocks, in addition to lineaments, attention should also be paid to the characters of individual flow units and interflow formations (Chap. 14). In carbonate rocks, mapping of various solution (karst) features and springs are of special importance (Chap. 15).

Based on exploratory drilling and well log data (Sect. 5.12), subsurface maps and sections, viz. fence diagrams, isopach maps, structural contour maps etc. are prepared to project the subsurface distribution and configuration of aquifers, aquitards and aquicludes (e.g. Walton 1970; Erdelyi and Galfi 1988). Besides, subsurface geophysical exploration and well log data can be used to extract valuable information on fracture characteristics.

3.2 Geomorphological Investigations

Geomorphological investigations include delineation and mapping of various landforms and drainage characteristics. These contribute significantly in deciphering areas of groundwater recharge and their potentiality for groundwater development. Geomorphic mapping can best be done from remote sensing data using satellite images and aerial photographs on suitable scales (say, e.g. 1:20 000–1:50 000) (Chap. 4). Preferably, a river basin should be taken as a unit for geomorpho-

Table 3.1 Hydrogeological classification of rocks

Rock group	Rock types	Mode of occurrence	Main features important for groundwater occurrence
Crystalline rocks	Non-volcanic igneous and metamorphic rocks, viz. granites, gneisses, schists, slates and phyllites, etc.	Large size massifs and plutons; regional metamorphic belts	Weathered horizon, fracture and lineaments
Volcanic rocks	Basalts, andesites and rhyolites	Lava flows at places interbedded with sedimentary beds	Fractures, vesicles and interflow sediments
Carbonate rocks	Limestones and dolomites	Mostly as chemical precipitates with varying admixtures of clastics in a layered sedimentary sequence	Fractures and solution cavities
Clastic rocks	Consolidated: sandstones and shales; unconsolidated: gravel, sand, clay etc.	Interbedded sedimentary sequence	Intergranular pore spaces and fractures

logical data analysis, though, it may be also realized that surface water basin may not always coincide with the groundwater basin.

3.2.1 Landforms

Landform is an end product of natural weathering. It depends on three main factors: (a) present and past climatic conditions, (b) rock types and their structural features, and (c) the time span involved in weathering.

Genetically, the landforms are divided into two groups: (1) erosional landforms, and (2) depositional landforms. Erosional landforms are typically associated with the resistant hard rock terrains. They comprise: (a) residual hills, (b) inselbergs, (c) pediments, (d) buried pediments with weathered basement, and (e) valley fills. These are described in Sect. 13.2. Depositional landforms are developed by depositional processes of various natural agencies, e.g. river, glacier and wind etc. The depositional landforms are typically made-up of unconsolidated sediments and may occur in the regional setting of hard rock terrains. Therefore, they may play an important role in the groundwater development for local needs (Chap. 16).

3.2.2 Drainage Characteristics

Qualitative and quantitative drainage characteristics of a basin provide an indirect clue to the hydrogeological characteristics of the area and therefore are useful in

the assessment of groundwater resources. The important characteristics are drainage pattern and drainage density. These are related with the lithology, structure and permeability of the bedrock.

Drainage is said to be internal when few drainage lines are seen on the surface and drainage appears to be mostly subsurface, e.g. commonly in limestone and gravel deposits (Fig. 3.1). External drainage is the one in which the surface drainage network is seen to be well developed. Drainage channel-ways are characterized by the typical serpentine-sinuous shape and pattern. Their manifestation depends upon dimensions of the channel, scale of study and also on physical condi-



Fig. 3.1 Internal drainage in limestone. (Aerial photograph courtesy of Aerofilms Ltd.)

Table 3.2 Common drainage patterns in fractured and other hard rock formations and their geological significance

Type	Description	Geological control
Dendritic	Irregular, branching of streams, resembling a tree	Homogeneous materials and crystalline rocks; horizontal beds; gentle regional slope
Rectangular	Streams having right-angled bands	Jointed/faulted rocks, e.g. sandstones, quartzites etc.
Rectilinear	Straight line pattern	Strong linear structural control
Angulate	Streams joining at acute angles	Joints/fractures at acute angles to each other
Parallel	Channels running nearly parallel to each other	Steep slopes; also in areas of parallel elongate landform
Trellis	Main streams running parallel, and minor tributaries joining the main streams nearly at right angles	Dipping or folded sedimentary or low-grade meta-sedimentary rocks; areas of parallel fractures
Radial	Streams originating from a central point or region	Volcanic cones, domes and residual erosional features
Annular	Ring-like pattern	Structural domes

tions of the channel, which may change from season to season, viz. due to flooding, drought, change in sediment load and vegetation cover etc.

Drainage pattern is the spatial arrangement of streams, and is, in general, very characteristic of rock structure and lithology. The drainage patterns can be studied and mapped on topographic maps, aerial pho-

tographs as well as satellite images, on scales as per requirements. Common types of drainage patterns, characteristic of fractured and other hard rock terrains are listed in Table 3.2 and illustrated in Fig. 3.2.

Among various other drainage characteristics of a basin, drainage density, D_d is an important parameter. Drainage density (D_d) is the ratio of total channel

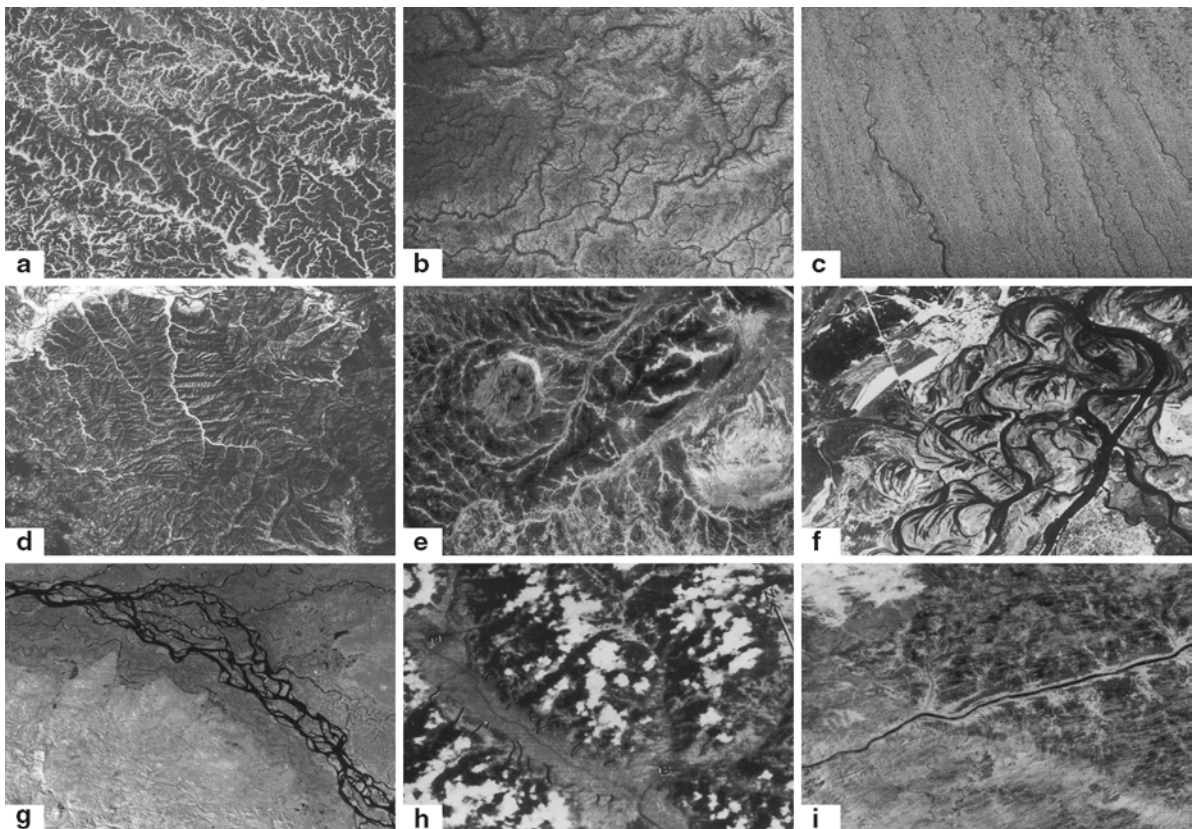


Fig. 3.2 Drainage patterns: **a** dendritic, **b** rectangular and angulate, **c** parallel, **d** trellis, **e** annular and sub-radial, **f** meandering, **g** braided, **h** barbed, **i** rectilinear. (Modified after Gupta 2003)

lengths of streams within a basin to the area of the basin. It has the dimensions of L^{-1} and can be expressed as

$$D_d = \sum L/A \quad (3.1)$$

where D_d is drainage density in per kilometre, $\sum L$ is the total channel length in kilometre, and A is the basin area, in square kilometre. The accuracy of measurement of the total lengths of all streams would depend on the scale of the map, as all the streams may not be shown on a map of small scale. Large scale aerial photographs therefore provide a better idea of drainage network for computing D_d .

Drainage density exhibits a very wide range of values in nature depending upon the relief, climate, resistance to erosion and permeability of rock material (Table 3.3). In general, low drainage density is characteristic of regions of highly resistant or highly permeable surface and low relief. High drainage density is found in regions of weak or impermeable subsurface materials, sparse vegetation and mountainous relief (Strahler 1964). Although low drainage density is considered to indicate regions of high permeability, but this criterion should be used with care as other factors like relief, climate and resistance to erosion may outweigh the influence of permeability of surficial material in a certain area. In areas of low relief, D_d may be more indicative of permeability of surface material and therefore could be used as a criterion for selection of suitable sites for shallow wells. Drainage density also influences runoff pattern and thereby infiltration capacity of the rock material. For example, high drainage density removes surface runoff rapidly, decreasing lag time and increasing the peak of the hydrograph. Among other drainage network parameters, bifurcation ratio, stream frequency and basin shape are also of hydrological interest. Readers may further refer to for example Strahler (1964), Gregory and Walling (1973) and Meijerink et al. (2007).

3.3 Geohydrological Investigations

These include groundwater level measurements, estimation of hydraulic properties of aquifers and assessment of groundwater quality. Study of springs including their location, variability of discharge, chemical composition and temperature also provide useful geohydrological information, especially in carbonate and other fractured rocks.

An observation well network is established for monitoring groundwater levels and groundwater quality. For estimating hydraulic characteristics of aquifers, pumping tests and tracer injection test are carried out. Tracer tests help in not only estimating hydraulic conductivity but also flow mechanism which is important from the point of view of evaluating contaminant transport. In fractured rocks, packer (Lugeon) test and slug test are preferred, at the first instance, as these do not require observation wells. Cross-hole hydraulic test and pumping test are necessary for detailed estimation of hydraulic parameters (Chap. 9). As pumping tests are expensive and require time and manpower, one has to be very selective in implementing such a programme. From groundwater development point of view, groundwater resources, both static and dynamic, are to be computed, and a management strategy for groundwater development has to be worked out (Chap. 20).

3.3.1 Water-level Measurements

3.3.1.1 Observation Wells—Design and Networks

The purpose of groundwater observation well network is to install observation wells or piezometers to monitor the water-levels and quality of groundwater. Keeping

Table 3.3 Drainage density (D_d) values for some terrains in USA. (After Strahler 1964)

D_d (km^{-1})	Geological terrain
1.9–2.5	Resistant sandstone strata of the Appalachian Plateau
5.0–10.0	Rocks of moderate resistance in humid central and eastern USA
12.5–19.0	Strongly fractured and deeply weathered igneous and metamorphic rocks in southern California under dry summer and sub-tropical conditions
125–250 and at places 688–812	In bad land developed on weak clays, barren of vegetation

Table 3.4 Types of observation well networks. (Modified after Heath 1976; UNESCO 1977)

Types of networks	Objectives	Products
Hydrogeological	(a) Status of storage (b) Areal extent and interconnection of aquifers (c) Demarcation of recharge and discharge areas and groundwater flow regime	Regional water-table and/or potentiometric surface map showing water-level fluctuations over a selected period
Water management	(a) Effect of stresses on recharge and discharge conditions (b) Degree of confinement (c) Hydraulic characteristics of aquifers	(a) Local water-level maps (b) Hydrographs showing changes in water-level with time (c) Time-drawdown curves
Baseline	To determine effect of climate, topography and geology on groundwater storage	Hydrographs showing effect of climate, topography and geology
Water quality	(a) Water rock interaction (b) Contaminant transport	Water quality maps and sections
Special purpose	Effect of mining, irrigation and drainage projects	Water-level and quality maps

in view the regional and local requirements, the planning and design of such a network should depend on hydrogeological situations, purpose of investigations, stage of development, as well as political and social demands (UNESCO 1972, 1977). Observation wells can be drilled by using any conventional method of water-well drilling (see Chap. 17). In unconsolidated formations, wells are provided with screens tapping the zone of interest. In consolidated rocks, open-end wells can serve the purpose. The design of piezometers for measurement of water-levels should be different than those installed for collection of water samples for chemical analysis. The piezometers for water-level measurements should have small diameter to accommodate the water-level measuring device and without filter pack (to minimize the effect on groundwater flow) and an effective seal at the top of the screen to check the ingress of water from the surface (Houlihan and Botek 2007). The various types of observation networks are listed in Table 3.4.

The water-level fluctuations in the fractured zones and matrix are likely to be different due to differences in their hydraulic properties. Therefore water-level fluctuations in observation wells in fractured rocks should be interpreted with care.

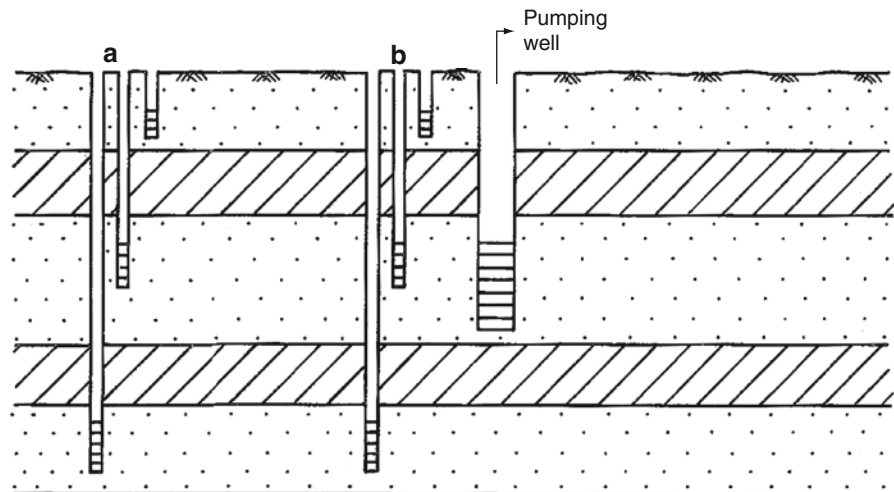
The magnitude of water-level fluctuation also depends upon the relative location of observation well in the basin with respect to groundwater recharge/discharge zones. Wells located close to surface water divide will exhibit greater fluctuation of water-table than those in the midregions or near streams, due to rapid drainage from the upstream areas.

The purpose of hydrogeological network is to allow preparation of water-table or piezometric surface maps. Such maps provide information on the direction of groundwater movement, effect of stresses and changes in groundwater storage as well as areal extent of aquifers and nature of boundaries. In heterogeneous formations, it is necessary to construct a group of observation wells (well nests) tapping different aquifer zones, in order to determine the possible aquifer interconnections and comparison of water-levels in various aquifers (Fig. 3.3). In fractured rocks, the observation wells should be put in relation to rock discontinuities tapping different fracture sets for assessing extent of interconnection and the role of different fractures as conduits for groundwater flow. Lineaments and intersection of vertical fractures are potential sites for monitoring wells. In situations where the matrix blocks have appreciable porosity, it may be necessary to monitor the blocks as well as the high permeability zones (NRC 1996).

The objective of water management network is to obtain information about the effect of recharge and withdrawal on groundwater system. Such wells should be located in proximity to pumping well fields in clusters tapping the pumped aquifer as well as the overlying and underlying aquifers. In order to determine the extent of interconnection, separate observation wells should be installed in unconfined and confined aquifers (Fig. 3.3).

The baseline network consists of observation wells located in areas which are not significantly affected by withdrawals or other man-made stresses. The purpose

Fig. 3.3 Network of observation wells tapping different aquifers in the vicinity of a pumping well



of this network is to determine effect of climate, geology and topography on groundwater levels.

The water quality network is used to determine changes in water quality due to rock-aquifer interaction in the direction of groundwater flow and also with depth, and the effect of man-induced contaminants on water quality. Water quality characteristics can be extremely variable in fractured rocks and karst aquifers. This is particularly true during and after recharge. In order to study the effect of contamination from a point source, at least one observation well should be located upstream from the possible source of pollution, in order to know the background quality. The other observation wells are installed in the down-gradient side from the source of contamination at suitable distances, depending on the rock permeability. In fractured rocks, the monitoring well network should be designed considering the fracture network to enable initial detection of the contaminant (Meyer et al. 1994). In addition to observation wells, data from springs and caves etc. can also provide useful information.

The special purpose network is designed to determine effect of mining and other engineering structures like dams, canals and drainage channels on groundwater levels. In case of open cast mines, the observation well network is put around the periphery of the excavation. In order to determine the effect of rivers and canals on groundwater regime, the observation wells should be put in line across the surface water bodies. If an area is bounded on both the sides by rivers or canals, the observation wells should be located not

only near these hydraulic boundaries, but also in the interfluvial area.

3.3.1.2 Timing and Frequency of Measurements

The frequency of waterlevel measurements in wells and discharge from springs depends on the nature of aquifer and the purpose of study, the broad guidelines being as follows:

Type of aquifer	Frequency of measurement
Confined aquifer	One per month
Unconfined aquifer	Three per month
Wells adjacent to rivers	Daily during flood times
Snowmelt areas	Daily
Irrigated areas	Related to time of irrigation

In drainage studies and also in the study of effect of external forces, viz. changes in barometric pressure, ocean tides, earthquakes, etc., continuous recording of water-level using automatic water-level recorders is necessary.

Spring discharge measurements are of importance for water resources assessment, especially in fractured and karstic rocks. Plots of spring discharge (or stage) and water quality in relation to time, known as spring hydrograph and chemograph respectively, have been used extensively in karst aquifer studies (see Sects. 15.3 and 15.6). Spring discharge in the range of $0.005\text{--}0.01\text{ m}^3\text{ s}^{-1}$ is measured by volumetric meth-

ods while higher discharges could be measured using weirs. Sampling frequency would depend upon the trend of variability of the parameter. Samples should be collected through at least one major recharge event, as such an event is likely to cause rapid changes in the spring discharge, hydraulic head in wells and also in water quality. Samples must also be collected during base-flow (lean period).

3.4 Hydrogeological Maps

Data obtained from field and laboratory studies is plotted on hydrogeological maps and sections. It is necessary to know the purpose of preparing such maps to decide the type of information to be provided and the manner of its presentation. Unlike geological maps, hydrogeological/hydrological maps deal with essentially transient phenomena, viz. groundwater resources, groundwater levels, water quality etc. Therefore, hydrogeological maps should also indicate the dates of surveys, reliability of data and methods of survey.

3.4.1 Regional Maps

Hydrogeological maps depict a number of parameters including the geology of the area, major rock discontinuities, extent of aquifers, hydraulic characteristics, contours of water-table and piezometric surface, water quality, surface water bodies and important meteorological characteristics. Hydrogeological maps may be international, national, regional or local. They usually vary from 1:1 000 000 to 1:250 000 in scale. Considerable variation may be there in the amount of information included in different maps depending on the chosen scale, size of the area and the purpose of the map. For example, a hydrogeological map of the Czech Republic was prepared on the scale 1:1 000 000, showing variations in transmissivities and yield characteristics (Krasny 1996). Further, Russian hydrogeologists (Zektser and Dzhamalov 1988) compiled a World Groundwater Flow map on a 1:100 000 000 scale depicting data of specific groundwater discharge.

For geothermal studies, geothermal resource maps are prepared showing temperature and pressure distri-

bution of a hydrogeological unit which are of practical importance for development of geothermal power.

In the earlier years, different workers and organisation used differing legends and colour codes to depict various groundwater features. This created difficulties in proper interpretation, comparison and compilation of data. To overcome this problem, a common legend including colour code for hydrogeological maps has been suggested for international adoption (UNESCO 1983; Castany et al. 1985). Hydrogeological maps of several countries have been published using the above code (Castany et al. 1985; Verma and Jolly 1992; Struckmeier 1993).

One of the earliest attempts to prepare hydrogeological map of India was made by Taylor (1959). Subsequently, the Geological Survey of India published a geohydrological map of the country on scale 1:2 000 000 (GSI 1969). In 1976, the Central Ground Water Board, compiled and published a hydrogeological map of India on 1:5 000 000 scale which was updated in 1989. The revised map (CGWB 1989) depicts major lithological units, their groundwater potential in terms of well yields and groundwater quality. A map of India showing major groundwater provinces is given in Fig. 20.3.

3.4.2 Map Media—Hard Copy and Electronic

Hard copy maps use paper, photographic film or other similar materials for map record and display in colour or black-and-white. Most of the hydrogeological maps are available as hard copy prints throughout the world. However, with the transformation in information technology, recently, computer coded maps in electronic media are now becoming available in some countries. These maps may use raster or vector format in GIS, and may be restructured and re-formatted as per requirements. Further, such maps can depict different hydrogeological parameters and also use the standard internationally accepted legend or colour scheme.

The computer coded maps have the advantage of digital compilation and processing in the GIS environment (Chap. 6). Further, the original resolution of data may be retained in such maps in comparison to the hard copy medium where the resolution gets generally

reduced. These maps and data may be available in electronic media such as cartridges, tapes and diskettes for transfer to other systems where they could be put as monitor (soft copy) for display, processing, editing etc. With the developments in information super-highways, it is not far that hydrogeological data on public domain may be available on networks like internet/world wide web etc. facilitating world wide super fast accessibility.

3.4.3 Special Purpose Maps

Special thematic maps can also be prepared giving certain specific information, e.g. water-table maps, isopiestic maps, water quality maps and other such parameters as spatial distribution of permeability, transmissivity, specific yield, well yields, and specific capacity etc.

3.4.3.1 Groundwater Level Maps

Based on water-level measurements, various types of contour maps, e.g. water-table maps, piezometric surface maps, depth to water-level and water-level fluctuation maps can be prepared. These maps depict the spatial and temporal variations of the groundwater resources of an area. Water-table maps represent the position of water-level in unconfined aquifer while piezometric surface represents the pressure conditions in a single or a group of confined aquifers. The construction of such maps assumes that the vertical hydraulic gradients are not significant and that the well intersects enough fractures. Measurements of water-levels over an area should be completed within

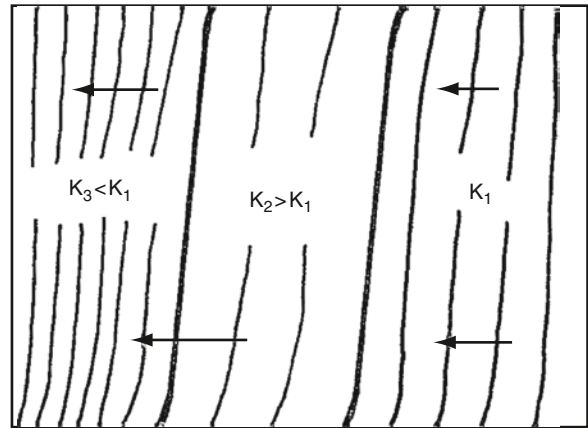


Fig. 3.4 Effect of hydraulic conductivity (K) on the spacing of water table contours. K_1 , K_2 and K_3 are the hydraulic conductivities of the three layers from right to left

a short time interval. The contours represent the lines of equal potential and therefore flow lines can be drawn at right angles to these contours. The spacing of the contours depends upon flow rate, aquifer thickness and hydraulic conductivity (Fig. 3.4). The shape of contours and their values indicate recharge and discharge areas. The upward and downward swing of water-table contours along a stream would indicate effluent and influent condition respectively. Groundwater mounds represent areas of recharge while groundwater depressions are developed due to excessive withdrawal (Fig. 3.5). In unconfined aquifers, the water-table is regarded to be a subdued replica of the ground topography, though this may not be necessarily valid in all the situations.

Care should be taken in the interpolation of water-table contours across the hydrogeological boundaries as illustrated in Figs. 3.6 and 3.7. This is even of greater importance when the observation points are

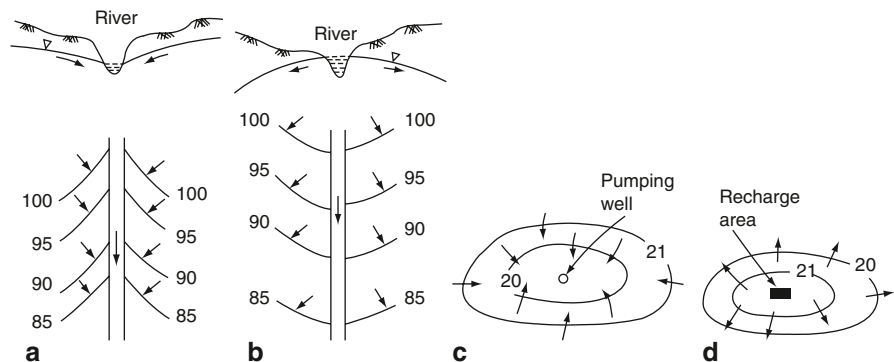


Fig. 3.5 Features exhibited by water table contour maps: **a** effluent seepage, **b** influent seepage, **c** groundwater depression, **d** groundwater mound

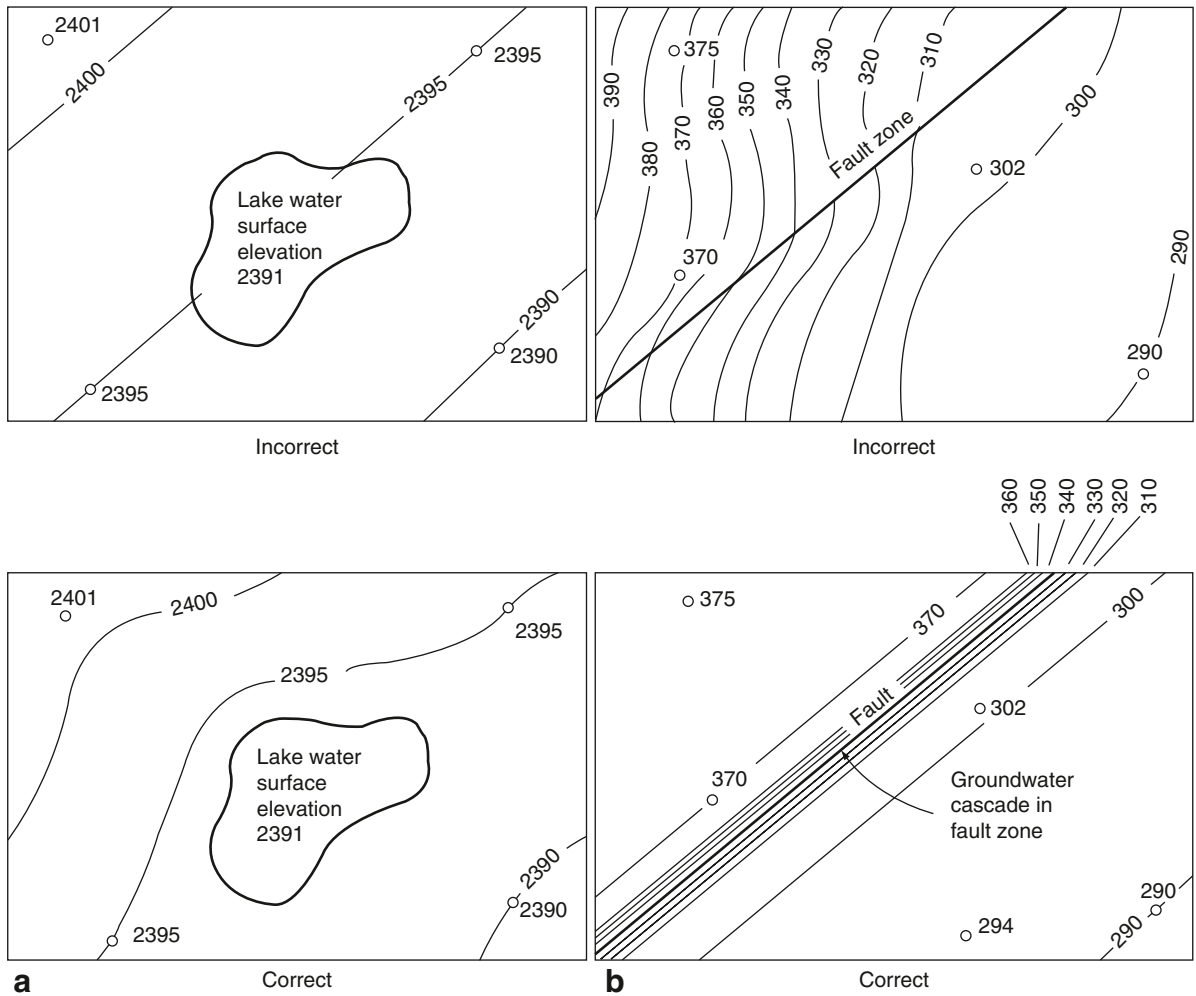


Fig. 3.6 Contouring water-table maps in areas of **a** topographic depressions occupied by lakes, and **b** fault zones. Incorrect and correct contour maps are shown. (After Davis and DeWiest 1966)

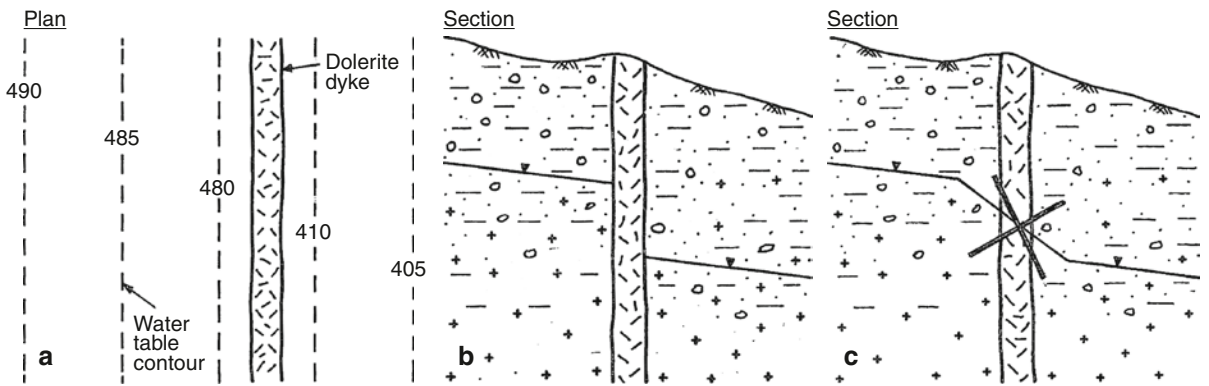


Fig. 3.7 Effect of dyke leading to groundwater compartments, inhibiting linear interpolation of water-table contours. **a** Plan, **b** and **c** are correct and incorrect interpolations respectively

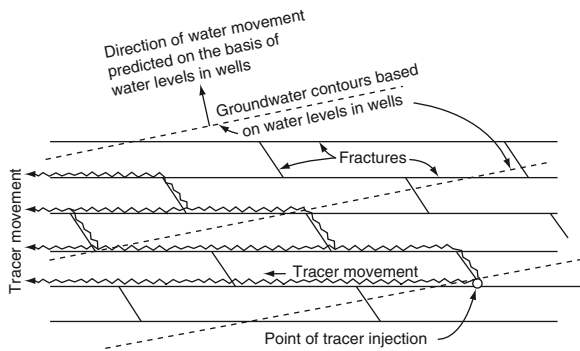


Fig. 3.8 Comparison of groundwater flow direction inferred from water-table contours with the actual flow direction determined from tracer studies in a fractured rock. (After Davis and DeWiest 1966)

limited and these are not uniformly distributed. In sparsely fractured rocks, the water-table will have the “stair-step” appearance due to large contrasts in hydraulic conductivity between matrix blocks and fractured zones. In these settings, water-levels measured in the wells may not be in continuity and the concept of “water-table” becomes less clearly defined. Therefore, maps prepared on the basis of such data may not give correct idea of groundwater flow. Figure 3.8 gives an example where the direction of groundwater flow estimated from water-table contours is different than the actual direction of flow determined from tracer studies.

Mountainous regions with fractured rocks pose special problems in the preparation and interpretation of water-table maps due to varying infiltration rates depending upon topography and intensity of fractures. The influence of topography, subsurface lithology, permeability and infiltration on piezometric surface is well demonstrated in fractured basalts region of Yucca Mt., USA, where in areas of high relief and fresh outcrops, the groundwater gradients are steep, as compared to that in plateau areas characterized by thicker weathered zones with higher transmissivities (Domenico and Schwartz 1998).

3.4.3.2 Depth to Water-level Maps

These provide information only about the spatial variation of depth to water-level, from the ground surface and therefore can not be used for determining direction of groundwater flow.

3.4.3.3 Water-level Fluctuation Maps

These maps indicate the change of water-level in wells during a given period of time. Such maps indicate rates of recharge and discharge to aquifers and changes in storage of water within the aquifer and aquitards. The reasons for such fluctuations are described in Sect. 20.4. Groundwater level trends can also be depicted by hydrographs where variation in groundwater level is plotted against time of observation (see Fig. 20.3). These are of importance in groundwater management studies.

Water-level fluctuation in granular aquifers are of smaller magnitude compared to fractured media as fractures and other conduits respond quickly to recharge events. Therefore, moderately fractured and karst aquifers may show complex response to recharge events (see Chap. 20).

Summary

Hydrogeological studies include lithological, structural, geomorphological and hydrological studies. This should be supported with surface and subsurface geophysical investigations. In hard rocks, fractures studies form an important components of field investigations. Geomorphological investigations include landform and drainage characteristics which in turn depend on the lithology and rock structures.

Groundwater level measurements in time and space form an important component of hydrogeological investigations which requires careful planning of the observation well network and also the time and frequency of water-level measurements. Interaction of surface water and groundwater should also be assessed. The groundwater level data are expressed as water-table maps or sections. The interpretation water level data needs proper integration with geological, structural and geomorphological information.

Further Reading

- Davis SN, DeWiest RJM (1966) *Hydrogeology*. John Wiley & Sons, Inc., New York, NY.
- Walton WC (1970) *Groundwater Resource Evaluation*. McGraw-Hill, New York, NY.