**Lecture 7 Groundwater Investigation**

As we know that groundwater is widely distributed beneath the earth, but its occurrence is confined to only certain geologic formations and structures. As the occurrence of groundwater cannot be seen from the earth’s surface, a variety of techniques are used to explore/investigate groundwater. In view of declining groundwater levels in different parts of the world, including India, the exploration of groundwater is increasingly becoming important in both urban and rural regions of a country, especially in developing countries. This lesson deals with the scale of groundwater investigation as well as an overview of surface methods and subsurface methods of groundwater exploration.

7.1 Scale of Groundwater Investigation

Groundwater investigations can be carried out at a regional scale, local scale or site scale (Schwartz and Zhang, 2003). Regional scale investigation is the largest scale for groundwater investigations, which typically encompasses hundreds or thousands of square kilometers. It provides somewhat an overall evaluation of groundwater conditions. Local scale investigation covers an area of a few tens or hundreds of square kilometers. This type of study provides more detailed information about geology, groundwater dynamics, aquifer characteristics and water quality. On the other hand, site-scale investigation is the smallest scale for groundwater investigations, wherein a particular site is involved such as a well field, mining site, waste disposal site, industrial site, etc. Site-scale groundwater investigation provides in-depth field investigations at the site under study.

Regardless of the scale of a study, detailed planning is required to make sure that the approaches followed in the study are appropriate for the formulated objectives and that the standard procedures are adopted with utmost accuracy for field and laboratory measurements as well as for the analysis of field and laboratory data.

7.2 Surface Methods of Groundwater Exploration

7.2.1    Introduction

The exploration of groundwater can be done from the earth’s surface or above-surface locations, which is known as surface investigation. Groundwater exploration can also be done using equipment/instruments extending underground, which is known as subsurface investigation. Surface investigations of groundwater usually do not provide quantitative data/information concerning aquifers or groundwater as obtained from subsurface investigations. Correct interpretation requires supplemental data from subsurface investigations to verify the findings of surface investigations. Although the surface investigations of groundwater provide an incomplete picture or qualitative information of hydrogeologic conditions below the ground, they are usually less expensive and less time consuming than the subsurface investigations (Todd, 1980).

The surface methods of groundwater exploration can be classified into two major groups (Todd, 1980): (a) geologic methods (also called ‘reconnaissance methods’), and (b) geophysical methods. Geologic methods involve interpretation of geologic data or geology related data and field reconnaissance using ‘Test pits and trenches’, ‘Adits’, ‘Continuous cone penetrometer’ and ‘Auger’. They represent an important first step in any groundwater investigation. On the other hand, geophysical methods are ‘Electric resistivity method’, ‘Seismic methods’, ‘Gravity method’, ‘Magnetic method’, and ‘Remote sensing techniques’ (Todd, 1980), of which ‘Electric resistivity method’ is widely used for groundwater exploration. A brief description of the geologic methods and geophysical methods is provided below.

7.2.2 Geologic Methods

The occurance and movement of groundwater is mainly dependent on the geology of an area, so it is essential to study the geology as a preliminary step. The geologic methods enable to evaluate large areas for groundwater development rapidly and economically (Todd, 1980). The type of geophysical method to be conducted later can be decided only after the geologic investigations. The geologic investigation involves the collection, analysis and hydrogeologic interpretation of existing topographic maps, aerial photographs, geologic maps, well logs and other relevant data/information. This should be supplemented by geologic field reconnaissance and hydrologic data such as streamflow, springs, well yield, groundwater levels, groundwater recharge and discharge, and water quality (Todd, 1980). These field data and information indirectly/directly indicate the possibility of water-bearing formations (aquifers), their extent and continuity, interconnection of aquifers, aquifer boundaries, nature and thickness of overlying strata, presence of faults, etc. Such prior information is quite helpful in planning detailed field exploration by subsurface methods of groundwater investigation.

7.2.2.1 Test Pits and Trenches

Test pits and trenches are excavations on the ground surface for in situ examinations of near surface soil, rocks or any other geologic formations. These excavations can be done by hand tools or by power equipment like backhoes, bulldozers, scrapers, etc. The depth of the excavation depends on the field conditions, type of equipment used and the budget available.

Test pits are usually square or circular in shape with 1-3 m length or diameter, respectively. These are deeper than trenches which are about 1 to 2 m wide and may extend to any lengths. Some of the advantages of test pits and trenches are: (i) they are cost effective, (ii) information can be obtained on lateral and vertical extent of subsurface features, (iii) in situ examination is possible, and (iv) they facilitate sample collection.

7.2.2.2 Adits

Adits are horizontal or nearly horizontal excavations mainly used to drain water from mines and also serve as an entrance and ventilation. Typical dimensions of adits are 1 m × 1.5 m or 2 m × 2.5 m. They are mainly used for the exploration of rocks, their structural features such as joints, fractures, faults and shear zones. The main limitation to this method is that it is costly for small projects; generally it is not used in the soil.

7.2.2.3 Continuous Cone Penetrometer

Continuous cone penetrometer is a device consisting of a cylindrical probe with a cone shaped tip with different sensors in it. The cylindrical probe is 3 to 5 cm in diameter with its cone tip having a cross sectional area of 10 to 15 cm2 and apex angle of 60°. A porous filter element is present above this cone tip used to measure the pore water pressure. The device is pushed into the ground with its tip facing the surface at a controlled rate of 1.5 to 2.5 cm/s. The data is recorded by a field computer through a cable connected to the device. This is used to measure stress, sleeve friction and porewater pressure. It provides a continuous record of penetration resistance and friction.

7.2.2.4 Auger

Auger is a drilling device consisting of a rotating helical blade with an extendable steel rod and a handle. The auger is driven into the ground to remove the drilled materials. It can be hand driven or power driven. It is a cheap and fast method, but restricted only to soft unconsolidated formations. Depending on the geology, augers can be used up to a depth of 15 to 25 m. Many types of augers can be used based on the type of geologic formations available in a particular region. Hand augers are used in sand, silt and soft clay, while bucket augers are used in relatively hard grounds. Augers are cheaper, and easier to operate and maintain.

7.2.3 Geophysical Methods

Geophysical methods are scientific measurements of differences or anomalies of physical properties within the earth’s crust. Electric resistivity, density, magnetism, and elasticity are the most commonly measured properties by different geophysical methods (Todd, 1980). Some of the geophysical methods are briefly described in subsequent sub-sections.

7.2.3.1 Electric Resistivity Method

Among all surface geophysical methods of groundwater exploration, the electric resistivity method has been applied most widely for groundwater investigations, even these days. Electric resistivity of a rock formation limits the amount of current passing through the formation when an electric potential is applied. If a material of resistance R has a cross-sectional area A and length L, then its resistivity can be expressed as:

171              (7.1)

The unit of resistivity is Ohm-meter (W-m). Resistivity of rock formations varies depending on the material density, porosity, pore size and shape, water content, water quality and temperature (Todd, 1980). Electric resistivity methods are based on the response of the earth to the flow of electrical current. In these methods, an electric current is introduced into the ground by two current electrodes, and the potential difference is measured between two points using potential electrodes 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 parameter of the ground.

The measured current (in amperes) and potential differences (in volts) yield an apparent resistivity (ρa) over an unspecified depth. If the spacing between electrodes is increased, a deeper penetration of electric field occurs and a different apparent resistivity is obtained (Todd, 1980). In practice, various standard electrode spacing configurations/arrangements are adopted, but mainly two types of electrode configurations known as Wenner electrode arrangement (Fig. 7.1) and Schlumberger electrode arrangement (Fig. 7.2) are most commonly used in resistivity surveys. The Wenner electrode arrangement is used almost exclusively for shallow subsurface exploration, while the Schlumberger electrode arrangement is used for both shallow and deeper subsurface investigations.

In the Wenner electrode arrangement (Fig. 7.1), A and B are current electrodes, M and N are potential electrodes, and ‘a’ (distance between adjacent electrodes) is called spacing or separation of the electrodes; the value of ‘a’ is taken as the approximate depth of resistivity measurement. In this case, the apparent resistivity (ρa) is given as:

172                 (7.2)

Where, ΔV = potential difference between the potential electrodes M and N on the earth’s surface (volts), and I = direct current introduced into the earth by means of two current electrodes A and B (amperes).

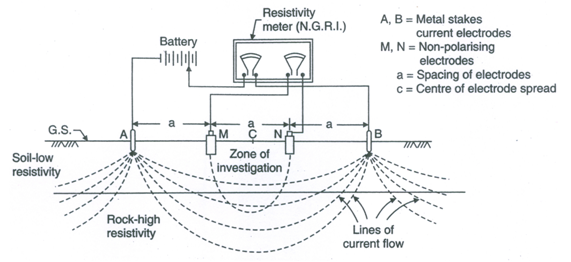


Fig. 7.1. Schematic view of the Wenner electrode arrangement.

(Source: Raghunath, 2007)

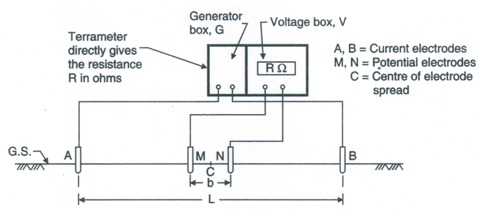
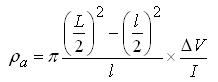


Fig. 7.2. Schematic view of the Schlumberger electrode arrangement.

(Source: Raghunath, 2007)

In the Schlumberger electrode arrangement (Fig. 7.2), the distance between the current electrodes A and B is denoted by L and that between the potential electrodes M and N is dented by l. Note that in this case, the potential electrodes are placed close together and that half of the current electrode spacing (i.e., L/2) is taken as the approximate depth of resistivity measurement. For the Schlumberger electrode arrangement, the apparent resistivity (ρa) is given as:

               (7.3)

Theoretically, L >> l, but for practical application good results can be obtained if L ³ 5l.

Electric resistivity surveying is carried out by using an Electric Resistivity (ER) Meter. Two commonly used ER meters are: NGRI Resistivity Meter (manufactured by the National Geophysical Research Institute, Hyderabad, India) and Terrameter (manufactured by Atlas Copco ABEM AB, Sweden). Electric resistivity surveys are generally done in two ways: (i) Vertical electric sounding (VES) or sounding, and (ii) Horizontal electric profiling (HEP) or profiling. Many surveyors do both simultaneously. Vertical electric sounding is used when the zone of investigation varies vertically more than horizontally; it is frequently used for finding out suitable sites for well drilling. On other hand, in profiling, the lateral distribution of resistivity is studied by maintaining a relatively constant depth of investigation (i.e., constant electrode spacing).

When the apparent resistivity data obtained by a VES survey are plotted against the electrode spacing (‘a’ in case of Wenner and ‘L/2’ in case of Schlumberger) for various spacings at a given location, a smooth curve can be drawn through the data points. The interpretation of such resistivity-spacing curves in terms of subsurface conditions is complex and it is usually accomplished with the help of Type Curves and computer programs. The computer programs are based on the theory of resistivity inversion and employ conventional optimization techniques (e.g., Levenberg-Marquardt technique) or non-conventional optimization techniques such as Genetic Algorithm (GA), Artificial Neural Network (ANN), and Simulated Annealing (SA).

Finally, the salient advantages of the electric resistivity method are (Todd, 1980): (i) its portable equipment and the ease of operation facilitate rapid measurements; (ii)  it frequently aids in planning efficient and economic test-drilling or well-drilling programs; (iii)  it is especially well adapted for locating subsurface saltwater boundaries, because the decrease in resistance due to the presence of saltwater becomes apparent on a resistivity-spacing curve; (iv) it can be used for delineating geothermal areas and  estimating aquifer permeability;  and (v) it can also be used for defining areas and magnitudes of polluted groundwater. However, the limitation of the resistivity method is that the factors like lateral geologic heterogeneities, buried pipelines, cables, and wire fences can disturb the electric field close to the electrodes, thereby invalidating resistivity measurements! In addition, it is not effective for determining actual resistivities below a few hundred meters, as the change in resistivity at large depths has only a slight effect on the apparent resistivity compared to that at shallow depths.

7.2.3.2 Seismic Methods

Seismic techniques involve the measurement of seismic waves travelling through the subsurface. Since seismic techniques require special equipment and trained persons for operation and data interpretation, they have been applied to a relatively limited extent for groundwater investigations.  Three most commonly used seismic methods are: (i) Seismic refraction, (ii) Seismic reflection, and (iii) Seismic surface wave analysis.

Seismic refraction method involves the creation of small shock at the earth’s surface either by impact of a heavy instrument or by a small explosive charge and measuring the time required for the resulting sound or shock wave to travel a known distance. Seismic waves follow the same laws of propagation as light rays and may be refracted or reflected at any interface where velocity change occurs. The changes in seismic velocities are governed by the change in elastic properties of formations. The refraction method assumes that the velocity of seismic waves increases with depth, and hence the layers must be thick enough and should have velocity contrast to be resolved. This method can provide data up to a depth of 100 m. The major limitations of seismic refraction method are that it is sensitive to acoustic noise and vibration, and cannot detect thin layers. Also, for deep measurements, it may require explosives as a source of energy.

Seismic reflection method is similar to the seismic refraction method, but field data and processing procedures are employed to maximize the energy reflected along near vertical ray paths by subsurface density contrasts. Reflected seismic energy is never a first arrival and therefore must be identified in a complex set of overlapping seismic arrivals by collecting data from numerous shot points per geophone placement. This method can be performed in the presence of low velocity zones. The lateral resolution is high and can delineate very deep density contrast with much less shot energy compared to refraction method. This can also provide information on geologic structures thousands of meters below the surface. The limitations of this method are the high cost and longer field processing time.

Seismic surface wave analysis is a geophysical method that uses the dispersive characteristics of surface waves to determine the variation of shear wave velocity with depth. Data are acquired by measuring seismic surface wave generated by an impulsive source and received by an array of geophones. A dispersion curve is plotted from the data, with velocity of surface waves as a function of frequency. From these curves, a shear wave velocity profile is modeled for multiple locations and combined into a 2-D cross section of shear velocity. The shear wave velocity is a function of elastic properties of soil or rock and is directly related to hardness and stiffness of the material. This method can be used in water-covered areas as well.

7.2.3.3 Gravity Method

The gravity method measures the difference between the gravitational fields at two points in a series of different locations on the earth’s surface and the variation is associated to the type of rock (i.e., geologic structure). Since this method is expensive and the differences in water content in subsurface strata seldom involve measurable differences in specific gravity at the surface, it has little application to groundwater exploration.

7.2.3.4 Magnetic Method

This method involves the measurement of direction, gradient or intensity of earth’s magnetic field and the interpretation of variations in these quantities over an area. It uses a simple principle of balancing the force exerted by the vertical component of the earth’s magnetic field on a magnet against the force of gravity. The distortion of magnetic field produced by a magnetic material in the earth’s crust is called magnetic anomaly which is measured by the magnetic method and is indicative of type of rock producing it. Since magnetic contrasts are seldom associated with groundwater occurrence, the magnetic method has little relevance. However, this method can provide indirect information related to groundwater studies such as dikes that form aquifer boundaries or limits of a basaltic flow.

7.2.3.5 Remote Sensing Techniques

Remote sensing from aircraft or satellite has become an increasing valuable tool for understanding subsurface water conditions. Remote sensing techniques offer many types of investigations about an area without causing any damage to the sites. Satellite images and aerial photographs are the most commonly used remote sensing techniques.

Aerial photographs and satellite images taken at various electromagnetic wavelength ranges can provide useful information about groundwater conditions. Other non-visible portions of the electromagnetic spectrum (e.g., infrared imagery, near-infrared imagery, radar imagery, and low-frequency electromagnetic aerial survey) hold promise for a whole array of imaging techniques that can contribute to hydrogeologic investigations/surveys (Todd, 1980).  Fractures and faults appear on aerial photos and satellite images as tonal variations in surface soils caused by the difference in soil moisture. The lines of springs or seeps are caused by the movement of groundwater along the fracture zones. Thus, fracture patterns and other observable surficial features obtained from remote sensing data serve as interpretive aids in groundwater studies because they can be related to the porosity and permeability of subsurface formations, and ultimately well yield (Todd, 1980; Fetter, 2000).

With the advent of powerful and high-speed personal computers and rapid development in remote sensing (RS) and geographic information system (GIS) techniques, the importance of RS technology in the fields of surface hydrology and subsurface hydrology has dramatically increased (Engman and Gurney, 1991; Jha et al., 2007). The RS technology, with its advantages of spatial, spectral and temporal availability of data covering large and inaccessible areas within a short time, has emerged as a powerful tool for the assessment, monitoring and management of groundwater resources (Jha and Peiffer 2006; Meijerink 2007; Rodell et al., 2009). In particular, the integrated use of RS, GIS and multicriteria decision analysis (MCDA) techniques has been found to be efficient and very useful  for mapping and evaluating groundwater potential as well as for identifying sites suitable for artificial recharge (e.g., Jha and Peiffer, 2006; Jha et al., 2007; Jha et al., 2010; Machiwal et al., 2011).

7.3 Subsurface Methods of Groundwater Exploration

Detailed and comprehensive examination of groundwater and conditions under which it occurs can be made by subsurface investigations only. Subsurface investigations are conducted by a person or a group of persons on the earth’s surface who operate the equipment/instruments extending underground through a borehole which provides direct access to subsurface formations and groundwater. Various subsurface methods of groundwater exploration can be classified into three major groups: (a) Test drilling, (b) Borehole sensing (sometimes it is also called ‘television logging’), and (c) Geophysical logging.

Test drilling provides information regarding subsurface formations in a vertical line from the ground surface, whereas the borehole sensing provides more detailed information about the borehole, geologic strata, and well casing and screen. On the other hand, geophysical logging techniques provide information on physical properties of subsurface formations, groundwater quality, and well construction. A variety of geophysical logging techniques are available, of which the following are most important in groundwater hydrology (Todd, 1980; Roscoe Moss Company, 1990):

1. Resistivity logging,
2. Spontaneous potential logging,
3. Nuclear or Radioactive logging (viz., Natural-Gamma logging, Gamma-Gamma logging, and Neutron logging)
4. Temperature logging,
5. Caliper logging,
6. Fluid-Conductivity logging,
7. Fluid-Velocity logging,
8. Sonic or Acoustic logging, and
9. Casing logging.

7.3.1 Test Drilling

Drilling a small-diameter (usually 1” or 1.5” diameter) hole to ascertain geologic and groundwater conditions at a particular location/site is known as test drilling. Test drilling is the most reliable method to obtain information about subsurface formations at different depths, which is very useful in verifying the results of other investigation methods as well as to obtain assurance of underground conditions before well drilling. During test drilling, geologic samples are collected at regular depth intervals and the air-dried samples are subject to sieve analysis (also called ‘grain-size or particle-size analysis’ or sometimes ‘mechanical analysis’) for determining the proportion of sand, silt, clay and gravel in a given geologic sample. If such information is presented in a graphical or physical manner as a function of depth at a given site/location, it is known as a ‘well log’, ‘borehole log’ or ‘geologic log’ of that site/location. Fig. 7.3 shows a typical well log/borehole log at a groundwater-monitoring site consisting of unconsolidated formations. Well/borehole logs provide reliable information about subsurface conditions (i.e., variation of subsurface materials and their thickness, availability and type of aquifers, type of other layers, etc.), thereby enabling aquifers and confining layers to be delineated. They serve as a standard source of valuable information in the design and construction of production wells, monitoring wells, and foundations as well as for environmental projects and geologic studies.

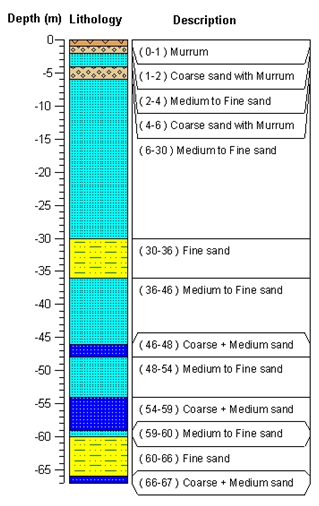


Fig. 7.3. Well log of a site prepared from geologic samples collected during observation-well drilling in an unconsolidated formation.

If the test drilling proves fruitful, it is re-drilled to a larger diameter to form a pumping well (also called ‘production well’). The test holes created by test drilling also serve as observation wells (also called ‘monitoring wells’) for measuring groundwater levels, taking groundwater samples, or for conducting pumping tests. Although any well-drilling method can be used for test drilling, the ‘cable-tool method’ and ‘hydraulic rotary method’ (described in Lesson 18) are most common in unconsolidated subsurface formations (Todd, 1980). In fact, the choice of drilling method for test drilling depends on the type of information required, type of material encountered, drilling depth, and the location of investigation.

7.3.2 Borehole Sensing

A borehole sensing or television logging is a convenient technique with increasing use for investigating boreholes (uncased or cased). Specially designed wide-angle cameras, typically less than 7 cm in diameter (Todd, 1980), are equipped with lights and when lowered into a borehole (uncased or cased), provide continuous visual inspection of the borehole which can be preserved in electronic storage devices. Borehole sensing has a variety of applications such as locating changes in geologic strata, pinpointing large pore spaces, inspecting the condition of well casing and screen, checking for debris in wells, locating zones of sand entrance, and searching for lost drilling tools (Todd, 1980).

7.3.3 Geophysical Logging

This involves lowering sensing devices in a borehole (cased or uncased) and recording a physical parameter that may be interpreted in terms of subsurface formation characteristics; groundwater quantity, quality and movement; or physical structure of the borehole (Todd, 1980). Table 7.1 summarizes the types of information that can be obtained by various geophysical logging techniques. The details of various geophysical logging techniques can be found in Todd (1980), Roscoe Moss Company (1990), and Fetter (2000).

Table 7.1. Summary of logging applications to groundwater hydrology (Source: Todd, 1980)

|  |  |  |
| --- | --- | --- |
| Sl. No. | Type of Information | Possible Logging Techniques |
| 1 | Lithology and straitigraphic correlation of aquifers and associated rocks | Resistivity, sonic, or caliper logs made in open holes; radiation logs made in open or cased holes |
| 2 | Total porosity or bulk density | Calibrated sonic logs in open holes; calibrated neutron or gamma-gamma logs in open or cased holes |
| 3 | Effective porosity or true resistivity | Calibrated long-normal resistivity logs |
| 4 | Clay or shale content | Natural gamma logs |
| 5 | Permeability | Under some conditions long-normal resistivity logs |
| 6 | Secondary permeability-fractures, solution openings | Caliper, sonic, or television logs |
| 7 | Specific yield of unconfined aquifers | Calibrated neutron logs |
| 8 | Grain size | Possible relation to formation factor derived from resistivity logs |
| 9 | Location of water level or saturated zones | Resistivity, temperature, or fluid conductivity logs; neutron or gamma-gamma logs in open or cased holes |
| 10 | Moisture content | Calibrated neutron logs |
| 11 | Infiltration | Time interval neutron logs |
| 12 | Dispersion, dilution, and movement of waste | Fluid conductivity or temperature logs; natural gamma logs for some radioactive wastes |
| 13 | Sources and movement of water in a well | Fluid velocity or temperature logs |
| 14 | Chemical and physical characteristics of water, including salinity, temperature, density and viscosity | Calibrated fluid conductivity or temperature logs; resistivity logs |
| 15 | Construction of existing wells, diameter and position of casing, perforations, screens | Gamma-gamma, caliper, casing, or television logs |
| 16 | Guide to screen setting | All logs providing data on the lithology, water-bearing characteristics, and correlation and thickness of aquifers |
| 17 | Cementing | Caliper, temperature, or gamma-gamma logs; acoustic logs for cement bond |
| 18 | Casing corrosion | Under some conditions caliper, casing, or television logs |
| 19 | Casing leaks and/or plugged screen | Fluid velocity logs |

At the end, it is worth mentioning that apart from the above-mentioned subsurface investigation techniques, there are some other important subsurface investigation methods which can provide important information about the hydrogeologic conditions and the dynamics of groundwater in a basin. These methods are: tracer tests for groundwater flow; groundwater-level monitoring for flow directions and aquifer conditions; pumping tests for aquifer parameters, well parameters, well yield and well evaluation; groundwater-level fluctuation measurements for analyzing spatio-temporal changes in groundwater storage, groundwater behavior and surface water-groundwater interaction; and groundwater sampling for water-quality assessment.

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Suggested Readings

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