GEOPHYSICAL TECHNIQUES FOR GROUND WATER EXPLORATION

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GENERAL

The basic objective of geophysical investigations is to study the subsurface formations and structural configuration of earth by measuring physical properties on or near the earth surface. The success of a particular geophysical method largely depends upon the presence of significant and detectable contrast in the physical properties of different lithological units.

Geophysical techniques can be used for a number of purposes in ground-water studies: (i) **Geologic characterization,** including assessing types and thicknesses of strata and the topography of the bedrock surface below unconsolidated material, and generating fracture mapping and paleochannels, (ii) **Aquifer characterization,** including depth to water table, water quality, hydraulic conductivity, and fractures, and (iii) **Contaminant plume identification,** both vertical and horizontal distribution including monitoring changes over time.

Geophysical techniques are used to assess the physical and chemical properties of soils, rock and ground water based on the response to either (1) various parts of the **electromagnetic** (EM) spectrum, including gamma rays, visible light, radar, microwave, and radio waves, (2) **acoustic** and/or **seismic** energy, or (3) other **potential** fields, such as gravity and the earth's magnetic field.

Geophysical methods of prospecting available for ground water may be classified into three groups.

1) Surface Methods

a. Gravity and magnetic methods (including aerogravity and aeromagnetic surveys)
b. Seismic methods
c. Electrical and electromagnetic methods
d. Radioactive methods.

2) Downhole Methods

Well logging methods.

3) Airborne Geophysical Methods

I. SURFACE METHODS

No other surface geophysical methods have been used more widely than electrical and electromagnetic methods in the study of ground water and contaminated sites. Terms such as geoelectrical, geoelectromagnetie, and resistivity survey may be used in the literature to apply to one or more of a variety of geophysical methods. The same method may be called by different names. Various surface geophysical methods are described below in brief:

Gravity Method

Gravity method, based on the measurement of density contrast between anomalous body/material and the surrounding rocks, may be used for exploration of minerals, ground water, oil and gas. Gravity surveys help in locating ground water by mapping key beds, bearing stratigraphic or structural relation to the water bearing bed. Not commonly used in ground water targeting.

Magnetic Method

Magnetic method, based on the measurement of susceptibility contrast between the anomalous body and the surrounding rock, is used for exploration of magnetic minerals and associated minerals. The magnetic method may be used for locating structures where the basement rock is magnetic. In ground water, the method is mainly employed in detection of dolerite dykes and other intrusive bodies which act as flow barriers.

Seismic Methods

These methods are based on the measurement of seismic wave velocity contrast obtained from available time-distance curves. Seismic Refraction method may be used for locating aquifers having a velocity contrast. Shallow salt domes as possible places for occurrence of oil and gas may be detected by Refraction technique. The Reflection seismic is generally not used for shallow mineral and ground water exploration.

Electrical and Electromagnetic Methods

Electrical and electromagnetic methods, based on the measurement of the electrical resistivity or conductivity of the subsurface minerals and formations, are most useful for exploring ground water.

Various such methods are enlisted below:

(i) Resistivity methods
(ii) Electromagnetic methods
(iii) Induced polarization method
(iv) Very low frequency (VLF)

One of the most widely used methods of geoelectric prospecting is the resistivity method. Resistivity studies may be broadly classified into resistivity sounding and profiling depending on field procedure. Resistivity sounding where positions of the electrodes are changed with respect to a fixed central point (known as the sounding point).

Fig.1 is particularly useful for locating horizontal discontinuities whereas in profiling, useful for vertical discontinuity, all the electrodes are shifted simultaneously along a predetermined line. The well known electrode configurations, which may be, used either for sounding or profiling are Schlumberger, Wenner and dipole arrangements.

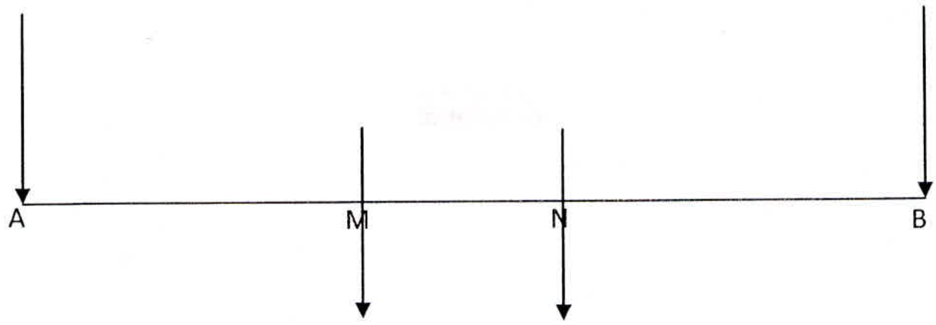

Figure 1. Layout of Symmetrical electrode array used for resistivity measurement in field survey. A & B represent the current electrodes and M and N represent the potential measuring electrodes

Sounding may be conveniently used for ground water exploration. Profiling is useful in exploration of minerals and ground water in hard rocks. Lately, a more effective resistivity imaging (tomography) technique has become more popular due to its capability to produce 2-dimensional resistivity sections of the subsurface earth. This technique brings out detailed information of aquifer zones and intervening layers [Fig.2].

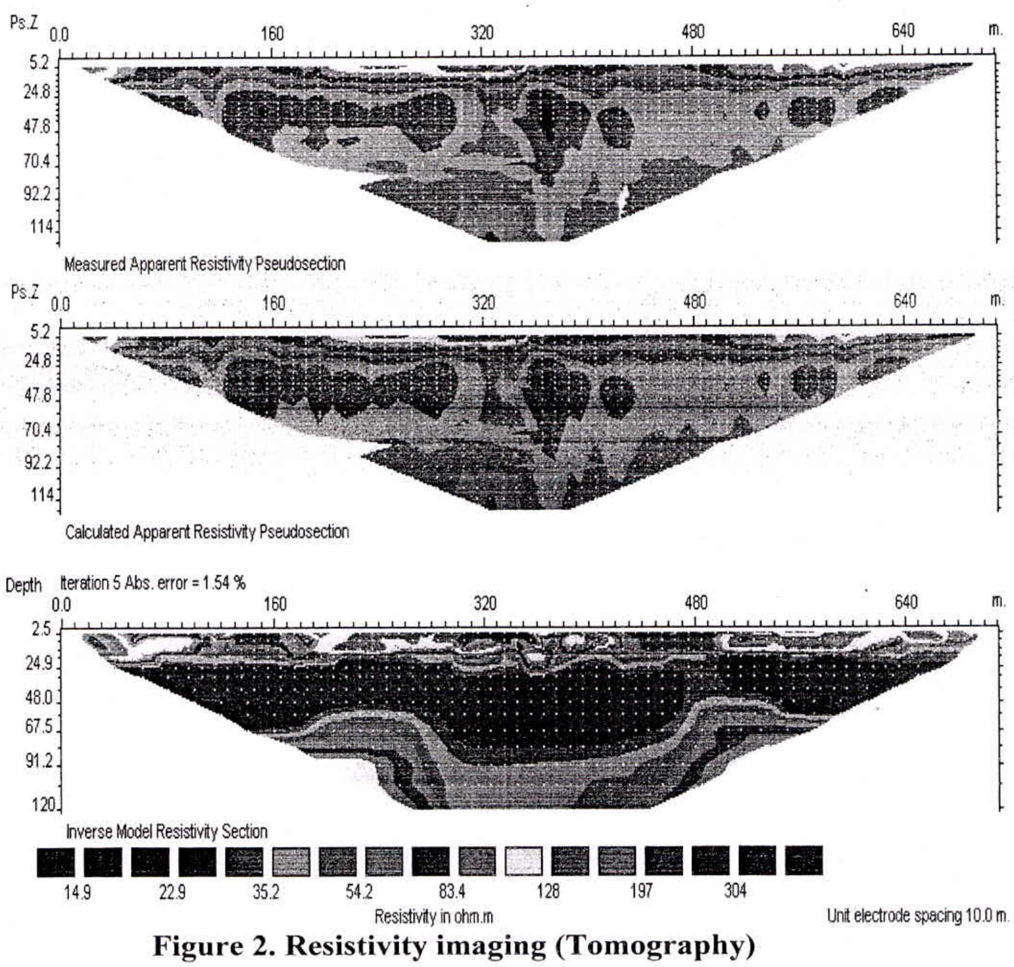

Figure 2. Resistivity imaging (Tomography)

TIME DOMAIN ELECTROMAGNETIC (TDEM) Technique is used for a sounding in which Transmitter loop of metallic wire with specific length is laid on the ground and a time varying (AC) current is injected. The transmitter current is abruptly reduced to zero which induces a short duration pulse in the ground and causes a loop of current to flow in the immediate vicinity of the transmitter loop. However, because of ground resistivity, the amplitude of the current starts to decay immediately. This decaying current induced a voltage impulse which causes more current to flow but at a large distance from transmitter loop, and also at a greater depth. This deeper current flow also decays due to finite resistivity of ground, further inducing deeper current flow and so on. The amplitude of the current flow is measured as a function of time by measuring its decaying magnetic field using a small receiver coil. This process forms the basis of sounding in the time domain [Fig.3]. This method is most useful in shallow groundwater exploration when the surface rock is highly resistive.

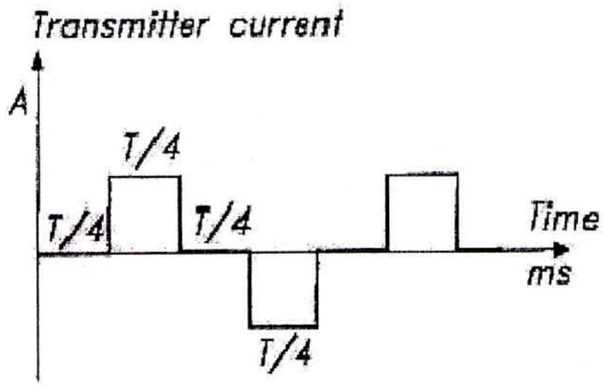

Figure 3. Transmitter current wave form

Induced Polarization (IP) method based on over-voltage effect makes measurement of the decay voltage (in time domain or frequency domain) produced due to polarization of the electrode interfaces at the subsurface after the current flow has stopped. The IP values are typically high in clay rich sandy horizon whereas in the sands with no clay, these are low. This helps to distinguish between sands with and without clay content.

Very low frequency (VLF) method makes use of the available fields due to electromagnetic waves transmitted from powerful radio broadcasting stations as the source. The depth of investigation is limited and only the shallow conductors and water-saturated zones may be detected.

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 detect sources of such disintegration by means of G-M counter or Scintillation counter. Depending on whether measurements are done at the surface or from air, these are called - Ground radioactive methods and airborne radioactive methods. These methods are not used in groundwater exploration.

Ground Probing Radar Method (GPR)

It is based on transmission of e.m energy at radar frequencies (0.5 MHz – 1GHz) into the ground through transmitting radar coupled to the ground and receiving the reflected e.m energy in a receiver antenna kept at a small distance away from transmitter. The basic physical property governing the transmission of high-frequency em wave in the earth medium is dielectric constant and dielectric component predominates over conduction current part in the governing Helmholtz equation. It resembles acoustic wave equation and GPR data processing is quite similar to seismic reflection prospecting.

Water has highest dielectric constant. Hence, the stacked GPR reflections can identify the water table clearly and the GPR signals can be inverted for soil moisture variation with depth. However, presence of shallow water table may mask the fracture controlled groundwater signal in the GPR time or depth sections. Moist clay/shale in shallow region might weaken the deeper GPR signals. As a result, it is not quite sure as to whether it works in mapping the groundwater carrying fractures or not. But this can be included in the list of geophysical methods for groundwater prospecting in a hard rock region.

II. SUBSURFACE WELL LOGGING METHODS

Any characteristic information regarding the formation met within a well and recorded in terms of depth is known as a "well log". Such logs help in evaluating porosity, permeability and water saturation of the formation and are useful in the development stage of groundwater.

Geophysical logging involves lowering sensing devices in a borehole and recording a physical parameter that may be interpreted in terms of formation characteristics; groundwater quantity, quality, and movement; or physical structure of the bore hole. A wide variety of logging techniques are used to determine various parameters as given below:

Required Information	Possible Logging Technique
Lithology and stratigraphic correlation of aquifers and associated rocks	Resistivity, sonic, or calliper logs made in open holes; radiation logs made in open or cased holes
Total porosity or bulk density	Calibrated sonic logs in open holes; calibrated neutron or gamma - gamma logs in open or closed holes
Effective porosity or true resistivity	Calibrated long-normal resistivity logs
Clay or Shale content	Natural gamma logs
Permeability	Long-normal resistivity logs
Secondary permeability-fractures, solution openings	Calliper, sonic, or television logs
Specific yield of unconfined aquifers	Calibrated neutron logs
Location of water level or saturated zones	Resistivity, temperature, or fluid conductivity logs; neutron or gamma - gamma logs in open or closed holes
Moisture content	Calibrated neutron logs
Infiltration	Time-interval neutron logs
Dispersion, dilution, and movement of waste	Fluid conductivity or temperature logs; natural gamma logs for some radioactive wastes
Source and movement of water in wells	Fluid velocity or temperature logs
Chemical and physical characteristics of water, including salinity, temperature, density and viscosity	Calibrated fluid conductivity or temperature logs; resistivity logs

Though various type of logging techniques are available, only electrical resistivity, Spontaneous potential (SP), calliper, radiation logging is common in groundwater exploration.

Resistivity log

In resistivity logging, current and potential electrode are lowered to measure electrical resistivity of the surrounding media and to measure its variation with depth. The resistivity curves thus obtained indicate the lithology of rock strata penetrated by the well and quality of the water. As the resistivity of the material in controlled by porosity, packing, water resistivity, degree of saturation, and temperature, these parameters can also be estimated by the electrical resistivity logging.

Spontaneous potential (SP) logging

The spontaneous potential method measures natural electrical potentials found within the earth. Measurements, usually in millivolts, are obtained from a recording potentiometer connected to two like electrodes. The potentials are primarily produced by electrochemical cells formed by the electrical conductivity differences of drilling mud and groundwater where boundaries of permeable zones intersect a borehole. Therefore, SP logging may be used to identify the permeable zones.

Radiation logging

Radiation logging, also known as nuclear logging or radioactive logging, involves the measurement of fundamental particles emitted from unstable radioactive isotopes. Logs having application to groundwater are natural gamma, gamma-gamma, and neutron logs.

Natural-gamma Logging - All rocks emit natural-gamma radiations, a log of theses radiations constitutes a natural-gamma log. The radiation originates from unstable isotopes of potassium, uranium, and thorium. In general, the natural-gamma activity of clayey formations is significantly higher than that of quartz sands and carbonate rocks. The most important application to groundwater hydrology is identification of lithology, particularly clayey or shale-bearing sediments, which emit higher gamma intensities.

Gamma-Gamma Logging - Gamma radiation originating from a source probe and recorded after it is backscattered and attenuated within the borehole and surrounding formation constitutes a gamma-gamma log. Primary applications of gamma-gamma logs are for identification of lithology and measurement of bulk density and porosity of rocks.

Neutron logging - Neutron logging is accomplished by a neutron source and detector arranged in a single probe, which produces a record related to the hydrogen content of the borehole environment. In most formations the hydrogen content is directly proportional to the interstitial water; therefore, neutron logs can measure moisture content above the water table and porosity below the water table.

III. SATELLITE AND AIRBORNE GEOPHYSICAL METHODS

Airborne geophysical surveys, extensively used in the mineral exploration industry, are now widely used in hydrogeological investigations. Recent advances in technology and the integration of multiple geophysical data-sets including aeromagnetic, radiometric and gravity surveys can provide useful information on lithology and structure. Additionally advances in data analysis, processing and image enhancement techniques have improved the resolution of geophysical datasets so that very subtle variations in the geophysical responses can be identified.

Airborne gravity exploration techniques are used predominantly in regional geophysical exploration to delineate significant geological formations and structures in both the Petroleum and Mineral exploration industries. Once again, recent advances in technology have warranted assessment of this technique on targets with more subtle geophysical responses.

The latest gravity satellite, GRACE has mapped gravity of the entire globe to a very high accuracy. Gravity and tectonics go together. The satellite gravity maps in association with satellite imageries of study region can infer probable fractures/shear zones within hard basement on a regional scale. The follow-up can initially be undertaken with airborne magnetic and VLF surveys and later by ground-based geophysical surveys.

Aeromagnetics is a cheap but effective subsurface geological mapping aid at reconnaissance level and airborne electromagnetic (VLF) methods can map subsurface conductors within hard rock terrain. Presently, these could be groundwater bearing deep fracture zones. These tools can provide regional subsurface geological picture sufficient enough for proper implementation of ground follow-up.

Irrespective of the nature of magnetic polarization, lateral intensity of magnetization contrast(s) within rock masses lead to magnetic anomaly source(s) in the vicinity of geomagnetic field. Presence of water saturated subsurface fractures within hard basement may lead to linear anomaly pattern, provided there exists a sufficient homogeneous distribution of ferri-magnetic minerals throughout the rock mass.

In aero-magnetic method, minute changes in geomagnetic field of the order 1nT (10^{-5} Gauss) can be mapped with highly sensitive quantum magnetometers working on a combined nuclear magnetic resonance and optical pumping principles. Latest methods of position location (Differential GPS receivers) and data acquisition and processing procedures have helped achieving such high accuracies in geomagnetic field mapping. The specially processed aeromagnetic map for mid-latitudes, pertinent to Indian conditions can be presented either as contour maps of geomagnetic total-field intensity or in visually appealing image formats, could be of much interpretative value. The geographic information system (GIS) based qualitative interpretation methods are also gaining importance. For a more serious quantitative interpretation, one has to opt for geophysical literature; for example, introductory material can be found in Grant and West (1965) and Parasnis (1998).

Initially, air-borne VLF method was introduced in mineral exploration for mapping locales of conductive minerals. However, in hard-rock regions its deployment can lead to mapping of fractures and shear zones, which are occupied by groundwater on a regional scale. The aeromagnetic methods implemented with low flying air- carriers like helicopter-borne surveys could scan large areas and are proved to be cost-effective at reconnaissance level. The analysis of remote sensing imageries along with aeromagnetic total-field intensity map could be an ideal combination for fracture mapping and air-borne VLF maps then could be of much help in locating ground-water bearing fractures on a regional scale. Then the ground follow-up by ground geophysical surveys is a logical step for better detailing.

CHOICE OF GEOPHYSICAL METHODS

The problems of the use of geophysical methods in the assessment and management of ground water may be classified into two categories:

(1) Soft rock areas
(2) Hard rock areas

Soft Rock Areas

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

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

(1) Schlumberger vertical electrical sounding and seismic refraction studies at prospective sites.
(2) Recommendation of the borehole points.
(3) Electrical logging of the borehole after drilling for detailing of the water well.
(4) Planned utilization of available ground water after water quality analysis, for a sustained yield throughout the year and over the years.

Hard Rock Areas

Fractured rock hydrogeology had been of marginal interest for ground water so far. Of late, the hydrogeologists have discovered that the favourite sand and gravel aquifer is not commonly available in hard rock terrains. Thus, the importance of hard rock for water supply has increased. In shield areas in temperate regions, hard rocks have been found to be important for rural water supply. The step-wise plan given for the soft rock areas have been found suitable for hard rock areas as well.

Several conventional geophysical methods like gravity magnetic and seismic methods may be used in hard rock area surveys following remote sensing for delineating the overall targets. Detailing may be done using the geophysical methods.

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

A combination of electrical, electromagnetic and seismic refraction methods will be used for detailed ground water exploration in areas where faults and fractured zones have been located by means of remote sensing. The procedures will be as follows:

(1) Resistivity profiling/sounding
(2) Very low frequency (VLF) method.

VLF is the cheapest electromagnetic method for ground water survey. 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.