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GEOPHYSICAL INVESTIGATIONS FOR HYDROLOGICAL STUDIES

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1985-86

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SUMMARY

Geophysical investigations are effectively utilized in various hydrological applications. They provide fast and economic means of handling hydro-geological problems like exploration for groundwater, studies on movement and quality of groundwater, geothermal exploration, water balance studies of lakes and reservoirs, seepage losses from reservoirs and canals, etc.

Various geophysical methods have been classified as surface and sub-surface methods. Surface methods include natural field methods(e.g.telluric, magneto-telluric and S.P.) as well as resistivity, electromagnetic, seismic(refraction and reflection), gravity, magnetic and nuclear methods. Latter class of methods includes borehole geophysical techniques comprising of S.P., resistivity, induction, induced polarisation etc. logging methods and selected nuclear methods.

After introducing different geophysical methods and their relevant details, general applications of these methods in hydrological studies have been reviewed. A comprehensive list of references is provided for detailed knowledge of various methods.

1.0 INTRODUCTION

1.1 General

Geophysics, as its name implies, is the study of the earth and its atmosphere by physical methods. The physical laws governing these methods are based on gravity, magnetic, electric, thermal and elastic properties of the earth.

In the widest sense, geophysics deals with the study of the physics of the solid earth(lithosphere), of the oceans, rivers, lakes etc.(hydrosphere) and of the gaseous envelope around the earth(atmosphere). Its fields of study are so vast and diversified that many of the fields have gradually developed as independent branches of science.

During the course of its development, geophysics has incorporated the latest advances in physics both theoretical and experimental, electronics and mathematics, and has grown into a science with its theoretical and practical contributions. The advances in modern physics and technology, especially the construction of high sensitivity instruments have on one hand opened up new methods of investigation of the earth and refined the tools of geophysical data acquisition on the other. The new approaches of mathematical analysis and increasing use of computer methods have contributed a great deal in geophysical data processing and interpretation.

Basically, the science of geophysics is classified into two major branches General and Pure Geophysics and Applied or Exploration Geophysics. The former branch aims at understanding the physical nature of the earth and the physical processes taking place on the earth's surface and in the interior. While the latter branch is concerned with the application of geophysical methods to the study of relatively shallow subsurface in homogeneities and structures, and is aimed at specific investigations of economic significance like exploration for oil and gas, ore deposits and groundwater, and for solving certain problems of civil engineering.

1.2 Use in Hydrology

The population on our planet is multiplying very fast as also its demands of natural resources like water. Where surface water resources are not sufficient, it becomes imperative to find additional sources in the form of ground water of desired quality in adequate quantities for catering to the ever increasing agricultural, industrial and domestic demands.

The utility of the hydrogeological methods for ground water exploration on a regional or a detailed scale is well established. However, application of geophysical methods can help a great deal in solving those problems which can not conveniently and economically be solved by hydrogeological surveys alone.

Thermal observations which have been systematically carried out since the end of the last century for mineral water prospecting are considered to be the first geophysical investigations in hydrogeology(Ogilvy, 1969). Electrical prospecting and electrical logging have been put into practice since 1929. Seismic investigations, on small-scale experimental basis, for prospecting of water have also been reported from mid-thirties.

Usually, any groundwater project passes through the phase of regional surveys, leading to detailed surveys and ultimately resulting in the exploration of ground water by means of boreholes/wells. The regional surveys are undertaken in geographically large areas(for example river basins) covering several thousands of square kilometers. The main objectives of these surveys are to study and understand the inputs in the hydrological cycle of the region, to have an overall concept about the type, nature and number of aquifers, the quality of ground water etc., in the region.

Geophysical surveys made in conjunction with reconnaissance, surface geologic investigations, and exploratory drilling may permit a rapid and relatively low-cost evaluation of the subsurface geology and possibly the general ground water conditions of an area. Such surveys may materially reduce drilling require ments and resultant overall costs of groundwater investigation.

Geophysical data should be correlated with geologic conditions of each area to assure reliable interpretation. Therefore, a survey is usually started near a outcrop or drill hole(U.S.D.I., 1981) where subsurface conditions are known or can be readily known. Such correlation permits projection of geologic conditions to distant areas through analysis of the geophysical measurements. The accuracy and reliability of data obtained from a geophysical survey depend in large part on the amount of subsurface control available as well as the geologic complexity of the area.

A wide range of geophysical methods is available for geohydrological investigations. Each geophysical method makes use of a particular physical field caused by the difference in the physical field caused by the difference in the physical properties of the rock formations. These differences in physical properties are determined (Bhimasankaram and Gaur, 1977) by the mineral and granulometric composition of the rocks their texture and structure, the degree of saturation with water and its chemical composition, temperature etc.

The main geophysical methods which have been used to solve some or the other geohydrological problems are the electrical, seismic, gravity and magnitic methods(in this order). The first two depend on the introduction of mechanical or electrical energy into the subsurface and measurement of the effects of subsurface materials and conditions on the transmission of this energy. The latter two methods depend on the measurement of variations in the intensity and direction of the natural forces of gravity and magnetism.

Geophysical methods including nuclear methods have been successfully used, and are presently being used in the following types of hydrological studies.

i. Evaluating the aquifer properties and exploration for ground water,

ii) Studying the movement of ground water

iii) Determining the interface between fresh and saline waters and assessment of degree of salinity

iv) Studying the contamination of groundwater from hazardous wastes, etc.

v. Snow and glacier melt studies.

vi. Checking water leakages(seepage) from reservoirs, lakes and canals etc. and gauging of stream flow.

vii. Geothermal resources exploration

viii) Mapping burried river channels and valleys.

ix. Water balance studies of lakes and reservoirs.

x. Investigation of changes in soil moisture content, origin of recharge, recharge mechanism and quantitative estimates of recharge etc.

2.1 Brief Outline of Geophysical Methods

Among the geophysical methods, the electrical methods enjoy the greatest popularity. Electrical resistivity is a characteristic which makes possible the differentiation between different types of earth materials. Ground-based surveys are made by sending a direct or alternating current through the ground between two metal stakes and measuring the resulting potential of other stakes or special electrodes. For rapid coverage of large areas automobile or airborne versions of electrical methods are also becoming common. Electrical methods are most widely used in hydrogeological investigations for regional as well as detailed surveys because of low expenses involved, faster coverage and wider range of applicability. The theory and interpretation for most of these methods is well developed for their reliable application. These methods, however, are not usable in the vicinity of power plants, substations, high tension power lines, and similar sources of extraneous earth currents which would adversely affect the accuracy of the field measurements.

Two basic variations of this method are used in the field. If information is required from a vertical section of the subsurface i.e. from various depths, then vertical sounding is done. For this, the electrodes(or stakes) are moved farther apart and as a resualt the current penetrates progressively deeper. For information along a horizontal line or surface area, all the current and potential electrodes are moved simultaneously, and the method is known as profiling. A uniform depth is investigated(depending upon the seperation between electrodes) in profiling method. Lateral inhomogeneties like faults, dykes etc. are effectively detected by this method.

In hydrogeological investigations seismic methods occupy a leading place and are second only to the electrical methods. The ability of these methods to accurately determine the depths to different formation including basement and often to identify the formations on the basis of their seismic velocities make them useful in these investigations.

The instruments used for registering the seismic vibrations can be either a multichannel system or a simple seismic timer. The first category of system commonly uses explosines while the latter uses hammering as source of energy. Seismic surveys are based on measurement of the velocity distribution of artificially generated seismic waves in the earth's crust. The velocity of the seismic waves generated depends on the density and elasticity of the subsurface materials. The velocity is usually lowest for unconsolidated materials and increases with the degree of consolidation or cementation.

The seismic methods using explosive as an energy source are particularly adapted to use in large areas where deep probing is required. However, the mechanical introduction of energy by using a hammer is preferable for shallow depths(upto 30-40 m) and for environmental reasons.

The gravimetric survey is a valuable tool in investigating gross features such as depth to bedrock, old erosion features on bedrock, and other features such as buried intrusive bodies, riverchannels and valleys. In these surveys, the relative change in the force of gravity is measured at stations along a traverse or in a grid. Gravity variations result from the contrast in density between subsurface materials of various types. Usually low densities are observed for rocks which have large porosities, and hence sedimentary rocks possess lower densities than the igneous and metamorphic rocks.

Generally, the gravity method is employed on a regional scale to map the distribution of geological formaiotions. The data is obtained either along profiles or in the grid pattern. The equipment is light and portable, and field progress is relatively rapid. Field data required extensive altitude corrections. Drill hole data and similar references are necessary for accurate interpretation.

In a magnetic survey, the strength of the vertical component of the earth's magnetic field is measured and plotted on a map. Change in magnetic field is caused by the magnetic properties of the rocks. Analysis of the results may indicate qualitatively the depth to bedrock and presence of buried dikes, sills, etc.

In hardrocks, chemical activity during weathering breaks up the ferric mineral rendering them less magnetic compared to the parent mass. Also fracturing of the massive rock reduces the magnetic intensity at such places. Such zones favourable for groundwater accumulation can be identified by surface magnetic observations.

The magnetic surveys are carried out either along a profile or a system of profiles. When studying very small structures like joints and fractures micro-magnetic surveys are done on a grid of 5m x 5 m. The interpretation of data is done either qualitatively or quantitatively.

Geophysical surveys from air had its beginning immediately after World War II. By the midst of the war(1941), the U.S. had already developed the first electronic magnetic sensing device which is now called the flux gate magnetometer and by 1942, it was known as magnetic airborne detector. It was initially used by U.S.Navy for submarine detection from air, later on it was used in geophysical propecting from air. By early 1950s, many advanced countries had realized the potential offered by this new tool for hydrological investigations, mining and geological mapping etc.

Additional subsurface control such as deep drill hole data can greatly improve the interpretation. It is a rapid and low-cost method of determining limited amount of subsurface geologic information.

Airborne radiometric and electromagnetic devices also got coupled with the magnetometer for carrying out aerial surveying on all the three parameters simultaneously.

There are many advantages of surveying from air and in brief may be summarized as follows:

i) Rapid coverage

ii) Lower costs

iii)Easy accessibility

iv.`Freedom from the noise

Airborne surveying offers rapid coverage as compared the operations from ground. The time taken by ground survey may be at least 100 times larger than the air borne survey. These surveys are cheaper and have easy accessibility in regions such as swamps, deserts, tropical jungles etc. which can not be approached easily fromgroundThe interpretation approach of airborne geophysical data is the same as for ground based data.

Well logging is the investigation of the rock formations penetrated by a borehole and it envisages measurement of some physical properties of the formations by instruments lowered into the boreholes. Valid well logs, correctly interpreted, can be used to reduce future drilling costs by guiding the location, proper drilling, and construction of test hole and production or disposal wells. Well logging also enables the vertical and horizontal extrapolation of data derived from drill holes.

Geophysical well logs can be interpreted to determine the lithology, geometry, resistivity, formation-resistivity factor, bulk density, porosity, permeability, moisture content and specific yield of water-bearing rocks, and to define the sources, movement, and chemical and physical characteristics of water. Quantitative interpretation of logs provides numerical values for some of the rock characteristics necessary to design analog or digital models of groundwater systems, log data aids in the testing and economic development of groundwater supplies; and of recharge and disposal systems. This can be of considerable value in the design and interpretation of surface geophysical surveys.

Radiometric methods are based on investigating radioactivity of an area. Intensity of Gamma radiations is measured in the field using Geiger counter, scintillation counters and gammaray spectrometers.

Nuclear geophysical methods utilize artificially induced nuclear radiations in rocks and soils; and monitoring their scatterning and return rates.

The basic fact common in applying any of the above methods for exploration of water is that knowledge of the geology of an area is essential to the understanding of the occurrence of groundwater. This is important because geologic structure and stratigraphy provide the framework in which groundwater recharge, storage and discharge take place. Basically, all these geophysical methods aim at determining such geologic characteristics alongwith some hydraulic parameters e.g. permeability, transmissivity etc.

2.2 Electrical Methods

Amount and physio-chemical properties e.g. temperature, salinity etc. of water besides the properties of soil affect resistivity reciprocal of conductivity) of soils. The electrical properties of wet soils are dependent primarily on the amount of moisture, its salinity and distribution in the pore spaces. Saturated soils have lower resistivity than unsaturated and dry ones. The higher the porosity of the saturated rock, the lower its resistivity, and the higher the salinity of the saturating fluids, the lower the resistivity. The presence of clays and conductive minerals also reduces the resistivity of the soil(Zohdy, et.al 1980).

The electrical properties of earth materials (soils) are studied by measuring the electrical potential distribution produced at the earth's surface by an electrical current that is passed through the surface or by detecting the electromagnetic field caused by an electric current either by introducing through the surface or by natural phenomena like lightning etc. Two main variations are found in this technique viz.natural field methods and artificial field methods.

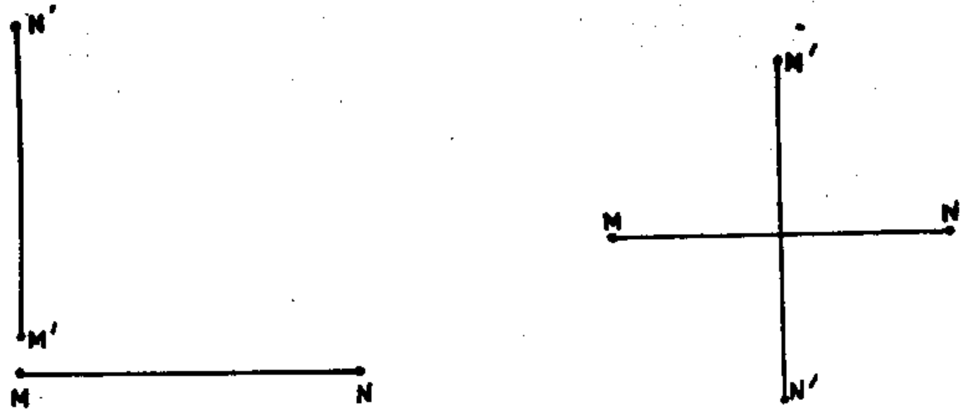


FIG. 1 ELECTRODE ARRAYS FOR MEASURING X-AND Y-COMPONENTS OF TELLURIC FIELD

2.2.1 Natural field methods

These include Telluric Current, Magnetotelluric, Spontaneous Polarization, and streaming Potential methods(et.al, 1980).

2.2.1(a) Telluric current method:

These are natural electric currents that flow in the earth's upper layers in the form of large sheets. They are related to ionospheric tidal effects and to the continuous flow of charged particles from the sun which become trapped by the lines of force of the earth's magnetic field.

Anomalies are detected if the subsurface is not homogoeneous and geologic structures such as faults, folds etc. are present. For measuring telluric field intensity, four potential electrodes M,N,M,' and N' are placed on the surface of the ground at the ends of two intersecting perpendicular lines(figure-1), and the potential differences are recorded on a potentiometric chart recorder or on an X-Y plotter. From these measurements two components Ex and Ey of the telluric field can be computed, and the total field obtained by adding Ex and Ey vectorially. In order to measure temporal variations, measurements are recorded simultaneously at two different stations. Interpretation of measurements reflectsthe major geologic structures of the basement rock.

2.2.1(b) Magneto-Telluric method:

This method is similar to the telluric current method. except that here two parameters, amptitude variations in Ex and the associated magnetic field Hy, are measured (Zohdy et.al, 1980) to determine earth resistivity. Magneto-telluric measurements at several frequencies provide information on the variation of resistivity with depth because the depth of penetration of electromagnetic waves is a function of frequency. Interpretation of data is done by comparing the observed curves with theoretical curves. The main advantages of this method are estimation of true resistivity of the layers and greater depth exploration.

Telluric current and magneto-telluric methods have been successfully used in petroleum exploration. They are recommended for reconnaissance surveys of large basins for groundwater exploration.

2.2.1(c) Spontaneous polarization and streaming potential method:

Spontaneous polarization(or self-potential) methods involve measurement of electric potentials developed locally in the earth by electro-chemical activity, electrofiltration activity, or both (Keller and Frischknecht, 1966). These have been more successful in the search for minerals etc. In groundwater investigations, potentials generated by water moving through a porous medium are measured; the method is known as streaming potential method. Measurements of these potentials have been used to locate leaks in reservoirs and canals. Koerner, et.al(1979) have described use of this method in detecting location of subsurface water and seepage. Water leakages from reservoirs makes it difficult to attain the planned storage capacity. In many cases, water leakages give rise to suffusion which results into catastrophes. These leakages are characterized by negative anomalies of natural currents; the more filtration discharge,a the higher these anomalies are. Temperature of water also affects these currents, and therefore, relationship governing the intensity of streaming potential and sand granulometric composition, electrolyte concentrations and other factors need be studies. Velocity of water flowing to leakage sites is determined by using a device, based on relationship between the temperature of a heated body and its reistance. Observations are made by non-polarizable electrodes and water velocity devices along the reservoir. Ogilvy et.al (1969) have described application of S.P.surveys for such studies in Alpine reservoirs (in Armenia)and Uzbekistan in the submontane part of the Pamirs. Koerner et.al(1979) have presented a comprehensive review of the methods available for detecting sub-surface water and seepage. Geophysical methods, including S.P.method, are compared with other methods, e.g. radio tracer techniques etc.

Another importaat application of this method is found in studying the techńical status of earth dams. Earth dams are constructed for hydrotechnical and reclamative purposes. However, the high permeability of soils and their bad gradation are frequently responsible for the development of mechanical suffussion and other phenomena resulting in dam failure. Intensified and uneven seepage cause these problems. A long-term observation of the seepage flow behaviour is necessary for efficient dam operation controls.

The seepage flow data is basic for hydrotechnical calculations which make it possible to compare the physical conditions of seepage with the design values. These data can also be used to check the proper location. of drainages and filter material in the downstream slopes as they are frequently designed takikng into consideration only constructional requirements and their erroneous location often intensifies the ground redistribution processes in the dam supporting mass and suffusion development which are very difficult to control.

Normally, seepage flow data are based on the measurements of water level percolating into the piezometers installed at various depths in the dam. For reliable calculations and modelling purposes, data from a dense network of observation points is needed, which is generally lacking with the piezometers. Moreover, piezometers provide information relating only to the depth of seepage flow and give a limited information about other parameters characterizing the interaction of soil and moving water. Geophysical methods may provide data from a large number of observation points in relatively less time and low expenditure. Electrical resistivity, induced polarization, S.P., and seismic refraction methods have been successfully applied in studying seepage flow through earth dams in Transcaucasia and Central Asia(Bogoslovsky and Ogilvy, Ground water table is reflected by the drawing contours of streaming potentials (S.P.) in studying seepage flow in a uniform permeable medium. The potentials grow in the direction of water flow and their intensity is proportional the hydraulic gradients. Maps of equal S.P.values obtained in homogeneous grounds supply information on the configuration, direction and intensity of seepage flow both in horizontal and vertical directions (Bogoslovsky and Ogilvy, 1973). In natural conditions, the electro-filtrational fields may be observed above natural drains, like fractures, or Karstic zones, tectonic dislocations and U.Shaped valleys filled with the redeposited material. Higher S.P.Values increasing in the direction of water movement are observed above these drains in case of ground-water discharge . Negative S.P.anomalies reach their maximum above the drain in case of concentrated infiltration of water into rocks. Such anomalies are common on the sites of leakage from rivers, canals and water reservoirs, their intensity reflecting that of leakages. Dobecki and Roming(1985) have mentioned some recent applications of this method.

2.2.2 Artificial field method

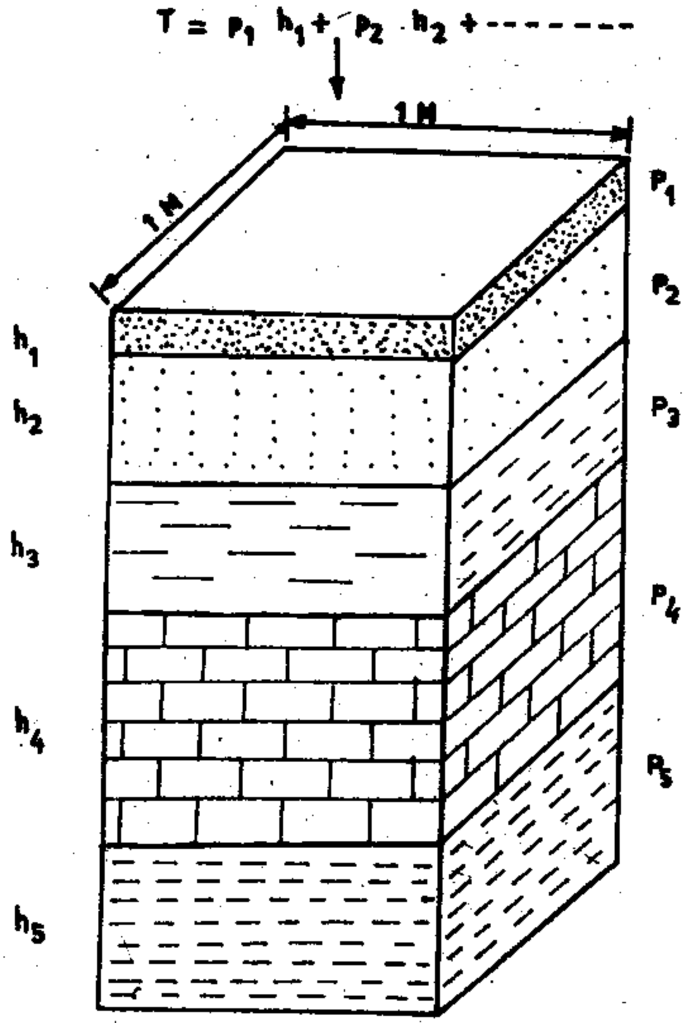
2.2.2(a) Resistivity method:

In conducting resistivity surveys a commuted direct current or very low frequency current is introduced into the ground via two electrodes. The potential difference is measured between a second pair of electrodes. if the four electrodes are arranged in any of several possible patterns, the current and potential measurements may be used to calculate resistivity. Many electrode configurations have been used in practice(Zohdy et.al.,1980) for groundwater exploration. Commonly used among these are Schlumberger, Wenner, Dipole-Dipole, Lee-partitioning and three electrode(pole-Dipole) configurations.
Resistance(= potential developed/current applied), determined from the field

measurements is multiplied by a factor, which depends upon the electrode configuration used, to obtain the resistivity value. For heterogeneous, stratified earth, the resistivity is said to be apparent resistivity and resistivities as well as depths of different layers are determined by interpreting the field data. Interpretation is done either by curve-matching techniques, for which standard master curves are available, or by automatic computer-inversion programs. Now a days number of computer-programs are commercially available (for example Zohdy and Bisdorf, 1975), for efficient interpretation of vast amount of field data.

Resistivity surveys are conducted basically in two modes: vertical sounding and horizontal profiling. Electrical sounding is the process by which depth investigations are made, and horizontal profiling is the process by which lateral variations in resistivity are detected. If the ground is comprised of horizontal, homogeneous, and isotropic layers, electrical sounding data represents only the variation of resistivity with depth. In practice, however, the electrical sounding data are influenced by both vertical and horizontal heteorogeneties. Therefore, the interpretation and presentation of sounding data should be such that horizontal variations in resistivity can be distinguished easily from vertical ones.

The interpretation of resistivity surveys is presented in form of geo-electric sections(figure 2), giving resistivities and thicknesses of different layers. A geologic section differs from a geoelectric section when the boundaries between geologic layers do not coincide with the boundaries between layers characterized by different resistivities. For example, when the salinity of ground water in a given type of rock varies with depth, several geoelectric layers may be distinguished with a lithologically homogeneous rock. Also, layers of different lithologies or ages, or both, may have the same resistivity and thus form a single geoelectric layer.



$$S = \frac{h_1}{P_1} + \frac{h_2}{P_2} + \cdots$$

Fig.2 Example of a geoelectric section
p = resistivity, h= thickness, S= total longitudinal conductance. T = total transverse resistance

A geoelectric layer is described by two fundamental parameters: its resistivity ρ_i and its thickness hi, where the subscript i indicates the position of the layer in the section (i=1 for the upper most layer). Following other parameters, derived from the two basic parameters ρ_i and h_i, are also used in interpretation:

1. Longitudinal unit conductance, $S_i = hi/\rho_i$
2. Transverse unit resistance $T_i = h_i \rho_i$,
3. Longitudinal resistivity, $\rho L = h_i \rho_i$,
4. Transverse resistivity, $\rho_t = T_i/h_i$, and
5. Anisotropy $\lambda = \sqrt{\rho_t/\rho_L}$

(For an isotopic layer, $\rho_t = \rho_L$ and $\lambda = 1$)

These parameters are particularly important when they are used to describe a geoelectric section consisting of several layers.

In groundwater studies, the resistivity method can furnish information on subsurface geology, which might be difficult with other geophysical methods. For example, electrical methods are unique in furnishing information concerning the depth of the fresh-salt water interface, whereas gravity, magnetic or seismic methods are incapable of providing such information. The method was applied to the Delta of Wadi Sudr in Sinai Peninsula (Sayed, 1984) to study the relation between the lithologic succession and the presence of both fresh and saline water bearing formations at different depths. The interpretation showed presence of four geoelectric layers representing the soil zone, aeration zone, fresh water zone and sea water zone at depths of 1-2.5 m, 4-10m and 21-27m respectively. Zohdy et.al(1980) have given references of the work done by various workers in this field. A thick layer seperating two aquifers usually can be detected easily on a sounding curve but the same clay may be low velocity layer in seismic refraction surveys and cause erroneous depth estimates.

Horizontal profiling, vertical sounding, or both can be used for mapping buried stream channels, which are important in planning for exploration and artificial recharge of groundwater. Use of resistivity technique for mapping burried stream channels have been reported by Zohdy et.al(1980) and by Page (1968). The burried stream channel in Penitencia area was discovered by making a few electrical soundings, the measurements of which were distorted by the effect of lateral heteorogencities. The area was then covered by horizontal profiling using Wenner configuration. The isoresistivity map thus prepared showed the course of the burried channel(figure 3).

As another example in area near Campbell, California, an apparent-resistivity map was drawn on the basis of horizontal profiling using Wenner array. The map indicated presence of high resistivity layers at shallow depth but did not delineate the trend of a buried stream channel as directly and as clearly as in the Penitencia area. Supporoting data from vertical sounding gave a cross section which was in confirmation with the results obtained from wells.

Groundwater recharge studies have been tried using electrical reistivity method. Transverse resistivity are determined using the layer resistivity and thickness values and these are correlated with percolation rates. It is found that higher transverse resistances would reflect sites more favourable for recharge. Empirical relations have been developed (Kelly, 1985) and used for subsequent predictions.

The resistivity method was initially used to study proposed damsites for measuring the depth of overburden covering the bedrock. The first commercial use of this method was the study of the Fifteen Miles Falls development on the Connecticut River, conducted in 1928 by the Schlumberger Organisation in New York for the New England Power Association(Kelly, 1962). Besides measuring the depth of overburden, electrical methods are also being used

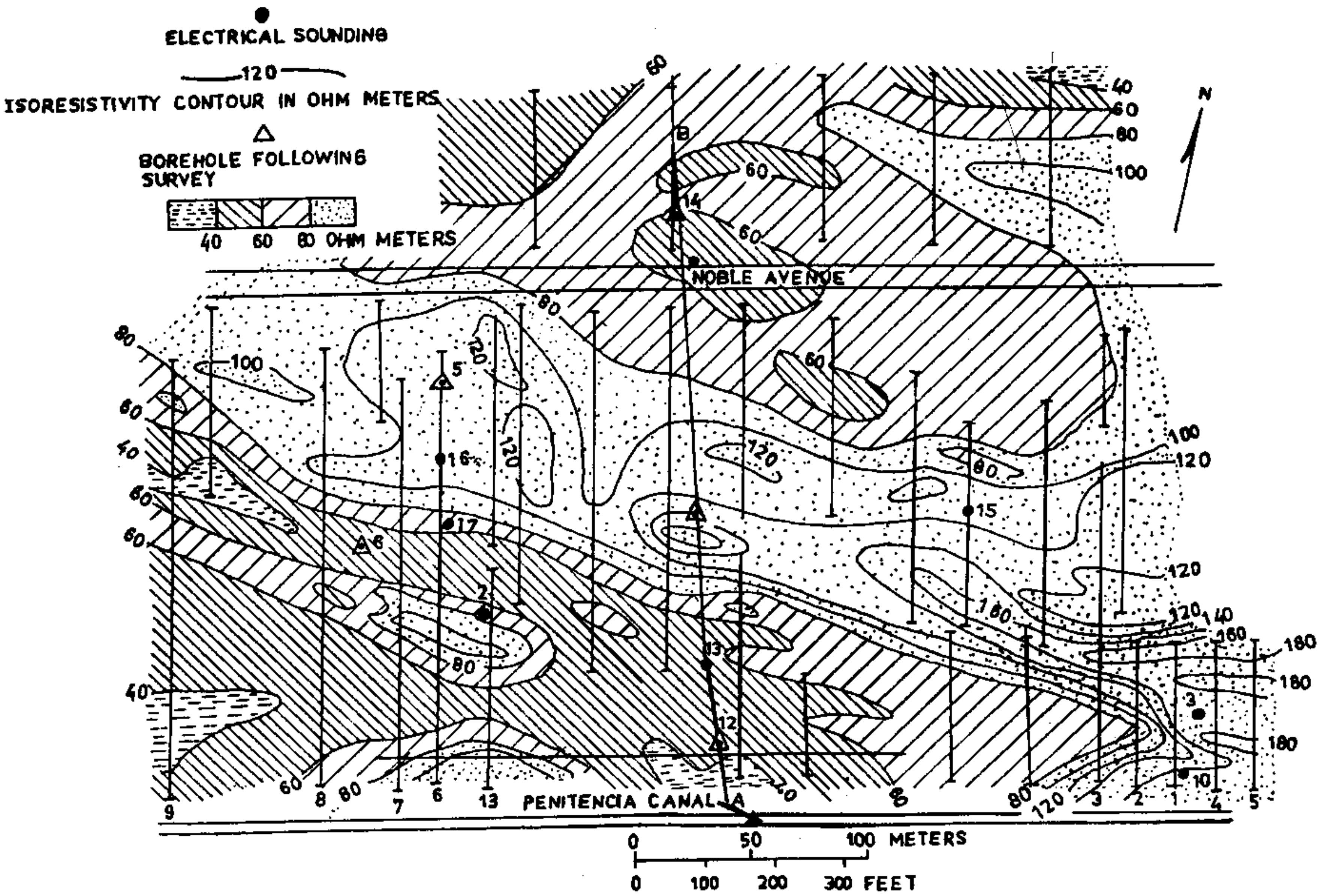


Fig.3 Isoresistivity map showing course of buried channel in Penitencia, California.

for determining physical and mechanical properties of soils. These may be used throughout a geotechnical investigation program, for general site assessment, definition of specific targets or for detailed subsurface mapping along with the drillhole data. Rock strength depends on many factors including the strength of the mineral assemblage, the interrelation of the rock grains and the porosity. As electrical resistivity depends on the water filled in the pore spaces, rock strength increases with the increase in resistivity of the formation. Young's modulus also shows a similar behaviour (Whiteley, 1983).

Recently geothermal energy as a major potential energy source has drawn considerable attention in the scientific community. The principal use of geothermal fluid is for the generation of electric power. It is also utilized for space heating, agriculture, industries, hydrotheraphy, extraction of chemicals which it may contain, and for fresh water. Electrical resistivity method is very effective in exploration of geothermal energy. The resistivity of water-bearing rocks largely depends on the amount of water they contain, the chemical and physical, including thermal properties of the water, and on the manner in which water is distributed in them. It decreases with increasing water content. Using relations between resistivity of aquifer and the porosity, volume of water contained in the aquifer can be estimated. The resistivity of a rock formation decreases with increase of temperature so that it is possible to map a geothermal area by resistivity observations. Jin (1977) has discussed findings of few workers in New Zealand and Italy. Zohdy et.al(1980 p.50-52) have also reported few surveys for geothermal explorations.

Landfill investigation is yet another field in which resistivity technique has been effectively used. This requires information on site geology, water-table location, contaminant plume location, and groundwater movement. Electrical methods have been effective in collecting two types of information(Wood, 1984): (i) analysis of the geologic stratigraphy, which includes boundaries between rock types and water-table depth variation, and (ii) area measurement of a leachate (contaminant) plume and identification of areas most feasible for sampling and monitoring.

Many contaminants contain an ionic concentration considerably higher than the background level of native ground water. When such a contaminant is introduced into an aquifer, the electrical resistivity of the saturated soil is reduced. Surface electrical resistivity profiling across a suspected area can identify this reduced resistivity zone as an anomaly. Urish (1983) has reported successful application of this method is location of plumes from contaminants including brine, uranium reprocessing liquid wastes and landfill lochate in glacial deposits of New England.

Besides examples described in the above paragraphs, the most widely employed application of resistivity method is in groundwater exploration. It gives estimates of various hydrogeological and hydraulic parameters like porosity, permeability, depths and thicknesses of aquifers etc. Transmissivities of aquifer is also computed from resistivity measurements. These parameters are used in computing ground water potential of an area. Application of this method, in ground water exploration has been reported by numerous workers, e.g.Scarascia (1976), Schwartz and McClaymont(1977), Kosinzki and Kelly (1981), Frohlich and Kelly (1985), Mazac et.al (1985), SriNiwas and Singhal (1985), etc.

Detailed geophysical investigations were carried out along E.W.traverses across the south western margin of Cuddapah basin(Balakrishna et.al 1978). Geophysical investigations comprising electrical resistivity and vertical magnetic survey were carried out with a view to understand spatial variation of subsurface in terms of lithology, mineralogy and structures. Askania vertical magneto meter was deployed for the measurement of magnetic field. Resistivity surveys employing dipole-dipole soundings were carried out in east Godavari district of A.P. by using Sintrex 15 KW RDC-10 resistivity equipment with current range upto 20 amperes and voltage from 400-500 volts (Paul et.al.,NGRI Annual Report, 1982) for locating aquifers within 700 meters and to delineate basement. Schlumberger soundings, resistivity profiling and vertical magnetic profiling were carried out in Godavari-Purna and Kukadi basins, Maharashtra (Gangadhara Rao et.al 1983a, 1983b) to identify shallow and deep aquifers. Mark et.al(1982) applied resistivity surveys to regional hydrologic reconnaissance. Vertical electrical soundings using DC resistivity methods were completed along over 60 miles of survey lines in SW Florida.

Detailed study of burried valley was undertaken by Jane et.al(1981). Gravity and seismic surveys were also carried out alongwith surface electrical resistivity soundings to evaluate two sites in Nemaha and Jefferson of Kansas.

2.2.2(b) Electromagnetic methods:

Electrical surveys also are made using time varying electromagnetic field as an energy source. These electromagnetic or induction methods generally use frequencies in the range between 100 and 5,000 Hz, but radio waves of higher frequencies are also being used. These surveys can be made either on the ground or from a low-flying aircraft. The measurements can be used in the similar manner as resistivity measurements to obtain horizontal profiles and depth soundings. Measurements may be made at one or several frequencies. Interpretation usually is accomplished by curve matching or modelling.

The technique has been used effectively in mapping buried, channels, soil moisoture studies, landfill investigations, mapping permarost thickness for arctic construction(Hoekstra et.al,1975; Hoekstra, 1978), mapping subsurface coal mine fires and petroleum firefloods (Bartel, 1982; Bartel et.al., 1985) and groundwater investigations, especially in hardrock and highly resistive area.

Buried channels have been located where the channel-filling material has a resistivity contrast with the enclosing medium(Collett,1967).

In applying electromagnetic waves for soil moisture studies, three properties are important in describing the interactions of electromagnetic waves with soil. These are conductivity, permitivity, and permeability.

Conductivity in the soil depends on its ion content and the currents result from motion of free elctrons. It is important in soils for frequencies below about 1 MHz.

Relative permitivity is known as the dielectric constant of the soil. It depends on soil texture as well as soil moisture. The change in dielectric constant is the main discriminator for soil moisture. Because of the large difference in the dielectric constant of water and soil components, it is possible to relate dielectric constant of the soil to the saturating fluid content. Alharthi and Lange(1984) have described a measurement technique alongwith interpretation procedure for this technique. Bernard et.al.(1984) have compared three measurement techniques of in-situ soil moisture measurements and presented a new instrument called dielectric probe for measuring dielectric constant automatically. It is predominate for frequencies above 1 Mhz. Permeability is not a strong discriminator for soil moisture (Wheeler and Duncan,1984).

The methods of detecting soil moisture using electromagnetic wave are very frequency dependent. Several bands in the electromagnetic spectrum could be used for soil moisture investigations.

EM methods have been used in outlining the regions of highest landfill-derived dissolved constituents in the sand aquifer. Two criteria (Greenhouse and Harries,1983) are to be satisfied in using this method in an effective manner;

i) the introduction of contaminants into the aquifer must produce a measurable change in the total conductance of the volume of earth being sampled by the surface method, and

ii) the lateral variation in electrical conductivity(or resistivity) throughout the site due to changing lithology must be appreciably smaller than or seperable from variations due to groundwater contamination.

Ground water penetration radar(GPR) are also used for determining boundary between rock or soil types and stratgraphic information. This information is important because such boundaries significantly influence the ground water flow system.

The GPR system is typically a one or two-antenna(transmitter/receiver) unit with the necessary power supplies and related electronics to direct an EM Pulse of 100-1000 MHz central frequency into the subsurface and then record reflected pule returns on either a digital tape format or on a single-channel recorder. Depth of penetration is limited by the resistivity and saturation of the soil or rock mass as well as by the power of the transmitter. The technique can be used upto depths of 20m(Dobecki and Roming, 1985, p.2628).

Another variation of radar technique, electromagnetic subsurface profiling (ESP), provides a continuous linear plot of subsurface features. Measurements with this system are independent of seasonal variations(Bhandari and Pandey). Its field of applications include mapping of variations in the composition and density of soils, soil-moisture detection, location of voids, seepage monitoring, estimation of snow thickness and layering, etc.

Electromagnetic(EM). methods are suitable for groundwater exploration, especially in hard rock areas. The advantage is that it produces a sharp anomaly over narrow vertical conductors thereby facilitating markation of boreholes. However, resistivity soundings and profiling are still necessary in order to obtain an insight into the depth to and character of the bedrock Patra and Shastri(1982), Dirks et.al.(1983), and Murthy et.al(1984) have reported application of EM Methods in groundwater exploration. These methods are capable of mapping groundwater pollution plumes around waste disposal sites. Variations in ground water quality is responsible for variations in subsurface electrical resistivity, which is monitored at the surface using EM instruments. Isoresistivity maps are prepared to locate a pollution plume and the movement of pollutants (Ritseema, 1983).

2.3 Seismic Methods

2.3.1 Refraction method

The seismic refraction method is probably the most widely used among the seismic methods for detailed determination of depth and nature of the bedrock and often to locate the water table in sandy sediments. This is possible because seismic velocities are lowered in unconsolidated materials with presence of moisture content.

The method involves timing first arrivals of seismic energy to a line of measuring instruments called geophones, arranged in a array. The most common energy source is a sledge hammer blow and successive hammer blows may be vertically stacked (summed) with modern signal enhancement recorders (seismographs) to achieve reliable ratio of signal to noise. Other sources of energy include weight drop and vaccum assisted weight drop units, air gun systems, shot guns and rifles modified to fire their projectiles into the ground safely. For deeper surveys explosive charges are used in shallow holes.

Interpretation of refraction method involves plotting of first arrival travel time data versus positions of geophones and fitting of straight lines to the data to define different layers. Various techniques have been used (Dobecki and Roning, 1985) to calculate velocities and depths. Now-a-days microcomputers are used to automate the processes of picking records, plotting time-distance plots, fitting straight lines for velocity calculations and calculating depths by various techniques.

The most common use of the seismic method in hydrology is in the determination of the thickness of sediments which overlie essentially non-water bearing consolidated bedrock. Burried stream channels as well as valley-train deposits in old water courses are convenveniently mapped using this technique. The seismic (compressional) wave velocities increase in saturated sediments. This abrupt increase in velocity helps in locating water table, provided thickness of the aquifer is large enough in comparison to its depth below the ground surface.

Seismic refraction measurements in areas where a large number of geophone spreads and shot points(or below points) are employed, may reveal systematic lateral variations in the velocity of unconsolidated deposits. Lithologic variations are reflected by measuring these lateral variations. Various geologic factors contributing to these changes in seismic wave velocities are geologic age, average grain size, grain size distribution, composition, degree and nature of saturation and porosity.

Seismic velocity measurements can be used for estimating average porosities of unconsolidated sediments and weakly consolidated sedimentary rocks.

2.3.2 Reflection method

Till recently, seismic reflection method has been economically used in oil exploration only. Cost of reflection surveys is higher than normal refraction surveys, because of large amount of data needed for carrying out the data processing to produce reliable results. With application of microcomputers for seismic data processing (Hunter et.al,1984,1986), use of reflection method for regular hydrological applications has started. Recent groundwater investigations have shown that with modern, digital seismic reflection equipment which is portable and of relatively low cost, aquifers several meters thick at depths of several hundred meters can be resolved(Whiteley,1985). One particular advantage of reflection method is that its analog graphical record clearly shows the positions of various reflectors, corresponding to different interfaces in the subsurface.

Haeni(1985) has reported the application of continuous seismic reflection methods on the Housatinic River in Connecticut and Massachusetts, two Connecticut lakes, and along river channel in the Sarasota-Port Charlotte, Florida. The method is claimed to be effectively used in shallow, water covered areas to define the geologic framework and continuity of aquifer systems, to locate hydrologic boundaries, to define and to interpret the lithologic character of aquifers and confining beds, and to map the thickness of organic deposits on lake bottoms.

Koerner et.al.(1979) have given a brief review on use of seismic methods for subsurface seepage detection. In studying seepage flow in dam supporting masses, reflection method has been used (Bogoslovsky and Ogilvy, 1970), because of the difference in seismic velocities in the zones of aeration and full saturation.

2.4 Gravity Method

Gravity method is based on measurement of acceleration of gravity. Although the gravitational attraction of any geologic body is a function of its mass, the total gravitational attraction measured by a gravimetric device on the surface above it represents the sum of attractions of both the body and the rest of the earth, as a whole. In geophysical prospecting, only gravity field due to the body is of interest. Therefore, the target of investigation is only the excess or deficiency of mass, which is represented by density contrast with the surroundings. Observed gravity variations, when corrected for non-geologic effects, reflect contrasts in density within the earth, particularly lateral contrasts in density.

This method is a rapid, inexpensive means of determining the gross configuration of an aquifer, provided an adequate density contrast between the aquifer and the underlying bedrock exists. It is useful in locating areas of maximum aquifer thickness, in tracing axis of a buried channel, and in locating a burried bedrock high that may impede the flow of groundwater. In figure 4, the irregular belt of unconsolidated sediments that runs from the northwest corner of the map to the south central part consists of buried outwash or ice contact deposits resting in a glacially overdeepened, preglacial bedrock channel of the Connecticut River(Zohdy et.al.,1980). Well data confirmed the course of this channel. Thus the gravity data reflect the locus of maximum thickness of the unconsolidated sediments.

Water in the interstices of a rock contributes to the total mass of the rock and if porosity is moderate or high, this effect is detectable with a gravity meter. In general, surface gravity measurements, are used primarily in a regional search and evaluation study.

2.5 Magnetic Method

The magnetic method of geophysical exploration involves measurement of the direction, gradient, or intensity of the earth's magnetic field and interpretation of variations in these quantities over the area of investigation. These surveys can be made on land surface, from an aircraft, or from a ship.

Magnetic anomalies are distortion of the magnetic field produced by magnetic material in the earth's upper surfaces. These anomalies of geologic interest are of two types: induced anomalies and remanent anomalies. Former are the result of magnetization induced in a body by the earth's magnetic field. The anomaly produced is dependent upon the geometry, orientation, and magnetic properties of the body, and the direction and intensity of the

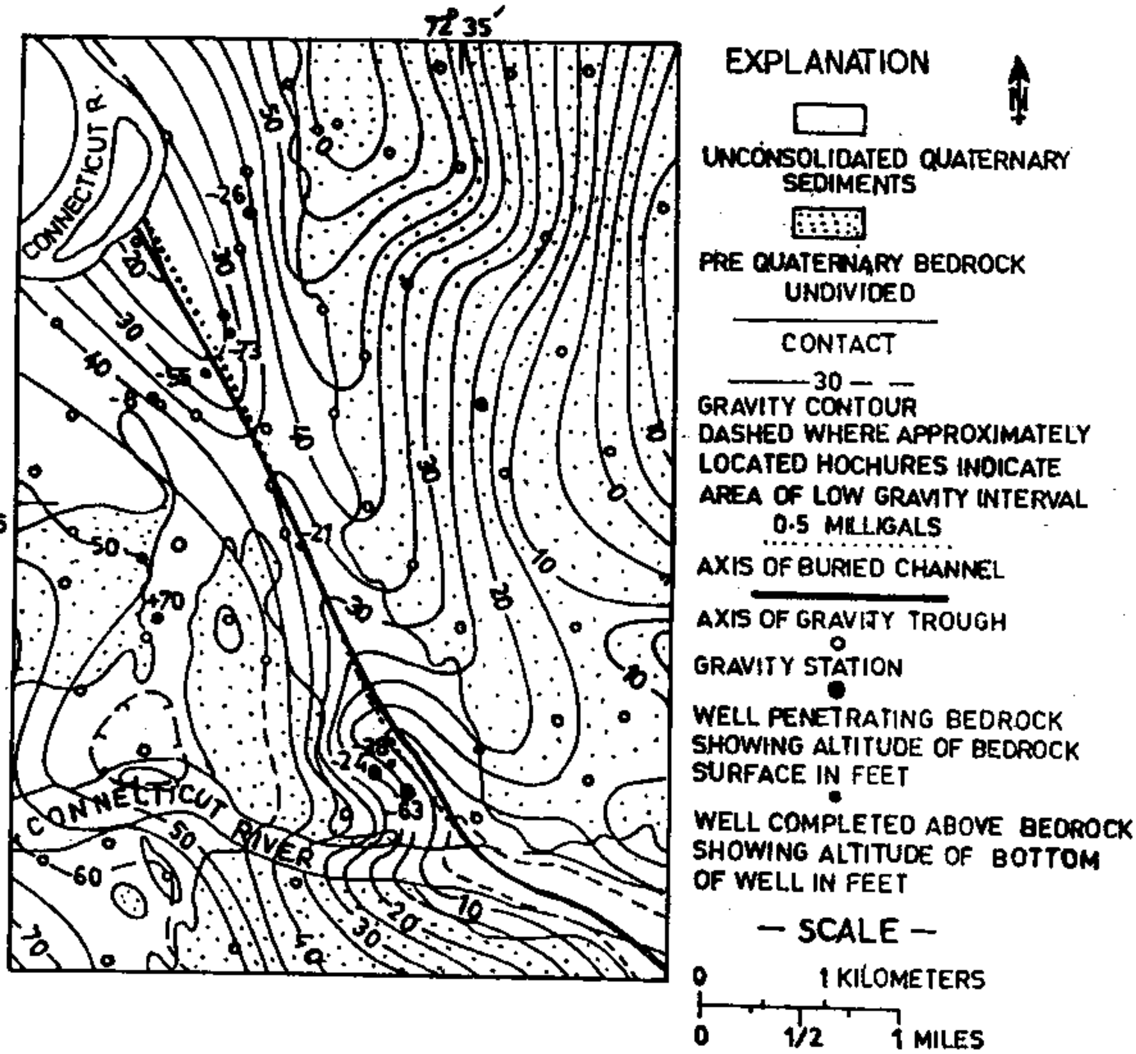


Fig.4 Gravity anomaly map of a buried channel of the Connecticut River

earth's field. Remanent anomalies are the result of 'permanent ' magnetization of a body and are controlled by the direction and intensity of remanent magnetization and the geometry of the distrubing mass. Most magnetic anomalies are a combination of the two types, but usually one type of magnetization is dominant and the other can be ignored in the approximate interpretation of results.

The character of a magnetic anamaly is often indicative of the type of rock producing the anomaly, and an experienced interpreter can identify a general rock type on the basis of character of the magnetic anomalies observed. Quantitative interpretation of individual magnetic anomalies yields information on the depth of burial, extent, structure, and magnetic properties of rock units.

The two major applications of magnetic surveys to groundwater studies have been the study of magnetic aquifers, mainly basalt, and the determination of the configuration of the basement rock underlying the water bearing sediments. The study of magnetic aquifers involves the identification of rock type and the determination of geometry and magnetic properties. The study of basement-rock configuration generally involves determining the depth to the surface of the basement at several points and contouring the depths.

Magnetic surveys have been used in the study of basalt aquifers in several areas, for example in the Snake River Plain and Columbia Plateau, with varying degree of success. Magnetic data from Gem Valley in southeastern Idaho illustrate some of the potentials and limitations of magnetic surveys in the study of volcoanic rocks(Zohdy et.al.,1980 p.112). The vall-floor consisted of basalt rocks, partly covered by windblown soil, which are enclosed by sedimentary rocks. This method is useful in locating edge of the basalt where it was at shallow depths.

2.6 Borehole Logging Methods

Well logging methods form a part of borehole geophysical methods which include all techniques of lowering a sensing device in boreholes to make a record of the physical properties of the formation cut across by the boreholes. However, in well logging methods only those methods are included by which a formation can be evaluated in terms of the rock characteristics, nature and amount of contained water/fluids. In general, these methods give information either directly or indirectly on the subsurface geology of the area. Exploratory drill holes or wells are our only means by which direct assess to subsurface geological information can be gathered. But these are expensive means of assess to the subsurface and technique such as well logging are economically justified because these recent prospecting techniques enable us to derive more data from each holes and extrapolate this information laterally. Apart from this main advantavge there are many other advantages which makes the use of the logging techniques essential.

The measurement of physical phenomena in boreholes is based on sound physical principles. In most of the methods direct measurements of the physical properties such as porosity, permeability, fracture in rocks etc. are not possible. However, based on the empirical relations, or in some cases based on mathematical theory, it is now possible to determine these properties accurately from the well logging data. Sometimes, this information can only be obtained by the judicious use of a combination of several different types of measurements on boreholes i.e. complex logging of boreholes. Borehole geophysical methods include all those operations which are carried out in boreholes. Some of these operations are used in the evaluation of the formations and others are used to control the technical conditions in boreholes and yet, some other method at the time of the completion of the boreholes for production purposes. Based on this, Mathur (1977) had classified the borehole geophysical methods under three major groups.

(i) Well logging methods in formation evaluation,

(ii) Geophysical methods for controlling the technical conditions in boreholes.

(iii) Well completion services.

Well logging methods based on the physical property measured are classified into nine main heads namely electrical, radioactive, acoustic, magnetic, nuclear geothermal geochemical, mechanical and visual methods. The second group of method includes those methods used in controlling the technical conditions in boreholes. Under this group, major problems which are commonly met with, are identified. The third group is the well completion services in which four types of operations are identified and the methods available to solve them are identified. Classification of borehole geophysical methods particularly for hydrological investigation is given in Table I. In electrical logging methods the electrical properties of rocks are determined. The electrical logging methods are based on the measurement of the differences in the electrical properties of rocks that exist in the section penetrated by boreholes. In logging practice, the following electrical properties are studied.

(i) Electrical resistivity or conductivity

(ii) Electrochemical activity

(iii) Induced electrochemical activity

(iv) Dielectric constant.

Based on the electrical property studies, there are number of electrical logging methods(as can be seen in the classified table no.I). The electrical resistivity of rocks is studied in different methods such as:

(i) Conventional electrical logging, potential and gradient sondes

(ii) Latero log

iii) Induction log

TABLE I

CLASSIFICATION OF BOREHOLE GEOPHYSICAL METHODS

ELECTRIC LOGGING METHOD	CONTROLLING PROPERTIES	PARAMETERS MEASURED
1. Spontaneous polarization logging	Electrochemical activity(SSP, ESSP)	Natural potentials
2. Resistivity logging with common sondes, (Potential or normal and gradient or lateral sondes)	Electrical resistivity	Apparent resistivity
3. Investigation with lateral devices	-do-	-do-
4. Laterologs	-do-	-do-
5. Micro resistivity logs, micro- laterolog, proximity log	-do-	-do-
6. Single electrode resistance log	-do-	-do-
7. Induction logging	electrical conductivity	Apparent conductivity
8. Induced polarization logging(IP)	Induced polarization activity	Potential of I.P.activity
9. Electrode potential method	Electrode potentials of electrochemical conductive minerals	Difference in electrode potentials

iv) Micro log

(v) Single electrode log

The resistivity of rocks is measured by the use of an artificial alternating current field. The main part of the borehole tool is the electrical sonde. The electrical sonde consists of a source or transmitter of alternating current or receiver devices which measures the characteristics of this field. Electrodes or coils are used as the transmitter or the receiver.

The electrochemical activity of rocks are studied in the method called self potential or S.P.logging. The electrochemical activity of rocks develops a local natural potential field around the boreholes. The variations of these potentials are measured in the S.P.method. The induced electrochemical activity is studied in the method called induced polarisation or in short called as the I.P.logging. In this method, the residual electrical field existing in rocks even after switching off the artificial current field, is measured.

Usually electrical logging is carried out in uncased boreholes filled with conductive muds or drilling waters. Only induction and dielectric logging can be carried out in dry boreholes or boreholes filled with non conductive muds or when the boreholes are lined with non conductive casing. Thus it can be generalized that electrical logging methods can not be carried out in boreholes with metallic (conductive) casing. The volume of investigation in electrical logging method varies from several hundreds of cubic centimeters as in micrologs to several cubic meters as in conventional lateral log and induction log. In other words, the depth of investigations in radial direction varies from few centimeters to several meters. In well logging practice, the media in the volume of investigation is electrically non-homogeneous because the volume of investigation include the borehold mud, the target formation and the adjacent beds. The target formation in turn are not homogeneous because of their layering. In such cases, it is more convenient to represent the result of measurements in terms of apparent values. These apparent values are generally used in resistivity logging methods and are called apparent resistivity (ρ a). or apparent conductivity(σa) values.

Using apparent values is quite convenient because in some cases these values are close to the true resistivity of the formation and in some other cases suitable corrections can be applied to get the resistivity of the formation. From such measurements, the true electrical resistivity of rocks can be calculated. The changes in the resistivity of the rocks along the axis of the borehole is studied by continuously recording the measured values with depth. For studying the changes in resistivity in the radial direction it is necessary to run several types of logs with different depths of investigations. For obtaining the resistivity of the formation with a good accuracy in logging practice, measurements are made with complex logging consisting of sondes having small depths of investigations(micro sonds); and medium depth of investigations(conventional logs with medium lengths, latero logs and induction log with medium depths of investigation) and with large depths of investigation(conventional sondes with large lengths, laterologs and induction lags with large depths of investigations).

In the spontaneous polarization (S.P.) logging electrochemical activity of rocks is studied. For such a study, the natural electrical field is measured in boreholes. The physical basis of this method is that there exist differences in electrochemical activity of rocks and due to this sources of natural electromotive forces are developed and result in the flow of natural currents. It is commonly observed that the deflections opposite clay or shales beds do not change very much with depths and it is possible to draw a vertical line called the clay or shale line. The deflection of the curve from this line will give anomaly. Anomaly may be positive or negative and depends upon the thickness of the bed. The apparent values thus obtained may be converted into true or static

S.P.values by using correction charts. If the origin of S.P.is only due to diffusion or absorption process then, from the measured potentials, it is possible to calclate the resistivity of formation waters by using the following equation:

$$\Delta U_{SP} = Ko \log \frac{\rho\ mt}{\rho\ w}$$

where Ko = The coefficient of chemical activity

(= 70.7 at 20°C)

ρ mt & ρ w = resistivities of the mud filtrate and formation waters respectively.

S.P.methods have proved to be more effective in the delineation of sand-shale or clay series. In hard rocks, such a limestones, granites and metamorpic rocks, the connection between the SP anomalies and the geological features become difficult and the interpretation of SP logs becomes difficult.

In restivity logging, a four electrode system (AMNB) in which two are the current electrode(AB) and the other two are potential electrodes(MN) are used. Current of known values is used to energise the formations and difference of potentials of M and N electrodes are measured. From these values the resistivity is calculated by using the following relation

$$\rho\ a_{(ohm\ metre)} = 4\pi\ K \frac{\Delta\ VMN}{I}$$

where K = geometrical factor ($= \frac{AM - AN}{Mn}$)

The record of these apparent resistivity with depth is called the electrical resistivity log. Depending on the geometry of the electrodes, two main types of sondes are called normal or potential and the lateral or the gradient. Potential of the electric field is measured with the potential sondes while with the gradient sondes the gradient of the field is measured. The curve shapes obtained and the maximum value recorded depend, on the thickness of the bed and the resistivity of the layer. The true resistivity of the formation can be determined using departure curves and it is also possible to obtain the bed thickness very accurately.

Mac Cary(1983) conducted logging experiments in carbonate aquifers. Logging methods which are inherently superior to others viz. density, neutron and acoustic velocity logs,.for the analysis of limestone and dolomite aquifers, were used. Contour maps derived from geophysical data were found useful to outline areas of recharge, direction of probable groundwater flow and locating saline areas.

Tselentis(1985) used microcomputers at the well site for providing timely answers to important hydrogeological questions. Computer oriented log interpretation techniques were in use in oil industry while their application in hydrogeological problems has been restricted. It was found possible for a microcomputer to handle, by relatively simple operations, complex analytical processes which may be used to advantage by the well log analyst in many hydrological problems. Tselentis(1985) also examined to what extent the hydrogeophysical properties of fissured aquifers can be derived from geophysical logs alone. To do this a theoretical double porosity model based on a tortuosity-free, parallel conduction path assumption was introduced to establish possible relations between geophysical parameters that can be measured from conventional geophysical formation logs and hydraulic characteristics of the aquifer.

Thomas(1986) used geophysical logs for determining formation water quality. Resistivity of the formation pore water was determined by cross plotting saturated formation resistivity, obtained from normal or lateral resistivity logs, against formation bulk porosity from neutron density, or acoustic velocity logs.

2.7 Nuclear Methods

Nuclear techniques have, in the past twenty years, made significant contributions to studies in surface and subsurface hydrology. They include application of radio-labelled compounds as water tracers and are the outcome of the ever widening multidisplinary approach in hydrological investigations. Physics, Chemistry, Geology and Engineering have all enriched the field of water resources investigation and management. Nuclear techniques in hydrology are mainly isotope based. The isotopes are used either as sources of radiation or as tracers. In the studies on the dynamics of any system, it is always rewarding to identify a small part of the system or a group of molecules and follow their behaviour as they progress through the system. The problem is how to identify that part of a group or molecule, if it is undistinguishable from the rest of the system. This is where the tracer comes into our reckoning. The choice of tracer is rather delicate since it has to behave like the material being traced, but distinguishable from it for purposes of detection.

In hydrology, the fluid of interest is water and the system could be a river, lake or an aquifer. The most ideal tracers to study the behaviour of water are the different isotopic species of water molecule itself. There are several situations where it is not feasible to use the isotopic species of water as tracers. Radioistope techniques may be classified, as:

(i) Environmental isotope techniques,

(ii) Artificial isotope technique, and

(iii) Techniques employing sealed radioisotope sources.

Water molecule is made up of two atoms of Hydrogen and one atom of oxygen. Hydrogen has three naturally occuring isotopes namely protium(^{1}H), deuterium(^{2}H or D) and tritium (^{3}H or T). Oxygen has also three naturally occuring isotopes, namely oxygen-16(^{16}0), oxygen-17(^{17}0) and oxygen-18(^{18}0). The important isotopic species of the water molecule such as $H_2{}^{16}0$, $HD^{16}0$, $H_2{}^{18}0$,$HT^{16}0$ are used in hydrological investigations. The first three molecules $H_2{}^{16}0$,$HD^{16}0$ and $H_2{}^{18}0$ are stable whereas fourth one($HT^{16}0$) is radioactive and is well known as tritiated water. Tritium(T) is a radioactive isotope of hydrogen and it emits radiation with a maximum energy of 18 Kev and has a half life of 12.26 years. It is produced in the upper atmosphere by the interaction of cosmic rays with nitrogen nuclei. Tritium is rapidly oxidized to HTO and enters the hydrologic cycle. Tritiated water can also be artificially produced. Some of the environmental isotopes used for hydrological investigations are tritium, carbon-14, silicon-32, chlorine-36, Krypton-85 argon-39 and Uranium isotopes etc. The long half life of Carbon-14(5730 years) and its presence as dissolved inorganic carbonate in groundwater have been responsible as the most studied dating tool in groundwater hydrology. Carbon-14 is also produced in the upper atmosphere like tritium, by the interaction of cosmic rays and nitrogen.

Chlorine-36, though not part of the water molecule, is known as a more conservative tracer than many other ionic species. It is ideal todate waters in the range of 50,000 to a million years. Its half life is 3,00,000 years. Silicon-32 is much shorter lived than carbon-14, but longer live than tritium. It is produced in the upper atmosphere by the spallation of ^{40}Ar. Artificially produced tracers have been very useful in establishing hydraulic connections in general and to estimate groundwater flow velocities.

The isotope tracers are used to estimate rainfall recharge, stream discharge measurements, studies on the efficiency of percolation tanks, canal seepage, leakage from dams and reservoirs, identification and bed load transport investigations, studying of moisture movement in the unsaturated zone, dating of groundwater, studying interconnection between surfaced and groundwater, measuring groundwater flow velocities and direction of flow,snow and glacier melt studies etc. The choice of technique is wide and depends upon the application. Few examples may be summarized as follows:

(i) Radioisotope such as Br-82, I^{131}, Sc-46 are used as tracers for surface and subsurface waters,

(ii) Environmental isotopes such as tritium, Carbon-14, silicon-32 are used for the study of case histories of water.

(iii) Stable isotopes of the water molecule such as deuterium and oxygen-18 are used for distinguishing waters of different origin and in the general understanding of the water balance of a given system,

(iv) Neuclonic equipment containing sealed radiation sources such as Co-60, Cd-109, Am-241 are used for the measurement of soil moisture, density and suspended sediment concentration. Nuclear logging tools with radiation sources emitting gamma rays and neutrons are also very useful in some areas of hydrology,

(v) Nuclear analytical techniques such a neutron activation analysis, X-ray fluorescence analysis are used on investigations relating to water quality.

(vi) Finally, a new and vast area of potential application is the use of intense radiation sources for disinfection and purification of waste water.

2.7.1 Soil moisture studies

The principle of measuring soil moisture by counting thermolized neutrons was first proposed in the late 1940's and the instrument required for carrying out field studies was developed. Soil moisture studies were carried out by Reginato et.al(1964) by using gamma attenuation method. Hewlett et.al(1964) used neutron scattering method for studying soil moisture variance. Soil moisture measurements of the surface layers were carried out by Pierpoint(1966) using neutron depth probe and a surface shield. Boodt et.al(1967) determined soil moisture characteristics for irrigation by using neutron moisture meter and tensiometers. Measurements of soil water storage changes for water balance purposes were taken up by Bell and McCulloch(1969). The neutron probe techniques were applied to irrigation research and management in Jamaica by Holds worth(1974). Studies of soil moisture were carried out by Grant(1975), Visvalingam(1975), Bell(1976). Shankar et.al.(1979) analyses variation of soil moisture at various depths by Ra-Be neutron scattering probe under ponding conditions. Singh(1984) discussed special features of isotope techniques and studied moisture movement in controlled conditions. Ramesh Chand(1986) and Ramesh Chand et.al(1986) have reported soil moisture studies carried out at the National Institute of Hydrology, Roorkee by using Troxler depth moisture gauge model no.3321.

2.7.2 Other nuclear applications

Environmental isotopes of natural or artificial origin are present in natured waters in varying proportions. These proportions depend on natural processes which can not be controlled by man. The isotopes normally used in hydrology are ^{18}O, ^{3}H, ^{13}C, ^{14}C, ^{34}S, ^{15}N and ^{234}U. Among the stable isotopes, oxygen-17 is not used as its variation is exactly similar to those of oxygen-18 and its measurement, which is more complex than that of oxygen-18, does not provide any useful additional information. Oxygen and hydrogen isotopes are ideal hydrochemical tracers for the study of certain problems, because they are incorporated in water molecule. These isotopes have been used to obtain a better theoretical and practical understanding of groundwater studies (Ramesh Chand and Seth 1986). Demand is increasing for better understanding of hydrologic systems to facilitate management of water as a resource and to evaluate environmental problems. The distribution of isotope species in water provides information on sources of groundwater, on flow paths, mixing and on physical and chemical characteristics of aquifers. Tritium is one of the heavy isotope of hydrogen and has one proton and two neutrons. It is produced in the atmosphere by interaction of cosmic rays. Since, 1953, this has also been formed in thermonuclear explosion and due to atomic bomb explosions. The tritium content of the atmosphere and water increased significantly, and is now one of the most important isotope used to identify recent ground water movement. The most commonly measured isotopes of dissolved constituents in ground water are ^{13}C and ^{14}C in the organic carbon species (HO_3,CO_3, H_2CO_3,CO_2aq.) ^{14}C is a radioactive isotope produced indirectly in the atmosphere by interaction of cosmic rays, and in recent years also by thermonuclear weapon testing. The amount of ^{14}C in a natural sample is expressed in modern percentages, that is to say in percentage of the amount of ^{14}C in plant carbon before 1890, since that time $\delta^{14}C$ in atmospheric CO_2 has slightly decreased due to production of CO_2 by industrial combustion (fossil fuel does not contain ^{14}C) and recently it has begun to increase following the nuclear explosions. The amount of $\delta^{13}C$ is expressed in ^{13}C % and is compared to the P.D.B.standard which has a ratio $^{13}C/^{12}C$ more or less equal to the average ratio of marine limestone(which gives $^{13}C = 0$). Atmospheric CO_2 carbon has an average value of $\delta^{13}C$ is $-7^{o}/_{oo}$ and that of biogenic origin has σ $-25^{o}/oo$ due to the isotopic formation in chlorophyllic synthesis, however significant variations in the ratio $^{13}C/^{12}C$ is observed in different plants. The age of ground water can be determined by measuring the decay rate and dilution factors of ^{14}C concentration. Water as old as 40,000 years can be dated with ^{14}C techniques now available. Fractionation of ^{13}C, a stable isotope, provides information on carbonate solution that causes the dilution of ^{14}C. In addition, photosynthesis, bacterial activity and other chemical reactions cause fractioation of carbon isotopes that help in identifying the source of carbon. ^{14}C is measured with proportional counters in the gas or liquid phase. ^{13}C is measured by mass spectrometry, with a precision of $\pm$ 0.1 $^{o}/oo$. In the last two decades both the use of environmental and of man made isotopes has proved to be quite a reliable tool in hydrological investigations. Ramesh Chand and Seth(1986) isotopes have wide applications both in surface water and ground water problems. In brief, isotope techniques provide the potential of routine operation to the following areas of application,

i. Investigation of changes in soil moisture content,

ii) Processes in the unsaturated zone,

iii) Investigation of recharge mechanism and origin of recharge,

iv) Quantitative recharge estimates,

v) Groundwater movement and storage,

vi) Dispersion in surface waters,

vii) Sediment transport,

viii) Stream flow gauging,

ix) Seepage losses from reservoirs,

x) Watershed investigations,

xi) Snow and glacier melt studies,

xii) Water balance studies of lakes and reservoirs etc.

First five applications are reviewed under the head of investigations in the unsaturated zone in another report (Ramesh Chand and Seth. 1986) covering studies on changes in soil moisture content recharge estimates and origin of recharge, and finally movement of groundwater, flow direction and flow velocity.

3.0 REMARKS

Basic methodology and brief operational details have been outlined for almost all geophysical methods which can be applied for hydrological investigations.

Surface methods of investigations are easy and fast in field operations, and prove to be economic as compared to the subsurface methods. Considering simplicity of field instrumentation, S.P.,resistivity, gravity, magnetic and some nuclear methods are preferred. However, gravity and magnetic methods can be applied only for some limited applications e.g. reconnaissance surveys for outlining subsurface structure of a basin, etc. S.P., resistivity and nuclear methods are applicable in many hydrological investigation programmes.

In many cases, electromagnetic methods provide useful data as supplement to the resistivity measurements, enabling reliable interpretation in terms of hydrological parameters. These are especially suitable for soil moisture studies and are comparable to only nuclear methods for this application.

Seismic methods also, although costlier, provide useful supplementary data to other methods in some cases where electrical methods are not effective because of power line disturbances, very resistive terrain etc. Heavy investments limit application of this method only in large-scale, well funded investigation programmes.

Borehole geophysical methods provide deeper insight into subsurface studies by taking observations directly from points generally within the zone of investigation. The data from these methods are valuable in correlating the results of surface investigations with the subsurface parameters.a These measurements are taken only at limited number of points since the cost and time requirements are high for these surveys. Different logging techniques have varying degree of applications. Before taking up any borehole logging programme, these characteristics should be taken into consideration.

Nuclear methods include applications of radio labelled compounds as water tracers, use of isotopic radiation sources for studying moisture in the unsaturated zone, use of environmental isotopes (H^2,H^3, O^{18}, C^{14} etc.) to investigate water circulation patterns in the hydrosphere. Injection of a suitable radiotracer into soil moisture in the unsaturated zone and following its transport by nuclear detector methods provide an useful approach to investigate rainfall recharge and regional water-balance. The nuclear studies have demonstrated Hu versatility of isotope methods in providing information on regional hydrological regimes. It is often difficult to obtain similar information by conventional hydrological methods. Nuclear methods are preferred over some other methods and can be conveniently employed in hydrological studies as outlined in the present report.

A variety of field problems including determination of geologic and hydraulic parameters e.g. lithology, permeability, transmissivity etc. estimation of seepage and recharge and reservoirs and canals etc., exploration for groundwater; geothermal exploration; water balance studies of lakes and reservoirs; etc. are effectively handled by a variety of these geophysical methods.

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