TN-39

RESISTIVITY AND S.P. TECHNIQUES FOR STUDY OF GROUNDWATER POLLUTION

SATISH CHANDRA
DIRECTOR

STUDY GROUP

V C GOYAL
RM P NACHIAPPAN

NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAWAN
ROORKEE-247667 (U.P.)
1987-1988

CONTENTS

LIST OF FIGURES

SUMMARY

Surface geoelectrical methods are now a days increasingly applied in solving a range of hydrogeological problems involving both quantity and quality issues, particularly in the problem of detecting and monitoring ground water contamination. While much of this work can be done by monitoring wells alone, the cost of such a program is often prohibitive. Electrical geophysics has proven to be helpful in mapping contaminants and in optimizing the location of monitoring wells.

In this report the two category of methods for detection and analysis of groundwater contamination, viz. hydrogeochemical and geophysical methods have been briefly outlined. Considering their low cost of operation and faster coverage, the geophysical methods are preferred during regional surveys, especially for monitoring of contaminant plume before it reaches the groundwater. This report focuses on the fundamental principles of geophysical surveying for pollution and protection studies. Geoelectrical methods, in particular resistivity and S.P. methods, have been reviewed in detail covering some Indian as well as foreign case-histories.

1.0 INTRODUCTION

1.1 General

In the holy books of all world religions, water is described as a source of life. There would be no life on earth in its absence. The distribution and occurence of water in the globe is given by L'vovich (1979) as ocean water 94% ; ground water 4% ; glaciers and ice 1.65; surface water 0.35%;. Thus it can be visualised that ground water is one of the most important sources of water supply.

Ground water can often be a carrier of diseases causing death in many cases. Quality of the ground water is therefore of utmost importance. The abundance of sites with potentially hazardous wastes in India demands that priorities be set for purification of water. The standard of water-quality varies from area to area depending on the availability of water and its use. Thus it is a matter of great urgency that criteria for water purification priorities should be worked out and a great deal of time will be needed for research. The development of quick field - survey systems would be useful in this context.

A brief note about the contaminants and their sources is discussed in the succeeding sections, and then two geophysica methods for detecting and delineating the contimination have been reviewed.

1.2 Overview of Contaminants

The major source of ground water is the rain fall.

The rainfall as it reaches the surface gets charged with elements in the atmosphere, and during its course to under ground reservoir gets further loaded with more mineral matters. Thus by the time rain water reaches the reservoir, it will have its own characteristic quality depending on the medium through which it has passed. In addition to this, the quality of water gets deteriorated by other processes which are inseparable from the existence of the living planet. The process of deterioration is called contamination and the elements responsible are the contaminants.

1.3 Sources of Contaminants

The causative sources of contaminants may be natural or artificial. Natural processes include mineralisation of ground water and salt water intrusion. Artificial sources are by the introduction of foreign chemicals and biological materials, into the subsurface environments by human beings.

The sources of contaminants may be divided into two categories based on the extent to which the contaminants may spread. They are point sources and non-point sources. The septic tank systems, land fills, etc. which are categorised under domestic pollution and industrial pollution are point sources. On the other hand, agricultural pollution, radiological pollution and salt water instrusion are non-point sources of pollution.

1.4 Delineating Contaminant Plumes

The process of contamination is controlled by several factors like nature and concentration of effluents, soil and sub-soil charactristics, time factors, porosity, permeability, hydraulic gradient, storage capacity of aquifers, etc.

A body of fluid introduced into an aquifer will tend to remain intact rather than mix with or be diluted by the natural ground water. In many cases of ground water pollution, the contaminating fluid is discharged into the aquifer as a continuous or nearly continuous flow. Thus the contaminated ground water will often be in the form of a 'plume' extending from the source of contamination towards its natural discharge point. The boundaries of the plume, usually distinct, will be established by the size of the source area and the natural ground water flow pattern caused by pumping wells. As contaminated ground water is usually found as a distinct body or plume, it is necessary to define the magnitude of the problem and, if necessary to design an efficient abatement system.

The standard methods for locating and defining a polluted water body can be broadly divided into the following categories:

(i) Geochemical methods and
(ii) Geophysical methods.

In geochemical method, water samples are collected from the aquifer in question through various techniques and are analysed for their quality. Water samples may be collected simply by pumping from existing wells, from different levels by separated screens, by seperated wells in the same location, by use of a sampler or by pumping of small volumes of water at different depths.

Generally, the water samples will be tested for conductivity, T.D.S., chemical composition, trace metals etc., from which rain water-ground water interaction, ground water-mineral equilibria etc., can be determined. The results are compared with the standard recommended by various organisations such as W.H.O., I.S.I. and decided whether the water is polluted or not.

One of the primary problems in field investigations of ground water pollution is locating the contaminant plume. In most cases the goal is to locate the pollutant and its movement by test holes and direct monitoring. In the interest of efficiency the investigative areas should as focussed as possible. Drilling of sampling hole on a hit or miss basis is both time consuming and expensive. It can also be destructive to the site involved. Geophysical methods can come to aid in these investigations without much destruction. Especially, Electrical Geophysics has proven helpful in mapping contaminants and in optimizing the location of monitoring wells.

The geophysical methods comprise of surface and subsurface methods. A very commonly utilized geophysical method is based on resistivity of earth materials. Since the measured earth resistivity is inversely propotional to the conductivity of ground water, bodies of water containing high concentration of conductive wastes will have lower resistivity values than the surrounding natural ground water. Therefore, the resistivity method can be used to quickly determine the boundries of the plume of contaminated ground water.

Number of investigators have established the usefulness of surface electrical resistivity as a tool in the detection of ground water contamination. Swartz (1937) used it to locate salt water boundaries in the Hawaiian Islands. Excellent examples of the use of surface electrical resistivity as a practical method in detecting ground water contamination from sanitary land fills are reported by Cartwright & McComas (1968). In 1969, Warner reported on attempts to detect and outline zones of ground water contamination by earth resistivity measurements, where a resistivity contrast exists between contaminated and uncontaminated ground water. These surveys over Long Island, Newyork sites were particularly successful as was one Western Texas survey.

Tracing water from land fills by resistivity method has been reported as successful by Greenhouse & Harris (1983), Kelly (1976); from sewage treatment effluent by Fink & Aulenbach (1974); from industrial waste disposal sites by Sinha (1984), Rogers & Kean (1980); and from salt water intrusion by Gorhan (1976) and Prasad et.al. (1983).

2.0 REVIEW

2.1 Geophysical Methods

Geophysical methods are based on gravity, magnetic, electric, thermal and elastic properties of the earth. Until recently, very little emphasis has been placed on the advantages of utilizing geophysical methods in performing subsurface investigations. The aplication of geophysics has been useful in locating and characterizing types of over burden, profiling bedrock surface, determining location and thicknesses of aquifers and monitoring of ground water quality. Geophysical techniques should be considered as a useful tool in project planning, design and follow-up evaluation and as a complement to the standard subsurface geochemical investigation methods.

Any ground water project must pass through the phase of regional surveys leading to detailed survey and exploration of ground water by means of bore holes or wells, which may be followed by determination of water-quality. For almost all geophysical methods which can be applied for hydrological investigations, basic methodology and brief operational details have been reviewed by Goyal et. al. (1986).

Both the surface and subsurface geophysical methods are used for ground water investigations. The surface methods of investigations are easy and fast in field operations, prove to be economical and hence, they are preferred to the subsurface methods. Considering simplicity of field instrumentation, S.P., resistivity, gravity and magnetic methods are preferred.

However, gravity and magnetic methods are not of much use in hydrological problems. This leaves S.P. and resistivity methods, which are commonly used in many hydrological investigations, viz., delineating aquifer zones, water quality zoning etc.

Ground water monitoring wells are commonly used to detect possible leakages from contaminant sources such as holding ponds and other containment structures or impoundment areas. But it has its own disadvantages too. In the first hand the leakage is not detected until ground water contaminants appear and are measured at a well. Thus significant contamination may occur before it is detected. Secondly the well data can provide at best only a rough indication of the location of the actual contaminant source.

A permanently installed electrical monitoring system can help to over come both of these problems. It can detect leaks from containment structures at a very early stage, before significant groundwater contamination has occured.

2.1.1 Streaming potential (S.P.) method

Self-potential, also called streaming potential, is a geophysical technique which measures naturally occuring voltage distributions in the ground. It has been used in mineral exploration for many decades. Recently, S.P. method has been applied to detect and monitor leaks in the liners of waste containment ponds.

S.P. singals in a pond may be derived form a number of sources which may be grouped into three main categories, viz., electro chemical, electro kinetic and back ground noise (Hughes et.al. 1986). Electrochemical effects arise from differences in fluid chemistry, biologic activity in the pond, the chemistry of the pond liner, the mineralogic composition of the underlying geology, etc; clays in particular produce larage electrochemical effects due to ion exchange, which results in diffusion potentials. These effects are secondarily dependent upon controlling circumstances. Electrochemical effects can also result from grounded features of no interest in the pollution survey.

Electro kinetic effects arise from fluid movement within the pond. Frequently this involves streaming potentials due to leakage through the bottom of the pond (Fig.1). Streaming potentials can be represented by the Helmhotz equation. (Corwin, 1986).

$$\Delta V = \frac{\rho E \xi}{4 \pi \eta} \Delta P$$

ρ = Pore fluid resistivity

E = Pore fluid dielectric constant

η = Pore fluid viscosty

ξ = Zeta potential; a property of the double layers

ΔP = Pressure difference

The magnitude of ΔV of a streaming potential anamoly generated by seepage flow thus is directly proportional to the pressure difference across the flow path and to the fluid resistivity.

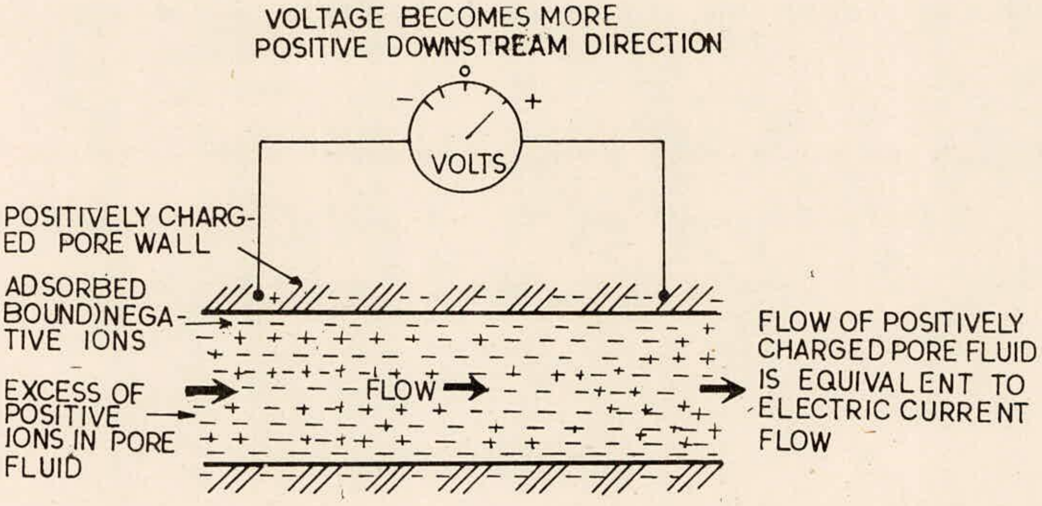

FIG.1. GENERATION OF STREAMING POTENTIALS

Implicit in the above relation is the dependence upon the geometry of the hole in the lines, permeability of the underlying geology, fluid salinity and T.D.S., and controlling factors (temperature and pressure), upon the fluid viscosity.

The third source, the unwanted signals (noise)includes sources such as ground tellurics due to solar activity, thunder storms, cathodic protection on pipelines, telephone cables, radio stations etc.

Hughes et.al. (1986) have recommended some remedial as well as precautionary measures, for mitigating these unwanted signals, such as filtering the received signals, placing reference electrodes, installing telluric monitors to monitor noise, using temperature probes for calibration of thermal effects.

The operating principles and configurations of S.P. method have been described in detail by Corwin (1986). The field logistics for an inpond S.P. survey are quite simple. A base or reference station is established in a portion of the pond that is thought to have nominal electrochemical and electro kinetic characteristics. A second mobile electrode in used for the measurements. It is placed near the bottom of the pond and a voltage measurement with reference to the base-station electrode is made. The electrode is moved to the required points on the survey grid in order to provide desired coverage. Pond temperature measurements may also be made concurrent with the voltage measurements.

Under water S.P. data are interpreted for anamolous responses as compared to background response. The absolute S.P. voltages are meaningless. However, relative changes are immensely significant in properly conducted surveys. Generally the interpreter looks for closures in the contoured data, changes in contour density and directional changes in contours at the edges of the pond. Local changes to relatively negative voltage are of greater interest, as these could indicate the prescence of fluid movement out of the pond due to a leak in the liner. Follow up hydrological investigations can then determine whether the S.P. anomalies are electrochemical or electro kinetic in nature.

The quality of the data and the extent to which it can be interpreted in terms of the desired parameters depend on the signal-to-noise level of data. Noise for streaming potential monitoring measurements includes all time-varying voltages that are not caused by contaminant flow. The sources of noise voltages include reaction of electrodes to changes in soil properties, such as temperature or moisture content, ground water movement unrelated to contaminant flow and currents generated by telluric activity. Such noise sources are common in industrial areas and must be carefully considered before a contaminant flow origin is assigned to a measured anomaly.

The S.P. method has been successfully applied by Hughes et.al. (1986) for detecting and measuring seepage from an flue-gas-desulfurising (F.G.D.) pond of a power plant near Wyoming, U.S.A., despite the presence of 2000 MW power plant

2 kilometers far data with an average precision of ±0.3mv or better were obtained. A total of seven anamolies were located and the follow-up confirmation was done by using seepometers and remedial measures were taken accordingly.

In an attempt to map the above specified F.G.D. pond leak Zonge et.al. (1985) found out a suspected compression fracture due to differential compaction as well as other previously unknown suspected leaks. They suggested that although geologic and chemical characters associated with the ponds of above type are complex, an understanding of the geologic environment, type of pond liner and fluid chemistry will make S.P. a very productive and valuable tool for delinenting pond leaks.

2.1.2 Resistivity method

Electrical resistivity surveying is a geophysical technique that estimates earth resistivity from surface measurements. Because various types of earth materials exhibit certain characteristic resistivity values, they can be distinguished from one another. Resistivity technique is particularly adaptable to locating ground water aquifers, but it should be noted that the resistivity approach also may be utilized in sand and gravel exploration, salt water instrusion problems and other ground water contamination problems that alter the electrolytic content of the ground water (Charles and Lee, 1975).

Resistivity of earth materials

A majority of earth materials conduct electricity because of the mineralized water that they contain in pores and fissures. This is known as electrolytic conduction. Other types of conduction, for instance metallic conduction, which occurs in certain ore minerals such as pyrite, galena, magnetite and graphite, and solid conduction in solid rock at high temperatures, do not contribute significantly in ground water aquifers.

The electrolytic conductivity of a rock depends on the conductivity of the contained water, the amount of water and the manner in which the water is distributed within the rock. It is therefore evident that the resistivity of a rock varies with porosity, degree of saturation and amount of dissolved solids in the water. Moreover, under certain circumstances, the water may not be free to move, becoming immobilized by clay which gives rise to the observation that argillaceous rocks, which retain moisture effectively, are generally more conductive than arenaceous rocks.

It is important to note that the resistivity of earth materials is a very widely varying parameter mainly because one of its determining elements, the resistivity of naturaly occuring water may vary form a few tenths of an ohm-m in the case of sea - water to more than 100 ohm-m in the case of fresh water. In practice, the low end of the resistivity scale is encountered where sea-water or salt water occurs in certain sediments. The high end of the scale is represented by solid igneous rock or dry unconsolidated overburden, for which the resistivity may reach several tens of thousands of ohm-m.

It should be noted that it is very exceptional for a formation to have a constant resistivity. Generally the resistivity changes progressively with distance reflecting subtle facies changes within the formation, such as an increase of argillaceous material away from the edges of a sedimentary basin, an increase in the salt content of the contained water or an increase in the degree of diagenesis. Geological formation can therefore be not regarded as being electrically homogenous, variations in resistivity of upto 30% over sub-outcrop areas are common.

When an electric current is introduced into saturated soil it tends to move in a tortuous path through intergranular spaces following much tne same path as the ground water. In case of ground water flow, the driving force is the hydraulic potential, whereas for electrical flow it is the electrical potential. If the soil material is nonconductive, such as quartz sand, and relatively free of clay, the magnitude of current depends primarily on effective porosity and pore water resistivity (or conductivity).

A relationship between the pore water resistivity ρ_w and bulk resistivity ρ_o is given as (Archie, 1942):

$$F = \frac{\rho_o}{\rho_w} \qquad (1)$$

Where F is the formation factor.

But, $$F = \alpha \phi^{-m} \qquad (2)$$ (Winsauer et.al.1952)

Where ϕ = Porosity

α = a constant ranging between 0.47 - 2.2

m = cementation factor, ranging between 1.3 - 2.6.

By combining the above equations (1) and (2),

$$\rho_o = \alpha \rho_w \quad \phi^{-m}$$ (3)(Urish,1983)

This implies that bulk resistivity values determined from surface surveys are influenced primarily by variations in effective porosity and pore fluid conductivity. In other words, higher porosity and pore fluid conductivity yields lower resistivities.

A summary of the basic relation between electrical and hydrological parameters, which are used for pollution surveys has been given by Mazac et.al. (1987).

Concept of Apparent resistivity (ρ_a):

The immediate objective of resistivity survey is to determine the distribution of resistivities in the subsurface. This is done by passing a known current into the earth between two current electrodes A and B, by studying the resulting potential distribution by means of potential difference measurements between two potential electrodes M and N, and then by comparing this potential with that created in a homogenous isotropic earth by the same current. Normally one lacks the ratio of the measured potential to the theoretical potential at a given point. This ratio has become the fundamental parameter of resistivity method and is known as apparent resistivity when the resistivity of the reference medium equals unity. Also, the apparent resistivity becomes true resistivity if the earth material being studied is homogeneous.

Electrode Arrays:

In surface electrical resistivity methods an electrical current is introduced into the ground at the surface using two out side electrodes, and the resultant electrical potential is measured between two central electrodes as shown in the figure 2. There are a number of electrode arrangements which have been developed for use in geoelectrical work. (Zohdy et.al.,1980). For ground water research, commonly used among these are schlumberger, Wenner, Dipole-Dipole, Lee partitioning and three electrode (Pole-Dipole) configurations. But Schlumberger and Wenner arrays are widely used in hydrogeological applications.

The relationship between the apparent resistivity (ρ_a) and the measurable quantities viz.,

1) I, the current applied,
2) v, the potential difference between the potential electrodes, and
3) the geometric dimensions of the array used,

varies accordingly to the electrode array adopted. For instance the relation for the Schlumberger array is $\rho_a = \frac{AM.AN}{MN} \frac{\Delta V}{I} \pi$

But for wenner array it is expressed as $\rho_a = 2\pi a \Delta \frac{V}{I}$

(Since in Wenner array AM=AN=NB=a)

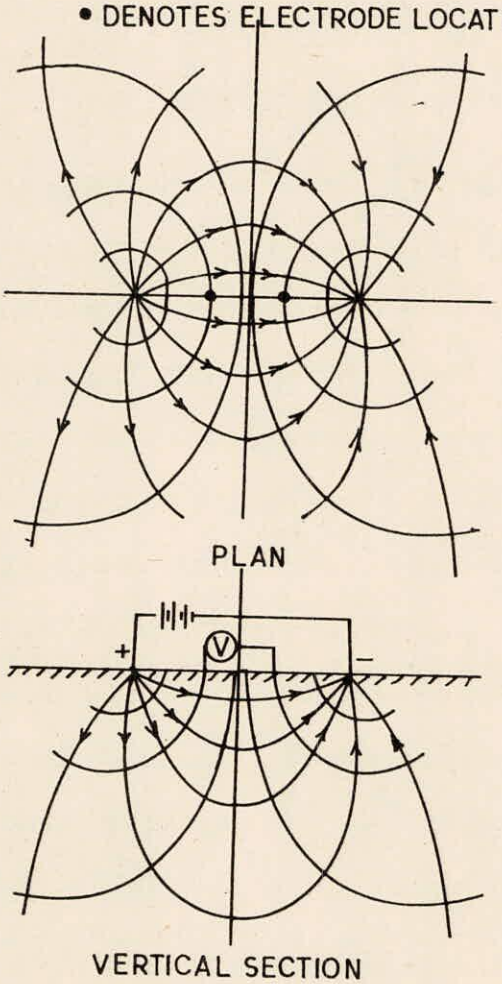

FIG. 2. ELECTRICAL CURRENT FLOW IN THE EARTH-WENNER ELECTRODE CONFIGURATION

Resistivity surveys are conducted basically in two modes: vertical sounding and horizontal profiling. In vertical electrical sounding, depth investigations are made, and in horizontal profiling lateral variations in resistivity are detected. For sounding, the Schlumberger and for profiling the Wenner arrays are most suitable (Urish, 1983).

An electric current imposed at the earths surface moves in a wide elipsoidal pattern from the positive current electrode to the negative electrode as shown in the figure 2. It should be noted that the current flows in lateral as well as vertical directions. As the probes are spaced further apart the zone caused by the pattern of the electrical flow becomes larger. Hence, the resultant apparent resistivity value is from a larger and deeper volume of material as the electrode seperation is increased. If one is only insterested in shallow effects, the electrode spacings should be small; for broader or deeper effects, the spacing should be large. Zohdy et.al. (1980) recommends that in making horizontal profiles atleast two different electrode spacings be used. As a profile line crosses a plume, a pattern of lowered value can be oserved. Assuming that the region is consisting of hydrogeologic and topographic characteristics the lower resistivity stations will delineate the plume (Urish, 1983).

Electrodes:

Electrodes are the only link between the resistivity equipment and the earth. Therefore it is necessary to give due importance to certain properties of the electrodes, such as the resistance of an electrode, electrode polarisation etc.

The resistance of an electrode mainly depends on its geometry and dimensions and the resistivity (ρ) of the ground in the vicinity of the electrode.

Heating up of the ground in the immediate vicinity of the electrode causes evaporation of moisture and there by an increase in resistivity, which in turn leads to an increase in the electrode resistance and a decrease in the emission current. To improve this situation, resistance of the electrode can be lowered by deep emplacement or by the use of multiple electrodes. The difference in the chemical nature between the electrolytes in soil and the conductive material of the potential electrodes gives rise to potentials at the contact of the electrodes with the soil. This can be rectifed by positioning the potential electrodes with care and leaving them in the ground long enough before resistivity measurements commences so that the electro chemical phenomenon which gives rise to the contact potential shall stabilize.

In the first phase of a pollution survey, it is necessary to determine the minimum number of parametric measurements necessary to establish the likelihood of obtaining meaningful regression relations between hydrogeological and geophysical parameters. Mazac et.al. (1978) have recommended the "method of iterative analysis" procedure by Sharapanov, which enables one to determine whether the number of paramatric measurements for a locality is sufficient or should be increased, or whether it is necessary to settle for a lower accuracy for the hydrogeological estimate or choose a different form of the regression equation. It is to be noted that the apparent resistivity at a given electrode separation does not afford a unique interpretation because it is due primarily to a combination of soil and pore-water charecteristics. For electrical profiling a hydrogeologic situation must be assumed in which the soil matrix is relatively constant. Then variations in apparent resistivity from one location to another can be assumed to be caused by changes in pore water resistivity. Many contaminants contain an ionic concentration considerably higher than that native ground water. In general, increased ionic concentration or T.D.S. results in higher electrical conductivity (lower electrical resistivity) in the water. Thus, in an aquifer zone containing a contaminant one would expect the pore-water resistivity to be lower than the sorrounding area.

Detection of an anomalous zone requires a sufficiently high resistivity contrast between native water and contaminated water to allow practical discrimination. It has been found out that, under most conditions, a minimum ratio of contrast is about 5 : 1. Sensitivity factors, in addition to the pore water-resistivity itself, are depth and thickness of the contaminated layer; greater depth and smaller thickness reduce the sensistivity of the method. Further, the change caused by this pore-water contrast must be more than sufficient to over come expected variations due to geology of the formations. The concept of threshold value (Klefstad et.al. 1975) is useful in this regard. Threshold value is defined as the minimum level of contamination which can be detected over the natural scatter of lateral variation of the subsurface material. It should be recognized that deposits of clay may also cause anamalous sensitivity lows. In regions where clay is frequently encountered, proper corrections for the clay-content should be applied in order to get the reliable results.

Interpretation:

The purpose of interpretation of electrical sounding investigations is to express the data obtained from field measurements in terms of lithological variations in the subsurface. Reliable interpretation demands a sound knowledge of and a considerable experience with the resistivity method alongwith a good concept of the geology of the area under study. Interpretation is based on the study of various sounding curves obtained for the study area, noting common charecteristics and progressive changes rather than on isolated study of individual sounding curves. The interpretation of an individual curve is rarely unique, but taken in conjunction with additional information from borehole and geological data it is possible to arrive at a reliable interpretation for the study area.

Interpretation can conviniently be divided into two stages. The first stage is physical interpretation where by the geoelectrical parameters (e.g. resistivity of different layers) of the subsurface are determined using the resistivity field data. The second stage of interpretation relates the geoelectrical parameters to the hydrogeology of the formations. Interpretation of resistivity field data can be attempted either qualitatively or quantitatively.

Qualitative interpretation:

Qualitative interpretation techniques are either used as a first step towards the quantitative interpretation of sounding curves or used because quantitative interpretation becomes impossible in certain cases.

Data for qualitative interpretation are represented in one of the following ways.

- as resistivity maps.
- as resistivity profiles
- as maps of the Dar Zarrouk parameters
- as profiles of Dar Zarrouk parameters.

The Dar Zarrouk parameters are the transverse resistance (T) and longitudinal conductance (S) of an geoelectrical section. (Goyal et.al.1986), defined as:

Transverse resistance $T = h \times \rho$

and longitudinal counductance $S = h/\rho$,

where h is thickness and ρ is resistivity.

Quantitatiave interpretation:

It is beyond the scope of this report to go into all the aspects of quantitative interpretation. Therefore, only a breif outline has been given. Basically there are four methods of quantitative interpretation.

- The method of curve matching of field and theoretical curves.
- The method of reduction of layer. (auxialary point diagrams)
- The method of indirect interpretation by means of a computer.
- The method of direct interpretation by means of a computer.

The first two methods can be used in the field. The last two methods involve the use of a computer and therefore only be applied effectively in the laboratory. The method of curve matching relies on the two and three layer earth models. Several albums of theoretical curves are available for this purpose(e.g. Orllena & Mooney, 1966).

The method of indirect interpretation by means of a computer involves the calculation of a sounding curve based on an assumed earth model. The calculated curve is then compared with the field curve. If the curves differ, the assumption is modified, another theoretical curve calculated, a second comparison between the field and the theoretical curves made and so on until a good fit is obtained. With the advent of the convolution technique, this method of indirect interpretation has become a powerful tool in the analysis of sounding results.

The direct method, on the other hand, involves the determination of a resistivity model starting from the ρ_a and $AB/_2$ values of the field sounding curve. To be effective the direct method of interpretation requires a large computer. A number of computer programs are commercially available (e.g. Zohdy & Bisdorf, 1975; Argelo, 1967; Sriniwas & Israil, 1986; Ghosh, 1971).

Greenhouse and Harris in 1983 used the D.C. resistivity survey sucessfully, for detecting migration of contaminants near a land-fill site at canadian Force Base, Borden, Toronto in Canada. The method was shown capable of mapping the plume at a reconnaissance level and at a cost far less than that was required for point sampling of the plume in boreholes. They used wenner soundings over the site. The electrode spacing for which contamination effects were maximized was found to be 20 m, which was then used to profile over the entire site. For interpretation the investigators used an FORTRAN program given by Davis (1979). They also suggested that for interpreting profiling data, a visiual examination of the contoured data will be often a major benefit.

Kelly in 1976 made use of 12 VES of Wenner configuration to delineate ground water contamination near the West Kingston landfil site which was in operation from 1952 to 1967, located north of the University of Rhode Island. Using the sound curves and logs of near-by test borings, a three-layer geoelectric model was prepared and studied. The differences in apparent resistivity were assumed to be due onlyto differences in specific conductance of ground water in the saturated zone. For computing specific conductance the formation factor was assumed to be 4.5. The attempt was sucessful that both the magnitude and trend of values computed from surface resistivity measurements and determined by sampling were in good agreement, although, no quantitative interpretations were attempted due to the non-availability of field control.

The depth profiles could be used to find the depth to bed-rock or to determine the piezometric surface. The horizontal survey could also be used to delimit the zone of contamination (a low resistivity area due to increased ionic concentrations in ground water) which by its shape would indicate the direction of ground water travel (by being elongated in that direction). Even though the horizontal survey is indirect, this was chosen by Fink & Aulanbach (1974) for determining the direction and location of the flow of the sewage effluent applied to the sand beds of Lake Georage village sewage treatment plant, New York, U.S.A., and in evaluating the quality of that discharge as it flowed through the ground. A D.C. resistivity meter was used adopting Wenner configuration with an electrode spacing of 50 feet which was supposed to be the approximate depth to the ground water table near the plant. An iso-resistivity map was prepared and visually examined, which provided useful information regarding the most likely direction and location of sewage effluent flow.

Sinha (1984) attempted to delineate the ground water pollution caused by the disposal of industrial wastes into Nagdeo nala of Hindon river using geoelectric sounding method. A total of 17 vertical soundings were carried out using Schlumberger configurations with electrode seperation varying from 20 to 200 m around Nagdeo bridge, near Saharanpur (U.P.), India. By the visual examination of Resistivity contours he concluded that the contamination is high and advancing gradually. The resistivity data were also interpreted using the computer program developed by Sriniwas et.al. (1982). Rogers and Kean (1980) monitored the groundwater at a fly ash disposal site, Sankville, Wisconsin, U.S.A. by using both sounding and profiling methods of resistivity survey. VES was carried out with Wenner configuration by increasing the electrode spacing from one feet to a maximum of 200 feet, which entailed 24 readings per sounding. Electrical profiles were measured on a monthly basis along lines approximately perpendicular to the suspected ground water flow direction. The distance between profile locations was 60 feet with a constant electrode spacing of 20 feet. The profiling was made on a monthly basis during spring, summer and fall. Since, the survey was of a long term one, temperature correction were made. The data were interpreted by using 2-layer curve matching method and partial curve matching techniques followed by interpretation using a computer modelling program which incorporated the Koefoed-Ghosh multilayer resistivity algorithm. They have shown that electrical sounding can very effectively locate both the horizontal and vertical extent of the leachate when limited subsurface information is available from well borings. The most critical information needed by them for the interpretation was an understanding of how the resistivity of the aquifer materials changed as a function of saturation and the temperature and conductivity of the pore fluid.

This they determined in the laboratory from well-boring samples. They have also shown that the electrical profiles can be very effective for monitoring the change in concentration of leachate in the ground water with time, provided the profile data are corrected to a common ground water temperature. Kean & Rogers (1981) have presented laboratory techniques to supplement and correct the field data.

In order that the resistivity method give useful results, resistivity contrasts must exist in the subsurface. For example, if the contaminant does not have a significantly greater conductivity than the ground water, or if the ground water is naturally highly conductive itself, a large enough resistivity contrast may not exist,and the method may not work. In addition if depth to ground water is too great, the thickness of the unsaturated sediments can mask any contrasts between contaminated and natural ground water. The geologic environment must be relatively uniform so that the resistivity values and profiles can be compared with one another.

Four major ground water pollution (From industrial and landfill sources) studies have been conducted by Stollar and Roux (1975) using resistivity method adopting Wenner configuration along with test drilling and water sampling programs for confirmation of resistivity results. In three cases, the resistivity survey proved successfulin defining the lateral extent of ground water. In the fourth case it could not. After discussing the similarities and differences which affected the results of the four resistivity surveys they reasoned for the failure of the resistivity survey in the fourth case as due to the extensive man-made obstructions in large portions of the study area, deep-water table, relatively small difference in the specific conductance between the contaminated and natural groundwater and extreme lateral variations in geology overlying the contaminated plume.

An integrated approach to delineate contaminated ground water has been attempted by Berk & Yare (1977). This approach, which include both surface resistivity method and ground water sampling and analysing procedure, was used by them for investigating a ground water contamination problem in a major unconfined aquifer, caused due to the disposal of industrial waste water into an unlined lagoon, in permeable Atlantic coastal plain physiographic province of New jersy, U.S.A. Several constant depth traverses were made, using Wenner configuration. Representative resistivity curves were prepared. An interpretation as to the general degree of aquifer contamination was inferred, by classifying the resistivity data as:

Significant contamination	(= 0 to 500 Ohm feet)
Intermediate " "	(= 500 to 1000 Ohm feet)
Uncontaminated	(= > 1000 Ohm feet)

The choice of limiting values for each of these zones was arbitrary. On the basis of these results, eight wells were drilled which verified the extent of contamination shown by the resistivity survey.

The combination of the electrical resistivity technique with the ground water sampling procedure developed during the investigation proved valuable and reliable technique for delineating in three dimensions a contaminant body with in an aquifer in unconsolidated sediments. It should be noted that, the relatively homogeneous subsoil, ;uniform shallow water table, flat topography, and significant resistivity contrast between the contaminated ground water and the native water contributed to the success of this attempt.

Electrical properties of rocks at low frequencies are dominated by effects due to the presence of pore fluids. Differences in conductivity between saturated and unsaturated rock depend primarily on inherent electrical properties of the rock, porosity and conductivity of the fluid. Electrical detection of subsurface contamination in either the saturated or unsaturated zones requires the existence of a zone of contrasting electrical behaviour produced by the contamination. Such contrasts or anamolies can be caused by the presence of increased or decreased concentration of ions. In areas where materials with contrasting electrical properties (such as sand stone and clay stone) are present in the subsurface with irregular geometry, anamolies can be difficult to interpret and additional information about geology and ground water conditions must be relied upon.

Two electrical methods viz. (1) Dipole - Dipole resistivity method-best suited for determining electrical changes with depth and (2) terrain conductivity-best suited for determining lateral changes in electrical properties at a particular depth, were used by Sweeney (1982) for detecting pollution near a solid waste landfill site within the California coast ranges, San Francisco, U.S.A. The investigator's main concern were to determine the possible contamination, to establish the base line conditions, and to design a sampling/monitoring system. The geophysical data were obtained prior to the start of the drilling program and later integrated with reconnaissance geologic data for the purpose of selecting sites for monitoring wells. He also found that the resistivity data were useful in checking for possible ground water contamination and also for extrapolating well data across the site.

Geo-electric soundings have proven to be a comparitively cheap and quick method of mapping the position of the saline and fresh water interface in both coastal areas and large inland basins though a sharp and well defined interface is not usually encountered in nature. Khouri & Agha (1979) investigated and studied the movement of salt water front in the Dawwa basin, central part of Syria. The study was carried out using hydrogeological, hydrochemical and geophysical methods. The investigators conducted 150 soundings using Shlumberger configuration. The sounding curves were interpreted by using theoretical schlumberger curves, and a number of resistivity maps were prepared. They found that the saline waters are distinguished by very low electrical resistivity values. Rocks which transmit saline water have resistivity values that are several times less than the values for that transmitting fresh water.

The resistivity map clearly showed the regions of saline water occupation. The resistivity values in these area fall to even less than one ohm-meter.

They have compared the geophysical and hydrochemical data to establish a correlation between apparent resistivity of the water bearing layers and water salinity.

Resistivity value	Water Salinity (TDS)
< 5 Ohm meter	Saline & highly saline (8000 - 1,00,000 ppm)
<5 to 10 Ohm meter	medium salinity (2000 - 8000 ppm)
10 Ohm meter	Fresh water (< 2000 ppm)

They also reported that water salinisation was also reflected on the various types of geoelectrical sounding curves; saline aquifers are charecterized by Q and 'OH' types where as 'AK' and 'HK' types charecterizes fresh water aquifers.

Electrical resistivity soundings were carried out by Patra & Battacharya in 1966 adopting Schlumberger configuration at 24 stations with a maximum spread of 1000 m around Digha in the coastal region of West Bengal, India, in connection with ground water investigations for Digha township. The geophysical surveys were conducted to examine the possibility of saline water invasion and to investigate the existence of saline water pockets reported earlier. The results were interpreted by the graphical analytic method, and the lithological logs were prepared. The interpretation of sounding data had been facilitated by the lithological logs of bore holes drilled at selected points and the resistivity data supplemented by bore hole data. The probable lateral and vertical extents of the aquifers were delineated. And finally the investigators reported that there had been no indication of saline water and suggested that it was probably due to the prescence of some impervious layers located in the area. They came to this conclusion by establishing through geological logs that the low resistivity was due to plastic clay and not due to saline or brackish water bearing formation.

Patra (1967) carried out geoelectrical resistivity soundings to verify the possibility of saline water invasion around the Jaldha coast, West Bengal, India. The VES were carried out using Schlumberger configuration and the sounding curves were interpreted by semi - empirical auxiallary point method given by Kelenov. He reported that a low resistivity of 0.7 ohm-m corresponds to a saline water bearing fine sand which was located 14 m below the surface. He also concluded that the isolated saline pocket was not due to the saline water invasion from the sea as a continuous resistivity increase was noticed in this region.

Sea water invasion is a common problem in coastal regions. Although Geo-electrical methods are widely used to identify zones of contamination with salt water, it is not an easy task. The similarity in electrical conductivity between clay, salt water and brackish water in sandy aquifers limits resolution by sounding methods. Prasad et.al. (1983) attempted to quantify the salt water intrusion along the N.W. coast of Scleswig-Holstein, F.R. Germany, by a combined approach using geological, geochemical and geophysical methods. Observed geochemical data were compared with simulated values of sea water intrusion, based on thermodynamic principles. The comparisions were used to confirm deductions drawn from the combined approach. Based on consistency in results of these methods, a low resistivity near the coast was interpreted as clay layers enriched in adsorbed salts of marine origin. They concluded that the combination of geophysical and hydrochemical concept afford a basis to delineate the boundary - of sea water intrusion under terrestial systems.

Gorhan (1976) after an attempt to determine the saline/fresh water interface in the delta area of the Nacaome river, Southern Honduras by resistivity soundings, concluded that the sounding revealed clearly the dangerous proximity of the saline/fresh water interface in the hazard of a saline water contamination of the aquifer due to ground water exploitation. He reported that it was also useful in selecting "Key locations" for exploratory drilling in order to delineate the zone for ground water extraction. In this view, geoelectric soundings are especially applicable for preliminary investigation where the knowledge of the approximate position of the interface over large areas is initially more important than great details at a few points.

2.1.3 Geophysical logging (subsurface) methods

There are three major geophysical bore hole operations viz., electric, electromagnetic and radiometric logging. The electrical survey include the S.P. log, the resistance log, the apparent resistivity log and the focussed current log. The electromagnetic survey includes the induction log. The radiometric survey mainly includes the natural gamma log, gamma - gamma log and neutron log. Besides these methods there are acoustic logging, caliper logging, flow-meter logging and the temperature logging.

First time in 1927, Schlumberger brothers introduced the electric logging, which plays an important role in subsurface geophysical pollution detecting and delineation methods. The electric logging techniques as applied to ground water exploration investigation and water wells, with principles, procedures, interpretation techniques and applications have been discussed in brief by Tanwar (1980) along with some field examples.

Kwader (1986) has shown that by using open borehole geophysical logs, in situ water quality measurements with respect to various ion and dissolved solids concentration can be approximated. He has done an extensive research project in which numerous porosity and resistivity logs were compared with actual cores and water quality samples from completed wells in tertiary corbonate aquifers of S.E. coastal plains, U.S.A.

Kwader has combined both the Archie equation, $F=a/\phi^m$ and a widely accepted equation $F = R_o/R_W$ and derived $R_W = \phi^m R_o$

Where, R_W = Resistivity of the formation pore water

ϕ = Porosity

m = Cementation factor

- R_o = Resistivity of the saturated formation.

The porosity($\emptyset$) values were obtained from neutron log and corrected with a caliper log. Saturated formation resistivity (R_O) values were obtained by normal resistivity and lateral logs.

The cementation factor (m) was taken as 1.3 to 1.4 as he considered that to be the best value for unconsolidated quartz sand aquifers. The porewater resistivity (R_W) was determined from the Resistivity - Porosity cross plots (R.P.C.P.), a graphic solution developed by Hingle.

Finally he showed that although porewater resistivity (R_W) is not a direct measurement of water quality, the calculated value can be directly related to the concentration of most of the dominant ions present in ground water such as chloride, sulphate, potassium, sodium, magnesium, hardness ($CaCO_3$) and T.D.S.

Guo (1986)has derived an empirical relationship between aquifer resistivity and total dissolved solids (T.D.S.) in ground water of alluvial sand aquifers of North China plain. The mean aquifer resistivity (in ohm-m) determined by area compensation method, was taken as aquifer resistivity from a resistivity log curve in lateral array with electrode spacing of 2.5 m. The T.D.S. in aquifer water was determined through chemical analysis. Both the aquifer resistivity and T.D.S. in aquifer water were plotted against each other.

Since the curve obtained was like a hyperbola, he chose the formula

$$M = b/_{R}a$$

to fit the data points.

where M = aquifer water T.D.S. (g/l)

R = mean aquifer resistivity (ohm-m)

a, b = constants.

Using linear regression to analyse the data he found $a = 1.2$ and $b = 45.3$.

Substituting the values for 'a' and 'b' the formula was modified as

$$M = \frac{45.3}{R^{1.2}}$$

This is that equation, which was used to estimate sand aquifer water T.D.S.

Tanwar (1980) viewed that the electric log, including the S.P. and resistance curve is a very useful tool in the approximate estimation of quality of ground water in different aquifers penetrated by the bore hole and to evaluate the formation water changes from fresh to brackish or saline. It should also be noted that electric log cannot be obtained satisfactorily near big electric installation; it has serious limitations in continous granular formations devoid of clay beds and above all it is a costly method.

3.0 REMARKS

The importance of geophysical methods for evaluating groundwater pollution problems has been outlined and illustrated by some case-histories. Particular emphasis has been placed on the surface geoelectrical methods, mainly resistivity and S.P. methods.

The choice of a suitable and effective methodology depends on the electrical properties of the medium, which depend in turn on whether the problem deals with the saturated or unsaturated zone. Field measurement technique must be selected both with a view to choosing the most suitable method of measurement and the optimum number of parametric measurements.

S.P. method is particularly useful in detecting and monitoring leakages in liners of waste contaminant plants and movement of contaminated fluid beneath landfills, etc.

Resistivity method has been applied successfully in locating the horizontal as well as vertical extent of leachate, which moves in form of a 'plume', and in mapping position of saline and fresh water interface. However, reliability of this method depends on uniformity of the surrounding geologic environment, presence of sufficient resistivity contrast between contaminated and fresh aquifer, and a not too deep ground water table, otherwise overburden would mask the effect of contaminated aquifer.

Hydrogeochemical and well-logging methods prove to be expensive as drilling is involved either for sampling or for logging purposes. In comparison, the surface geophysical methods are fast, cost effective and when used with proper geological insight, may give highly reliable results. To obtain best results, however, an integrated approach will help to a great extent in detection and monitoring of groundwater pollution. Thus the surface geophysical methods can be used for reconnaisance surveys on regional scale, which are followed by hydrogeochemical and logging surveys, in areas pointed out by reconnaisance surveys, for detailed information.

REFERENCES

1. Archie, G.E., (1942), The electrical resistivity in determining some reservoir characteristics, American Institute of Mining and Metallurgical Engineering, Tech. Pub. 1422.

2. Argelo, S.M., (1967), Two computer programs for the calculation of standard graphs for resistivity prospecting, Geophy. Prosp., V.15, pp. 71-91.

3. Berk, W.J. & Yare, B.S., (1977), An integrated anpraoch to delineating contaminated groundwater, Ground Water Vol. 15, No.2, pp. 138-145.

4. Bond, L.D. & Breadchoeft, J.D., (1987), Origin of seawater intrusion in a coastal aquifer- a case study of the Pajaro Valley, Calofornia, Journal of Hydrology, Vol. 92, NO. 3/4, pp. 363-388.

5. Cart Wright, K. & Mc Comas, M.R.., (1968), Geophysical surveys in the vicinity of sanitary land fills in North Eastern Illinois, Ground Water, Vol. 6, No. 5, pp.23-30.

6. Charles, R.D. & Lee, G.W., (1975), Changed sub surface conditions extra costs and delays & litigation, In : CLEARWATERS; New York Water Pollution Control Association publication, New York.

7. Corwin, R.F., (1986), Electrical resistivity and S.P. monitoring for ground water contamination, Proceedings of the conference on "Surface and borehole geophysical methods and groundwater instrumentation, National Water Well Association, Denver, Colorado, pp 1-12.

8. Davis, P.A., (1979), Interpretation of resistivity sounding data : computer programs for solutions to the forward and inverse problems, Minn. Geol. Survey, Eustin Stn., St. Daul Minn., Info.Circ. 17.

9. Fink, W.B. & Aulenbach, D.B., (1974), Protracted recharge of treated sewage into sand, Part II - Tracing the flow of contaminated groundwater with a resistivity survey, Ground Water, Vol. 12, No. 4, pp. 219-233.

10. Food & Agricultural Orgination, (1979), Irrigation and Drainage paper on ground water pollution, F.A.O., UN , ROME, 137 pp.

11. Ghosh, D.P., (1971), The application of linear filter theory to direct interpretation of geoelectrical resistivity sounding measurements Geophy. Prosp., Vol. 19, No. 1, pp 192-217.

12. Gorhan, H.L., (1976), The determination of the saline/fresh water - interface by resistivity soundings, Bulletin of the Association of Engg. Geologists, Vol. XII, No. 3, pp. 163-175.

13. Goyal, V.C., Ramesh Chand & Seth, S.M., (1986), Geophysical investigations for hydrological studies, NIH Review Note R.N. - 31.

14. Greenhouse, J.P. & Harris, R.D., (1983). Migration of contaminants at a landfill- a case study, Journal of Hydrology, 63, pp. 177-197.

15. Guo, Y.A., (1986). Estimation of T.D.S. in sand aquifer water through resistivity log, Groundwater, Vol. 24, No. 5, pp. 598-600.

16. Hughes, L.J., Emer, D.F., Figgings, S.J. Zonge, K.L. Kuhn, H.W., Bentaly, H.W., and Tinlin, R.M., (1986). Applications of two electrical geophysical techniques in mapping groundwater contamination (personal communication).

17. Kakar, Y.P., and Bhatnagar, N.C., (1981), Ground Water pollution due to industrial effluents in Ludhiana, India. In: W.Van Duijvenbooden, P. Glasbergen, H.Van Lelyveld (Eds), Quality of Groundwater, Elselvier, Asmsterdam, pp. 265-272.

18. Kean, W.F. & Rogers, R.B., (1981), Monitoring leachate in Ground water by corrected resistivity methods. Bulletin of the Association of Engg. Geologists, Vol. XVIII, No. 1, pp. 101-107.

19. Kelly, W.E., (1976), Geoelectric Sounding for delineating groundwater contamination, Groundwater, Vol. 14, No. 1, pp. 6-10.

20. Kelly, W.E., (1985), Surface geoelectric for detecting and monitoring ground water pollution, 2nd Ann. Geotech. Seminar, Omaha, Nebraska, U.S.A.

21. Khouri, J. & Agha, W.R., (1979), Hydrogeological and hydrogeophysical study of salt water intrusion phenomenon in the central area of the Dawwa basin in the Syrian arid zones, The arab centre for the studies of arid zones & dry lands, Damascus ASCAD/H.S.p. 5.

22. Klefstad, G., Sendlein, L.V.A. and Paluquist, R.C. (1975), Limitations of the electrical resistivity method in landfill investigations, Ground Water, Vol. 13, No. 5, pp. 418-426.

23. Kooper, W.F., Van Duijvenbooden, W., and Peeters,A.A. (1981)., Internal report of the National Institute of Water Supply, The Netherlands, NO. :H_y H. 81-13: 11.

24. Kwader, T., (1986), The use of geophysical logs for determining formation water quality, Ground Water, Vol. 24, pp. 11-15.

25. L' vovich, M.I. , (1979), World water resources and their future, American Geophysical Union, Washington 415 pp.

26. Mazac, O., Kelly, W.E. & Linda, I., (1987), Surface geo-electrics for ground water pollution and protection studies, Journal of Hydrology, V. 93/94, pp. 279-294.

27. Orellana, E.and Mooney H.M. (1966), Master tables and curves for vertical electrical sounding over layered structures, Inters_iencia, Madrid.

28. Patra, H.P. & Bhattacharya, P.K., (1966), Geophysical exploration for groundwater around Digha in the coastal region of West Bengal, India, Geoexploration No. 6, pp. 209-214.

29. Patra, H.P., (1967), A note on possibility of saline water invasion around the Jaldha coast, West Bengal (India), Geoexploration 5, pp. 95-101.

30. Prasad, P.R., Pekdeger, A., and Ohse, W., (1983). Geochemical and geophysical studies of salt water intrusion in coastal regions in relation of ground water quantity and quality, Proceedings of the Hamburg sysmposium 1983, I.A.H.S. Publication No. 146, pp. 209-218.

31. Rogers, R.B.& Kean, W.F., (1980), Monitoring groundwater contamination at a fly ash disposal site using surface electrical resistivity method. Ground water, Vol. 18, No. 5, pp. 472-478.

32. Sinha, S.K. (1984), Geoelectrical and hydrogeochemical studies of a part of upper Hindon basin, Saharanpur District, U.P., M.Tech. Dissertation (unpublished), University of Roorkee.

33. Sri Niwas and Israil, M., (1986), computation of apparent resistivities, using an exponential approximation of Kernel functions, Geophysics, Vol. 51, pp.1594-1602.

34. Stollar, R.L. and Roux, P., (1975), Earth resistivity surveys A method for defining ground water contamination. Ground Water, Vol. 13, No. 2, pp. 145-150.

35. Swartz, J.H., (1937), Resistivity studies of some salt water boundaries in the Hawaiian Islands, Tran. American Geophysical Union, Vol. 10, pp. 387-393.

36. Sweeney, J.J., (1984), Comparison of electrical resistivity methods for investigation of ground water conditions at a landfill site, Ground Water Monitoring Review Journal, Winter 84, pp. 52-58.

37. Tanwar, B.S. (1980), Electric logging techniques applied to ground water exploration and water wells, Journal of Irrigation and power, pp. 33-40.

38. Todd, D.K. & Mc' Nulty, D.K. (1984), Polluted ground water: A review of the significant literature, U.S.E. P.A. report, Newyork pp. 179.

39. UNESCO, (1980)., Aquifer contamination and protection, project 8.3 I.H.P., R.E. Jackson (Gen Ed), 440 pp.

40. Urish, D.M., (1983)., The practical application of surface electrical resistivity to detection of ground water pollution, Ground Water, Vol. 21, No. 2, pp. 144 - 152.

41. Van Duijvenbooden, W.P. Glasbergen, and H. Lelyveld (Eds). Quality of Ground Water, Elselvier, Amsterdam pp. 1128.

42. Van Zijl, J.S.V., (1977), A practical manual on the resistivity method, C.S.I.R. Report FIS 142, C.S.I.R. pretoria, S. Africa, 132 pp.

43. Waid, C.H., Giger, W., and Mc. Arthy, P.L. (Eds), (1985), Ground Water Quality, John Wiley inter science, New York, 547 p.p.

44. Warner D.L., (1969), Preliminary field studies using earth resistivity measurements for delineating zones of contaminated ground water, Ground Water, Vol. 7, No. 1, pp. 9-16.

45. Winsauer, W.O., Shearin, H.M., Mansoon, P.H. and Williams, M., (1952), Resistivity of brine saturated sands in relation to pore geometry, Bull, American Association of Petroteum Geologists, Vol.36, No. 2, pp. 253-277.

46. Zohdy, A.A.R. Eaten, G.P. and Mabey, D.R., (1980). Application of surface geophysics to ground water

investigations.Chapter D1 in Techniques of Water Resources investigation of the U.S.G.S. Book 2, U.S.D.I., 116. pp.

47. Zonge, K.L., Figgins, S.J., Hughes, L.J. and Emer, D, (1985). The use of electrical geophysics to detect sources of ground water contamination, Expanded abstracts & biographies, 55th Annual international SEG meetings and exposition, pp. 147 - 149.