1889

GEOPHYSICAL APPROACH FOR THE STUDY OF GROUNDWATER POLLUTION IN A PART OF DELHI.

DISSERTATION SUBMITTED TO THE JAWAHARLAL NEHRU UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE OF

MASTER OF PHILOSOPHY

VIJAY SINGH

JNU

SCHOOL OF ENVIRONMENTAL SCIENCES
JAWAHARLAL NEHRU UNIVERSITY
NEW DELHI- 110067
INDIA
JULY-2001

जवाहरलाल नेहरू विश्वविद्यालय
JAWAHARLAL NEHRU UNIVERSITY
SCHOOL OF ENVIRONMENTAL SCIENCES
NEW DELHI-110067

CERTIFICATE

The research work embodied in this dissertation entitled **"Geophysical Approach for The Study of Groundwater Pollution in a Part of Delhi"** has been carried out at the school of Environmental Sciences, Jawaharlal Nehru University, New Delhi. This work is original and has not been submitted in part or full for any other degree or diploma in any other university/institution.

VIJAY SINGH
(CANDIDATE)

PROF. D.K. BANERJEE
(DEAN)

DR. S. MUKHERJEE
(SUPERVISOR)

Gram : JAYENU **Tel. :** 6107676, 6167557 /Ext. 2302, 03, 04 **Telex :** 031-73167 JNU IN
Fax : 91-011-6165886 and 91-011-6172438

ACKNOWLEDGEMENT

I express profound gratefulness to my supervisor Dr. S. Mukherjee whose amiable guidance during all phases of the present work enabled me to complete the work successfully.

I am also grateful to Dr. D.K. Banerjee, Dean, School of Environmental Sciences for providing me all the necessary facilities in carrying out the present work.

I am especially indebted to my senior Anup Kumar Das who has helped me in each and every phases of the work with admirable patience. His presence has always been a constant source of inspiration for me.

I pay special thanks to my friends Ujjwal and Jayanand who in spite of their busy schedule accompanied me in all phases of the work.

I owe my thanks to all my Labmates especially Dr. Abdul Azzem, Pramod, Venkat, and Abhimanyu.

I am also thankful to my friends Rajiv Lochan, Swarna, Bala, Jagdish, Bharat and Anju for their cooperation and moral support.

I wish to thank all my batchmates M. Sridhar Reddy, Vijaya, Aditi, Anupma, Sweta, Sarmila, Abhijit, Vinod.

The role played by Mr. Dayaram Yadav in keeping my spirit up throughout the study is gratefully acknowledged.

Junior research fellowship provided by CSIR is duly acknowledged.

LIST OF TABLES

LIST OF FIGURES

CONTENTS

Chapter I INTRODUCTION

Water is the basic necessity of all life and an absolute requirement for domestic, agricultural and industrial activities for which no substitute exists. Groundwater resources are the major source of water for the population, industries, agriculture and irrigation. Hence groundwater quality is becoming an increasingly important issue in many parts of the world. During the last few decades industrial and agricultural development have adversely affected in many parts of our country due to water shortages. Significant increase in drinking water consumption is a distinct feature at present, at the same time groundwater reserves are reduced qualitatively by the pollution of ground water due to increasing anthropogenic activities and improper landuse/ landcover practices.

1.1 GROUND WATER

Ground water is the water found in spaces between soil particles and rocks, and within cracks of the bedrock. Because of its availability and general good quality, ground water is widely used for household needs and other purposes. Groundwater is more desirable than surface water for at least six following reasons:-

1. It is commonly free of pathogenic organisms and need no elaborate purification for Domestic and industrial Uses.
2. Temperature is nearly constant which is a great ad-vantage if the water is used for heat exchange.
3. Turbidity and color are generally negligible.
4. Chemical composition is generally constant.

5. Ground water storage is always greater than surface water storage, so that ground Water supplies are not seriously affected by short duration droughts.
6. Biological contamination in ground water is seldom noticed.

Ground water is often taken for granted, but recent circumstances indicate that it is seriously vulnerable to pollution and depletion. In many locations, pollution poses the greater threat. Contaminants, which threaten people's health, have been found in several important ground water reservoirs. Some of the contaminants may be so expensive to remove that they make the water virtually non-potable for years. Because of this threat, it is important to understand the processes that make ground water available for use and how human activities sometimes threaten this resource.

1.2 GROUND WATER IN THE WATER CYCLE

Ground water is an integral part of the water cycle. The cycle starts with precipitation falling on the land surface. Runoff from precipitation goes directly into lakes and streams. Some of the water, which seeps into the ground is used by plants for transpiration or evaporated from the soil surface. The remaining water, called recharge water, drains down through the soil to the saturated zone, where water fills the interstitial spaces between soil particles and rocks. The top of the saturated zone is the water table, which is usually the level where water stands in a well. Water continues to move within the saturated zone from areas where the water table is higher toward the lower water table areas. When ground water comes to a lake, stream, or ocean, it discharges from the ground and becomes surface water. This water then evaporates into the atmosphere, condenses, and becomes precipitation, thus completing the water cycle.

1.3 THE OCCURENCE OF GROUND WATER

Water can be found beneath the ground almost everywhere. About 97 percent of the world's fresh water is ground water. The quality and amount of ground water, which is available, varies from place to place. Major reservoirs of ground water are referred to as aquifers. Aquifers occur in two types of geologic formations. Consolidated formations are those composed of solid rock with ground water found in the cracks. The amount of ground water in a consolidated formation depends on how many cracks are there and the size of the cracks. For example, consolidated limestone formations often contain caverns with much water in them.

Unconsolidated formations are composed of sand and gravel, cobblestones, loose earth or soil material. The amount of ground water in an unconsolidated formation varies depending on how closely packed the solid materials are and how fine-grained they are. Sand and gravel, and cobblestone formations are generally high-yield aquifers, whereas, finer-grained earth materials may have low yields. Ground water may come to the surface naturally as a spring or be drawn to the surface from a well. A spring occurs where the water table meets the land surface.

1.4 GROUND WATER AND SURFACE WATER

People are more familiar with surface water than ground water. Surface water bodies can be seen around in the form of ponds, lakes, streams and ocean but ground water bodies like are quite uncommon. Some important differences between ground water and surface water bodies are noteworthy. Ground water usually moves much slower than surface water. Water in a stream may move several feet's per minute, but water in an aquifer may move only few feet per month. This is because ground water must overcome more friction or resistance, to move through small spaces between rocks and soil underground. There are exceptions to this rule. An example is underground streams in limestone caverns where the water may move relatively rapidly.

The exchange of water between surface water bodies and aquifers is important. Rivers usually start as small streams and get larger as they flow downstream. The water they gain is often ground water. Such a stream is called a gaining stream. It is also possible for streams to lose water to the ground at some points. In these cases, aquifers are replenished or recharged by water from the losing stream. A stream that flows near the surface of an aquifer will lose water to the aquifer if the water surface in the stream is higher than the water table of the aquifer. A stream will gain water if the water surface of the stream is lower than the water table in the adjacent area.

1.5 POLLUTION AND DEPLETION THREAT OF GROUND WATER

Ground water becomes polluted when undesirable substances become dissolved in water at the land surface and are carried down or leached, to the aquifer with the percolating water. To determine whether a particular substance will pollute a particular aquifer, the properties of the unwanted substance and the soil above the aquifer need to be considered along with the amount of the substance available for leaching.

Sometimes ground water contamination occurs naturally, but serious contamination is usually the result of human activities on the land surface. An aquifer providing a plentiful water supply often attracts a multitude of people to the overlying land. The water is used for such activities as drinking, personal hygiene, residential maintenance, and industrial and agricultural purposes. Many of these activities involve the use and disposal of chemicals which are potential pollutants. When these chemicals are used or disposed of incorrectly, unacceptable amounts of these chemicals may get into the ground water and contaminate it. Several valuable aquifers have been polluted by the people living and working above them. Since ground water moves slowly, many years may pass before a pollutant released on the land surface above the aquifer is detected in water taken from the aquifer some distance away. Unfortunately, this means that contamination is often widespread before being detected. Even if release of the contaminant is stopped, it may take several years for an aquifer to purify itself naturally. Although water can be treated to remove contaminant but, this can be very costly. The best protection against ground water pollution is prevention. Ground water becomes depleted in an area where more water is being drawn out of an aquifer and consumptively used than is entering or recharging the aquifer. This usually causes a lowering of the water table, making the ground water more difficult and expensive to obtain. (In general, this is a major problem in the dry western part of the United States. In the eastern United States, precipitation continuously replenishes ground water supplies, and so depletion is most likely to be a problem in certain localized situations, or during droughts). A situation may involve someone pumping a large amount of water from a small aquifer and causing a neighbor's well to go dry (lowering the water table below the well screen). Rapidly expanding urban areas often impose an extra burden on ground water supplies in the form of both depletion and pollution. In coastal areas, chronic over pumping can cause salt water intrusion. Salt water intrusion takes place in coastal areas where fresh water removal from the aquifer permits saline water from the ocean to intrude into the aquifer.

1.6 CAUSES OF GROUND WATER POLLUTION

Most human activities at the land surface cause some change in the quality of water in the aquifer beneath them. The importance of the effect of a particular activity is related to the amount and types of contaminants released. The severities of an occurrence is also related to the ability of the soil and ground water system to purity or dilute the contaminants, and the degree to which the contamination will interfere with uses of the water. Contamination is usually more serious in a drinking water supply than in water for other uses. Except where contaminated water is injected directly into an aquifer, essentially all ground water pollutants enter the aquifer through recharge water from the land surface. A change in pH and temperature may also lead to the leaching of harmful ions from in situ rocks of the aquifer.

Examples of contaminants are: synthetic organic chemicals, such as, pesticides and certain petroleum products, certain heavy metals, such as mercury, nickel, cadmium, arsenic, chromium, lead, nitrate and petroleum residues and combustion products from automobiles along roadways. These are considered harmful if ingested in sufficiently high amounts with drinking water, and in some instances may be carried into surface water bodies by ground water. Each human activity has a particular impact on ground water. Some agricultural activities add nitrate, nitrogen, and pesticides to ground water. Residential areas add nitrate, nitrogen, and pesticides from landscaping activities. Those with septic systems usually add nitrate, nitrogen, bacteria, viruses, and synthetic organics used in household cleaning products and septic tank cleaners to the ground water. Industrial activities tend to add organic chemicals and metals, though in widely varying amounts. Gasoline storage areas (including service stations) may have leaks and spills of petroleum products. Roadways contribute petroleum pollutants leaked from vehicles and metals from exhaust fumes. The most concentrated impact comes from older sanitary landfills, whose leachate may contain many different chemicals at relatively high concentrations.

Protecting our ground water from contamination will require thoughtful management and cooperation on the part of citizens and the various levels of government. In many cases, land use planning is the best instrument available for protecting aquifers still containing good quality water. If potential contamination sources are prevented from locating over critical recharge areas, the risk of contamination can be greatly reduced. Careful use and proper disposal of the chemicals causing contamination is also necessary. Industries, lands, and residential complexes located above ground water zones overlaid with permeable soil or rock strata need to practice good management with respect to the use and disposal of chemicals. Suitable regulations, which govern the use and disposal of hazardous wastes, need to be enforced. An equally important step is to make people aware of their potential impact on ground water. Action is needed now to protect the valuable ground water resources in many parts of our country.

1.7 ROLE OF REMOTE SENSING IN GROUND WATER STUDIES

Space technology in the form of remote sensing can play a useful role in hydrological studies. Remote sensing is defined as the science of deriving information from measurements made at a distance from the object without the sensor actually coming in contact with it.(Sabiens, 1997). Remote sensing though is a fledging phenomenon, seem to a shot in the arm by either substituting or complementing or supplementing the conventional technology with reasonably faster, efficient and accurate methods of survey in the domain of water resources planning, conservation, development, management and utilization.

Remote sensing buy virtue of its synoptic coverage, spectral behavior, repeatability, and availability, offers an effective first hand tool in mapping and monitoring resources in a reasonably short time frame (Dury, 1986). Synoptic view facilitates the study of objects and their relationships. Spectral signatures permit identification of various features, while the temporal aspect allows change detection in environment. The real advantage is the real time measurement that facilitates constant and effective monitoring. The main advantage of the remote sensing is that the data is in digital form and can be analyzed easily with the help of computers. The wavelengths widely used in the remote sensing are visible and near infrared in the wavelength of 0.4 to 3 μm.

The application areas for remote sensing data are both wide and varied (Slogget and MaGeachy, 1986). Radiometric data potentially represent a very useful source of information in pedological research and in the study of water quality (Leone et al., 1995). Though remote sensing technique cannot be used directly for groundwater studies. But the remote sensing data allows us to make indirect references regarding subsurface through surficial expression of the aquifer. the subsurface hydrological conditions are inferred based on identification and correlation of surface phenomenon involving geological features and structures, geomorphology, surface hydrology, soils and soil moisture anomalies, vegetative types and distribution, land use, and many others as indicators. the benefits that accrue in the use of remotely sensed data are usually greatest when they are applied for large scale preliminary investigations of groundwater reserves.

Although remote sensing technique can never replace conventional hydrologic observation networks, remote sensing data have two distinct advantages. Remote sensing platforms provide data with high resolution in space and data can be obtained for areas that have no record of measurements (e.g. in remote areas). Therefore remote sensing data, particularly satellite data can be most helpful for design and operation purposes, if they are used in combination with groundtruth. The disadvantages of satellite data are unfavorable combinations of resolution in time and space (Cracknell and Nirala, 1997). Air-borne geophysical exploration is highly used in groundwater prospects (Patterson and Bosschart, 1987). Conventional prospecting tools viz., hydrogeological and geophysical generally do not yield the relevant details and occasionally exhibit lack of resolution. Integration of satellite data and vertical electrical sounding (VES) data is therefore used to access the groundwater potentiality of various geomorphic units (Chandu, 1997).

In the present work, more thrust has been given on the detection of groundwater salinity and to correlate the data from the remote sensing and the geophysical studies. The area is studied and IRS 1c LISS III data along with the SPOT and LISS II was used for identification of saline aquifers. The subsurface salinity is detected studying the presence of white patches as efflorescence on surface (Mukherjee, 1989). A study of clay lenses and their relationship and their relationship with arenaceous facies (sandy layers) are attempted to identify the probable origin of groundwater salinity. Further the palaeo-interfluves are identified by satellite data (Mukherjee, 1996), which have bearing on the spatial deposition of clay lenses. Further the clay thickness, presence of arenaceous facies and groundwater salinity are detected through the vertical electrical sounding (VES) methods (Mukherjee and Sarin, 1990).

Chapter II LITERATURE REVIEW

Geophysical exploration is the scientific measurement of physical properties of the earth crust for investigation of mineral deposits or geological structures (Griffith, D. H. & R. F. King; 1965). With the discovery of oil by geophysical methods in 1926, economic pressure for locating petroleum and mineral deposits stimulated by development and improvement of many geophysical methods and equipment. Application of geophysical techniques for groundwater investigations was slow because the commercial value of oil overshadowed that of water. However, in recent years refinement of geophysical techniques as well as an increasing recognition of the advantages of the methods used for ground water studies has change the situation. Now a day, many organizations are using geophysical methods in groundwater investigations. The methods are however most useful when supplemented with subsurface investigations. Over the years many methods have been proposed and employed to find groundwater. Most of these methods are indirect, i. e. they examine surface features, such as vegetation, drainage patterns, lineaments etc. to find evidence of the presence of the subsurface water and its quality. The measurements provide an inexpensive alternative to drilling away wells, but have the disadvantage that interpretations methods are frequently non-unique. Various methods used are mainly,

- Electrical mapping and sounding
- Self-potential methods
- Seismic reflection and refraction.
- Gravity and geomagnetic methods

- Well –logging measurements (Gamma ray, radioactive log, Thermal log, Electrical resistivity log)

However, groundwater investigations are based on only one physical property of water i.e. its electrical conductivity. Almost all geological materials are inherently conductive and virtually all subsurface conductivity is related to the presence of water. Exceptions are metallic minerals and graphite formations but these present anomalies, can be easily identified. Clay content enhances the conductivity of a formation but dry clay is inherently resistive (Patterson, N. R. & Bosschart, R. A.; 1987).

Geophysical techniques are increasingly being recognized to study the contaminants in shallow aquifers and to infer subsurface hydrologic connections in geologically complex areas (Cartwright and Mccomas 1968; Warner 1969; Merkel 1972; Stollar and Roux 1975; Kelly 1976; Macaz and others 1987; Ebraheem and others 1990), but alternative techniques exist, including groundwater penetration radar and various other electromagnetic methods.

A major problem in measuring the quality of groundwater using geoelectric methods is the relationship between the bunk conductivity of rocks and conductivity of the fluids within the rocks. Most minerals are insulators, so electrical current must flow through voids field with electrolytic solutions. Archie (1942) proposed an imperical power law relating bulk conductivity, solution conductivity and porosity for clean sandstone. The relationship is

$$\sigma_{rock} = \sigma_S \varphi^m \qquad (1)$$

Where,

σ_{rock} is bulk electrical conductivity,

σ_S is solution conductivity,

φ is porosity and 'm' is exponent.

The value of 'm' is close to 2 (Toulokian and Ho 1981). When the rock contains clay, equation is no longer valid. Clay adds component of conduction by cation displacement along their surfaces and because they have large surface areas, this component can be large (Ward 1967).

Vinegar and Waxman (1984) proposed a conduction model for sandstones that included effects of electrolytes and clays. Park and Dickey (1989) applied Vinegar and Waxman model to obtain more accurate estimates of solution conductivity by correcting for the contribution from clay. They tied the data from the wells with the geophysical measurements. The results were impressive if the assumptions inherent in the model are considered. They have assumed that the porosity, formation factor, and cation exchange capacity are uniform throughout an alluvial unit. In other words the amount of clay, the distribution of grain size and the arrangement of grains don't vary within the alluvial. But, these are clearly dangerous assumptions because alluvial units are generally not homogenous. In the absence of the data on the variability of porosity, formation factors and cation exchange capacity, the uniformity within the alluvial was assumed. There are many geophysical methods,(Fig: 2.1) which can be applied in the hydrogeological exploration to define-

1. Water bearing reservoir geometry; determination of aquifer boundary may be limited to define only overburden / aquifer or aquifer / substratum boundary, but these can be useful to a hydrogeologist (fig. 2.2).
2. Analysis of aquifer pollution containing mineral and organic deposits that influences water resistivity (kauranne and lahermo 1989). The constituents can be generated either artificially (discharge into rivers or aquifers) or naturally (saline intrusion along seaside).
3. Correlation of the data to aquifer hydrodynamic parameter performs correlative tests between physical parameters by geophysical methods and aquifer hydrodynamic characteristics.

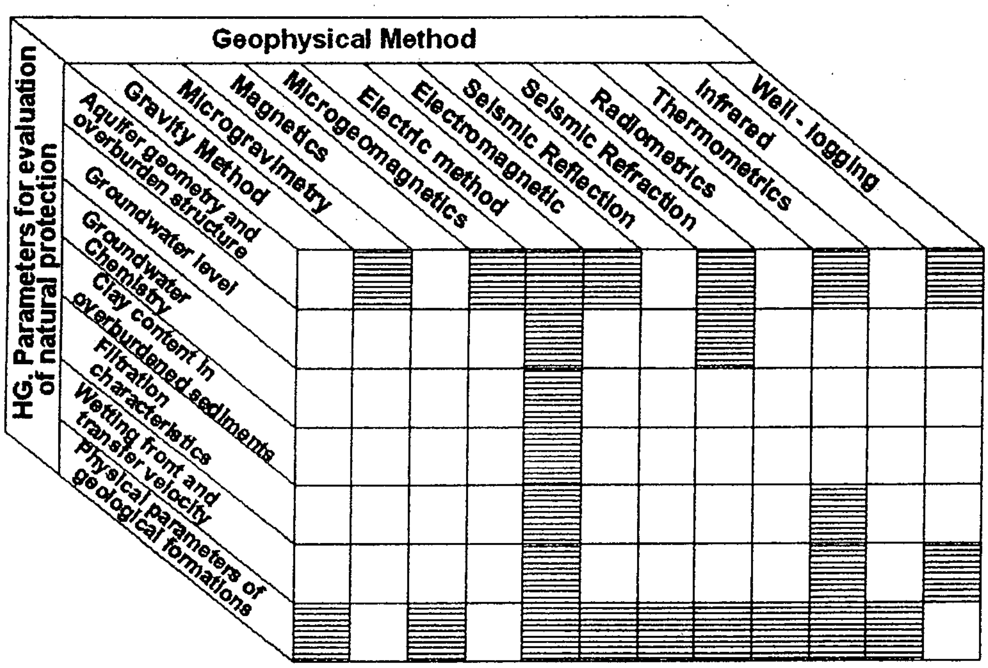


Fig.: 2.1 Diagram showing Geophysical methods application in hydrogeological studies (after Komatina 1994).

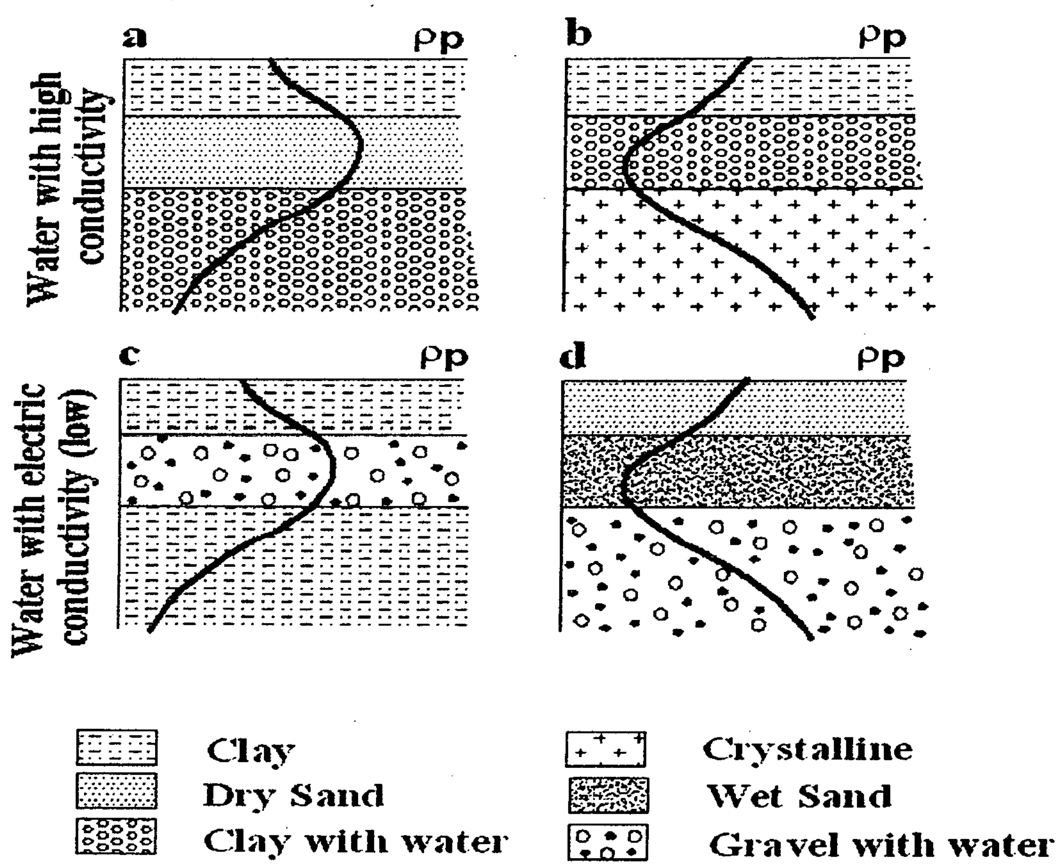


Fig.: 2.2 Diagram showing characteristic geological profiles with appropriate electric soundings (after Komatina 1990).

Geophysical data is used to obtain the following physical parameters of geologic formations:

- Density (gravity method)
- Elastic wave propagation velocity (seismic reflection and refraction).
- Magnetic susceptibility (magnetics)
- Resistivity (electrical and electromagnetic method)
- Radiation (radio metrics).
- Temperature (measurement of the temperature gradient, infrared method).

The attention of hydrogeologists and subsequently that of Geophysicists has turned to the problems involving detection of groundwater pollution and protection of Aquifer from pollution. Pollution investigations can involve: -

1. Determining hydrogeological, lithologial and structural characteristics at a site.
2. Assessment of relations and connections between the land surface and groundwater.
3. Detection of the presence of pollutants in vadose and groundwater zones.
4. Estimation of pollution concentrations and patterns of movement.

Besides surface geophysical methods, of which geoelectrical and seismic methods are the most frequently used, logging methods are also useful. The usefulness of geophysical measurements and their relative reliability and low cost, has led to research (Mazac and Landa, 1978a; Kelly et al., 1983; Skuthan et al., 1986) to define their effectiveness and hydrogeological information content in relation to potential or existing groundwater pollution.

Alluvial aquifers deserves special attention in the hydrological studies because:

1. Alluvial aquifer contains a very large restorable low mineralized groundwater.
2. Water utilization from river valley sandy gravel horizons is very great.
3. Alluvial aquifers are endangered by many sources of surface pollution (associated with the use of agriculture production – pesticides and fertilizers) (Neiri et. al. 1992, Kashkovsky et., al. 1989), (fig 2.3).

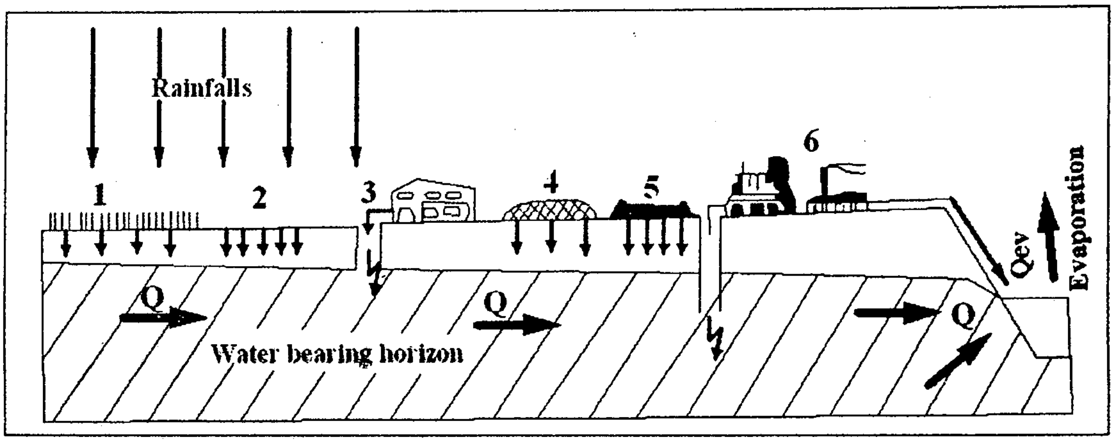


Fig.: 2.3 Groundwater pollution sources provoked by agricultural activities (Kashkovsky and others, 1989). Fertilizers and pesticides: 1-during irrigation, 2- during non-planted field fertilizing; wastewaters: 3- communal, 4- solid, 5- liquid, 6- industrial.

The cities are the worst affected due to the shortage of groundwater because of increasing population. The cities having the shallow water table are in fact worst hit because the shallow groundwater quality in cities is almost always poor for two reasons (Klimas, 1995).

1. Water table aquifers are vulnerable to pollution.
2. A city is a source of concentrated pollution of various origins.

Moreover the shallow groundwater gets polluted very easily because the pollutant reaches the groundwater in less time. Pollution from water table aquifers often spread to deeper water aquifers, if they are not protected from pollution (Klimas 1994). Thus there is growing need of protection of the ground water.

Factors influencing groundwater protection can be natural, anthropogenic or physiochemical (Shestakova and Orlopa 1984). Natural factors like the presence of non-

1. depth, lithology and permissivity of rocks covering groundwater.
2. depth to underground reservoir and groundwater level position.
3. absorption characteristics of rocks.

A comparative evaluation of pollution potential was made by Kotamina, (1993), by assigning points to natural factors, depth to groundwater level, low permeable layer thickness and lithology. On the basis of total points, it was determined to which of the six categories for groundwater pollution and alluvial sector belongs. The map based on the point contours becomes more accurate with additional knowledge of rocks and their hydrologic character in the zone of aeration. Regional geophysical exploration can provide regional measures for water resource utilization, protection planning and production, space plan production, identifying safe zones for hazardous waste placement and distinguishing zones where groundwater are not protected and for which prophylectic protective measures have to be planned (Barrons et.al.1988). Detail geophysical investigations on overburden sediments are significant in connection with drawing up plans for industrial, agricultural and other objectives. (Cox and Saundres, 1991).

2.1 PRINCIPLES OF GEOPHYSICAL SURVEYS FOR POLLUTION:

The principles of the different geophysical methods and site conditions must be taken into account in choosing a geophysical method for pollution surveys (Swoma 1978 Mares et al., 1983). (table: 2.1)

Table: 2.1 The use of Geophysical methods in Surveying the pollution of groundwater (Mares et al.,1983)

Purpose	Gravimetry	Magnetometry	Radiometry Enamometry	Geothermic	Atmogeochemistry Geometry	Resistivity methods	Electromagnetic methods	Conductometry	Spontaneous polarization	Induced polarization	Seismic methods	Gaoacoustics	Logging (drilling variants)	Remote sensing (airborne methods)
Determination of protective groundwater zones, construction of prognostic pollution maps.	B	B	B	A	A	A	A	A	A	B	A	-	A	B
Oil pollution	-	-	-	-	A	A	B	-	-	-	-	B	A	B
Agricultural pollution	-	-	-	B	B	A	A	A	B	B	A	-	A	B
Heat pollution	-	-	-	A	-	B	-	-	-	-	B	-	A	-
Chemical pollution	-	-	B	-	A	A	A	A	-	-	B	-	A	B
Pollution by infectious Germs	-	-	-	-	-	B	B	-	-	-	-	-	A	-
Radioactive pollution	-	-	A	-	-	B	B	B	-	-	B	-	A	-
Pollution prevention	B	B	B	-	-	A	A	B	A	A	A	-	A	B
Applicability Frequency	2	2	4	3	4	8	7	5	3	3	6	1	8	5

A= Geophysical methods used more frequently;

B= Geophysical methods used less frequently.

2.1.1 Types of pollution

The types of pollution, are industrial (i.e., petroleum products, toxic compounds, acids and dyes, solvents, and radioactive wastes), agricultural (fertilizers, pesticides, silage juices, and faeces), and thermal. The effect of pollutant on the electrical properties of water in the vadose zone or the zone of ground water flow is an important thing to be taken care of in groundwater studies.

2.1.2 Type of investigation

The choice of suitable geophysical method or set of methods depend on the type of investigation, here distinguishing between the surveys to detect pollution and those to develop protection zones for well fields must be made.

In surveys in support of groundwater protection planning, geophysical methods are used in defining hydro geological conditions similar to the manner in which they are used in aquifer development studies. The final result of such a survey will give protective zones for well fields.

Detection of pollution can be done as a part of a protection strategy or more commonly to investigate the extent of pollution at existing sources. Use of geophysical studies in developing a protection strategy is a relatively new concept. For facilities such as a landfill known to be contaminating groundwater, the purpose of the geophysical survey is to determine the extent of the pollution and, if required, to assist in mapping the pollution (Mazac et al., 1978). The choice of the geophysical methods and the methodology for the geophysical survey will depend on the protection aspect to be evaluated. Besides pollution protection, it may also be necessary to preserve or conserve the quantity of the resource.

2.1.3 Type of permeability

An important factor in interpreting Geophysical measurements is the type of permeability prevalent in the environment being investigated. This is especially important in connection with the choice of suitable interpretation model. In most cases, unconsolidated aquifer materials are represented as homogenous and isotropic layers for which relations can be expressed in simple mathematical terms. In contrast, fissured, fissured-karst, or mixed permeability media are characterized by heterogeneity making it difficult to choose suitable interpretive models and complicating determination of relations between hydro geological and geophysical parameters.

2.1.4 Degree of saturation

Relations between the geophysical and hydro geological parameters in the aeration or vadose zone are substantially more complicated and more difficult to define mathematically than for the saturated zone. However, detection and mapping of pollution in the vadose zone can be important detecting pollutants before they reach the groundwater.

2.1.5 Information content

In pollution studies, geoelectrics can be used to collect two distinct types of information. The first type is information on the subsurface conditions and the characteristics of subsurface materials. Such information can provide indirect evidence of the presence and movement of pollutants. Second are direct measurements to delineate the extent and levels of pollution for a plume. (Frohlich. R. K., and Parke., D, 1989).

In pollution detection surveys, the survey site is determined by the location of the pollution source, and perturbing sources (viz., underground and aboveground electrical conductors, piping, built-up areas, etc.) that may be present. Thus geophysical measurements can be difficult and sometimes they appear to be impossible at those locations where data are needed the most. Time can be important in designing a survey since clean up operations (Swoma, 1978) cannot be designed until the extent and degree of pollution are determined. Generally site assessment surveys can be done faster if geophysical methods are combined with drilling rather than relying on drilling alone.

2.1.6 Stageability

An important feature of geophysical surveys for, assessing and evaluating pollution is their stageability. In the first stage of an investigation, the geophysical data (A_0) expressing the integral properties of a site are obtained. This data is readily transformed to the so called apparent geophysical parameters (A_a). In the second stage, the data (A_a) are reduced to the true geophysical parameters representing the hydro geological units (A_t) this stage is the geophysical interpretation. Finally, the parameters (A_t), and in rare cases also the apparent resistivity (A_a), are related to the hydro geological parameters (e.g., thickness, hydraulic conductivity, porosity, material, etc) (A_h). This stage is the final stage that provides the quantitative evaluation of the hydro geological system "rock-ground-water-pollutant-air".

2.2 ELECTRICAL PROPERTIES OF SOIL

It is important to distinguish between the electrical properties of soils from the theoretical and practical point of view. This stems from the concept that the soil or rock medium being studied consists of four phases: solid (R), groundwater (W), pollutant (P) and the air (A). In the first approach, which has been widely developed in the literature, one analyzes the electrical properties of the separate phases of the medium under various conditions; e.g., the known dependence of the resistivity of groundwater on mineralization, temperature, etc. (Dakhnov, 1953), or the dependence of the resistivities of various pollutants on their concentration (Chudacek et al., 1982).

In the second approach, which is important in practice, one analyzes the electrical properties of the complete four-phase medium (system). For example, the dependence of the resistivity of a porous aquifer on the matrix resistivity and porosity (Mazac et al., 1985). Interpretations to determine the properties of the complete system (R-W-P-A) are impeded by the difficulties in describing an adequate mathematical model. In contrast, interpretations designed to determine the properties of the simpler subsystems are routinely applied in hydro geophysical surveys. In these cases, correlations obtained for a particular locality and a particular subsystem are constructed using parametric measurements. For example:

(a) in land improvement hydrogeology the subsystem is R-W-A;

(b) in petroleum hydrogeology the subsystem is R-P (oil), or R-P-A(gas);

(c) in contaminant hydrogeology the subsystems are R-W, R-W-P, R-W-A, or R-W-P-A;

(d) in water management hydrogeology the subsystem is R-W;

(e) in mineral water and mining hydrogeology the subsystems are R-W-A(mostly CO_2), or R-W.

To characterize the electrical properties of soils for contaminant hydrogeolgy, it is necessary to know, in addition to the electrical properties of the separate phases existing in the particular subsystem or system, the nature of the permeability (porous, fissured, karst, or mixed) which depend on the rock type, the degree of saturation and possibly other factors (e.g. the degree of cementation, texture, etc).

In the simplest case where the pollutant is electrolytic and miscible with water, the system can be treated as a simple two-phase subsystem R-W. In the R-W phase, the effect of pollutant is reflected in the changes in groundwater resistivity. Relations between the electrical properties of the subsystem as a whole and the electrical properties of the two phases depending on soil hydro geophysical properties, primarily porosity and matrix resistivity, are typically developed for unconsolidated aquifers, and are site specific and can not be generalized.

For example, Kosinski and Kelly (1981) gave a relationship between formation factor *F. F* and soil type based on the results of a number of vertical electrical soundings (VES) made adjacent to wells where pumping tests had previously been conducted. The formation factor *F.F* is defined as:

$$F.F = \rho_0 / \rho_w \qquad (2)$$

Where,

ρ_0 is the resistivity of the saturated subsystem R-W (i.e. of the after bearing aquifer) and

ρ_w is the water resistivity.

Formation factor can in turn be related to soil porosity using Archie's law:

$$\mathbf{F.F} = a\mathbf{P}^{-m} \qquad (3)$$

Where,

'm' is the coefficient of cementation, which is somewhat larger than 2 for cemented and well sorted granular rocks and somewhat less than 2 for poorly sorted and poorly cemented granular rocks.

The coefficient '*a*' varies from slightly less than 1 for rocks with intergranular porosity to slightly more than 1 for rocks with joint porosity (Keller and Frischknecht, 1966).

If the soil contains clay, a relation between resistivity ρ_0, effective porosity P, water resistivity ρ_w and matrix resistivity ρ_s, valid for arenaceous water bearing aquifers (Mares et al., 1976) with $a = 1$ and $\rho_w = 10\Omega m$:

$$\rho_0 = a\rho_s\rho_w\, 10^4 \;/\; a\rho_w\, 10^4 + \rho_w\rho^m \qquad (4)$$

Relations (2)-(4) are commonly used and, provided the constants a and m and the levels of pollution are known, reasonable estimates of pollution levels can be made for the range of soil resistivities found in arenaceous aquifers. Again, such relations hold for a particular locality of the same type, or to localities with other types of permeability.

A summary of the basic relations between electrical and hydro geological parameters, which are used for pollution surveys, is given in table: 2.2

Table: 2.2 Relations between geoelectrical and some hydrological parameters.(Mazzac, O., Kelly, W. E. and Landa, I., (1987))

Hydro geological parameters	Geoelectrical parameters	Permeability (medium, locality)	Relation	Author
Mineralization "M"	As a function of $\rho_w \rho_s$, $\rho_0[\Omega m]$	Porous (Saturated aquifer)	$\rho_w=\rho_s P^2 \rho_0/10^4(\rho_s-\rho_0)$	Worthington (1976)
Effective porosity "P"	$\rho_w \rho_s$ $\rho_0[\Omega m]$	Porous (Saturated aquifer)	P= [ρw(ρs–ρ0)1/2x 100] / (ρ_s ρ_0)	
Hydraulic conductivity "K_f"	$\rho_0[\Omega m]$	Porous (Saturated aquifer)	$K_f = c\rho^d_0$	Mazac and Landa(1979)
Hydraulic conductivity "K_f"	A*,ρ_0 = 2-6[Ωm] A*,ρ_0 = 20-30[Ωm] A*,ρ_0 = 20-60[Ωm]	Porous (Saturated aquifer)	ln K_f =5.98–2.3 ln A* ln K_f=2.99–2.3 ln A*	Sharapanov (1974)
Content of clay "J"	A*,ρ_0 = 5-10[Ωm] A*,ρ_0 = 30-40[Ωm] ρ_0, ρ_w	(Sediments aeration zone) Porous and fissured (saturated aquifer)	ln J =1.22+0.97 ln A* ln J =3.0+0.94 ln A* $\rho_0/\rho_w= F.F = a\,P^{-m}$	Keller and frischknecht (1966)
Porosity "P"	ρ_0, ρ_w ρ_0, ρ_w	Porous and fissured (saturated aquifer) Fissured	$\rho_0/\rho_w= F.F = a\,P^{-m}\,S^{-l}$ ρ_0/ρ_w = (1-P) ρ_s + Pρ_w	Kelly(1985) Topfer(1972) Parkhomenko(1965)

Coefficients a, c, d and m depend on the type of aquifer and on the physical properties of the hydro geological structures,

$$A^* = f(\rho_0, \eta)$$

Where,

η is the polarizability;

F.F. is the formation factor; and

S is the degree of saturation,

l is a constant, usually assumed to be 2.

Considerably more complicated is the subsystem R-W-P in a water-bearing aquifer where the pollutant is immiscible with the groundwater. In such cases, the pollutants forms an independent phase P, which is manifested as an independent geoelectrical layer. The possibility of detecting this layer must be analyzed with the aid of theoretical or model VES curves. (fig: 2.4 and 2.5).

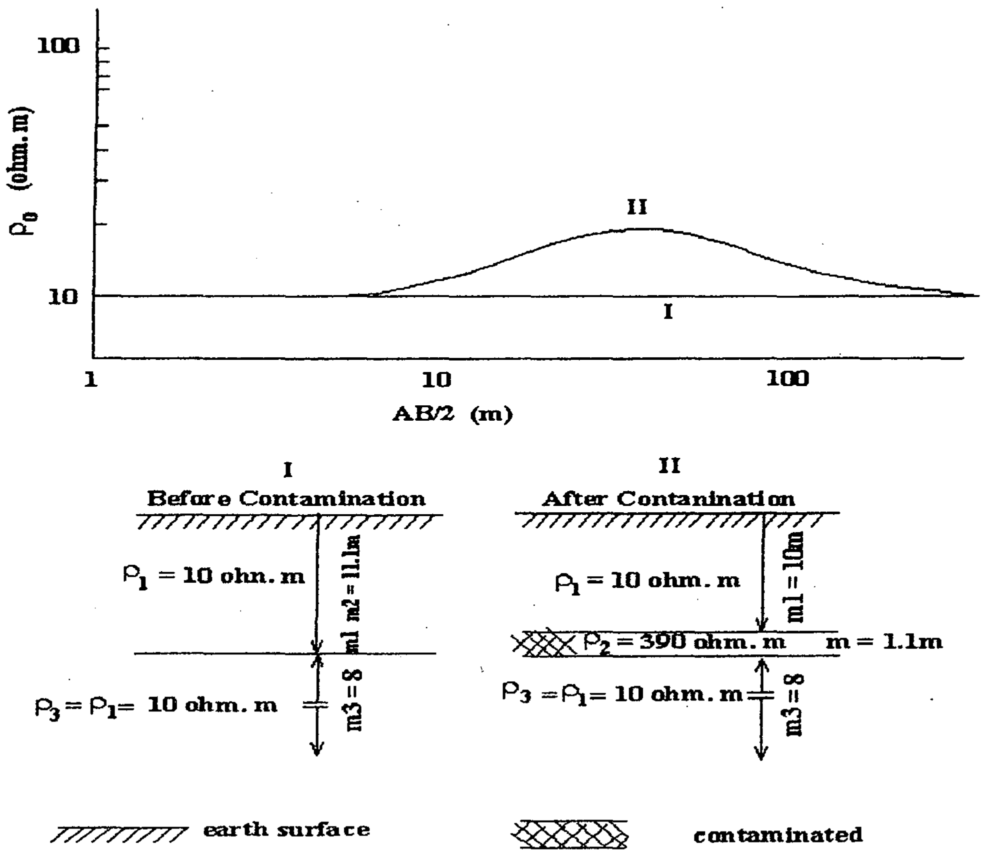


Fig.: 2.4. The effect of a contaminated layer (after Mazac et al., 1980)

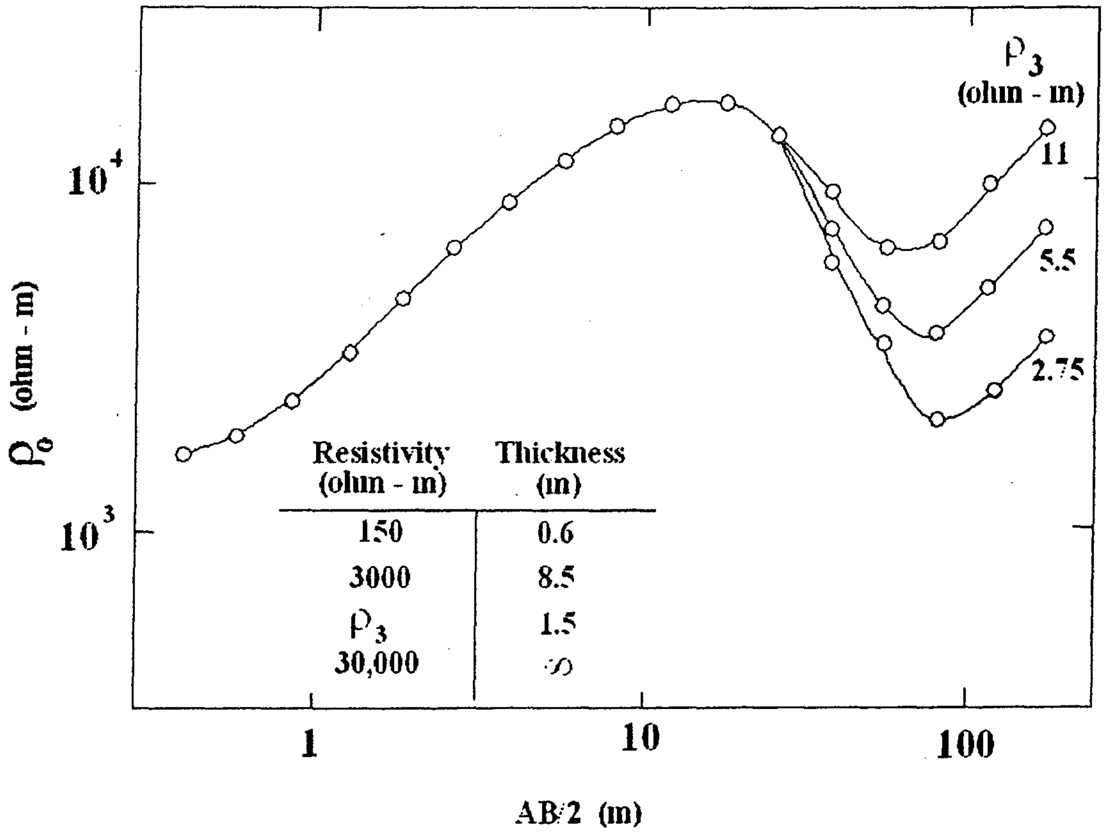


Fig.: 2.5 The effect of a thin high resistivity layer on the four-layer curve (Kelly, 1985).

For investigating movement in the vadose zone, an air phase must be added to the two and three phase systems already described. Soils in the unsaturated zone must be treated as R-W-A subsystems or complete R-W-P-A systems thus complicating the analysis further.

Geoelectrical methods have been most widely used in surface pollution studies. To make the methods more useful, measurement information content must be maximized and fully utilized. The factors that must be taken into consideration are described below. (Mazac et. al., 1987)

CHOICE OF MEASUREMENT

Direct current methods are still preferred. Electromagnetic (EM) methods are fairly widely used for qualitative surveys. However, interpretation techniques are not well developed for direct current (DC) measurements. By comparing, the mathematical modelling of DC measurements is relatively easier and DC flow is particularly easy for geotechnical engineers and geohydrologists to visualize since it is analogous to groundwater flow.

The main advantages of EM methods in pollution surveys are that measurements can be made considerably faster and that ground contact is not necessary. The dependence of the electrical properties of soils on frequency must be considered if alternating current (AC) is used. McNeill (1980) states that the electrical properties of soils are relatively unaffected by frequency and changes at the low frequencies used in equipment commonly being used in pollution surveys. Arcone (1981) and Cahyna (1985) showed in a field comparison that the two methods could yield comparable resistivity values.

In pollution studies, hydrogeologists have devoted considerable attention to contact less measurements of resistivity using dipole electromagnetic profiling (DEMP) (Keller, 1979; Cahyna, 1985). This method is successfully used to determine the extent and properties of natural contamination.

CHOICE OF SUITABLE METHOD

In choosing a suitable supplemental method either surface or borehole, it may be appropriate to combine, for example, geoelectrical surface and dilution logging methods (Grinbaum, 1965; Halevy et al., 1967; Mares et al., 1983), with the mise-a-la-masse method. The other possibility is to combine resistivity methods with other geoelectrical or other methods (atmochemistry, geothermics, emanometry, rheometry, gravimetry, magnetometry, seismic, etc.). The point is to increase the information content of geoelectrical method if they can be combined or supported by a suitable supplemental method. An example of a comprehensive approach to pollution evaluation is to determine migration parameters using a combination of resistivity methods, the dilution method, the mise-a-la-method, and pumping tests (i.e. so called migration tests) (Mazac and Landa, 1983).

Resistivity surveys can measure vertical variations (soundings) at selected locations by varying electrode spacing. Areal resistivity changes can be interpreted in terms of aquifer limits and changes in groundwater quality, whereas sounding surveys may indicate aquifers, water tables, salinities, impermeable formations, and bedrock depths. Among all surface geophysical methods, electric resistivity has been applied most widely for groundwater investigations. Its portable equipment and ease of operation facilitate rapid measurement. The method frequently aids in planning efficient and economic test drilling programs (Morris, L.W.(ed), 1964). It is especially well adapted for locating subsurface saltwater boundaries because the decrease in resistance when salt water is encountered becomes apparent on a resistivity-spacing curve. The method has been employed to detect the locations of highly permeable zones for groundwater recharge (Page, L. M., 1968). The method has been also employed for delineating geothermal areas (Hatherton, T., et al., 1966) and estimating aquifer permeability (Kelly, W. E., 1977).

An important new application of resistivity surveys involves defining areas and magnitudes of polluted groundwater. Results correlate best with groundwater, where a highly conductive pollutant, such as soluble salt, is moving in a relatively shallow zone with uniform geologic conditions (Bugg, S. F., and Lloyd, J.W., 1976). Studies of pollution from landfills (Cartwright,K.,and McComas,M.R.,1968; Klefstad, G., et al., 1975; Stollar, R., and Roux, P. 1975) wastewater disposal(Warner, D., 1969) industrial wastes (Hackbrath, D. A., 1971) and acid mine drainage(Merkel, R.H., 1972) have demonstrated the feasibility of the technique.

Chapter III STUDY AREA

3.1 LOCATION

A part of Najafgarh block which forms the southwestern part of the National Capital Territory, Delhi has been selected for the present study. The Delhi region, which is a part of the Indo-Gangetic alluvial plains, is at an elevation ranging from 198 - 220 meter above MSL and covers an area of 1483 sq. km. The study area lies between 28° 30′ N - 28° 40′ N latitudes and 76° 50′ E - 77° 05′ E longitudes (fig.: 3.1).

3.2 CLIMATE AND RAINFALL

The climate of the region is semiarid. The area is located in the 'monsoon-trough' and experiences 'monsoon- depressions', which are characterized by heavy rainfall events. The average rainfall (1931-91) is 611mm, most of which falls between June and September. The average annual evaporation is about 2540mm in Delhi. The mean minimum and maximum temperatures are 18.7°C and 30.5°C respectively. During the hottest month of May and June, temperature commonly exceeds 40°C.

3.3 GEOLOGY AND GEOMORPHOLOGY OF THE AREA

Delhi is situated at the triple junction of Aravalli mountain, Thar desert and Indo-Gangetic alluvial plain. It has 4 distinct physiographic units. (fig.: 3.2)

1. Alluvial plain on eastern and western side of the ridge.
1. Yamuna river flood plain deposits.
2. Isolated and nearly enclosed Chattarpur basin.
3. NNE - SSW trending Quartzite ridge.

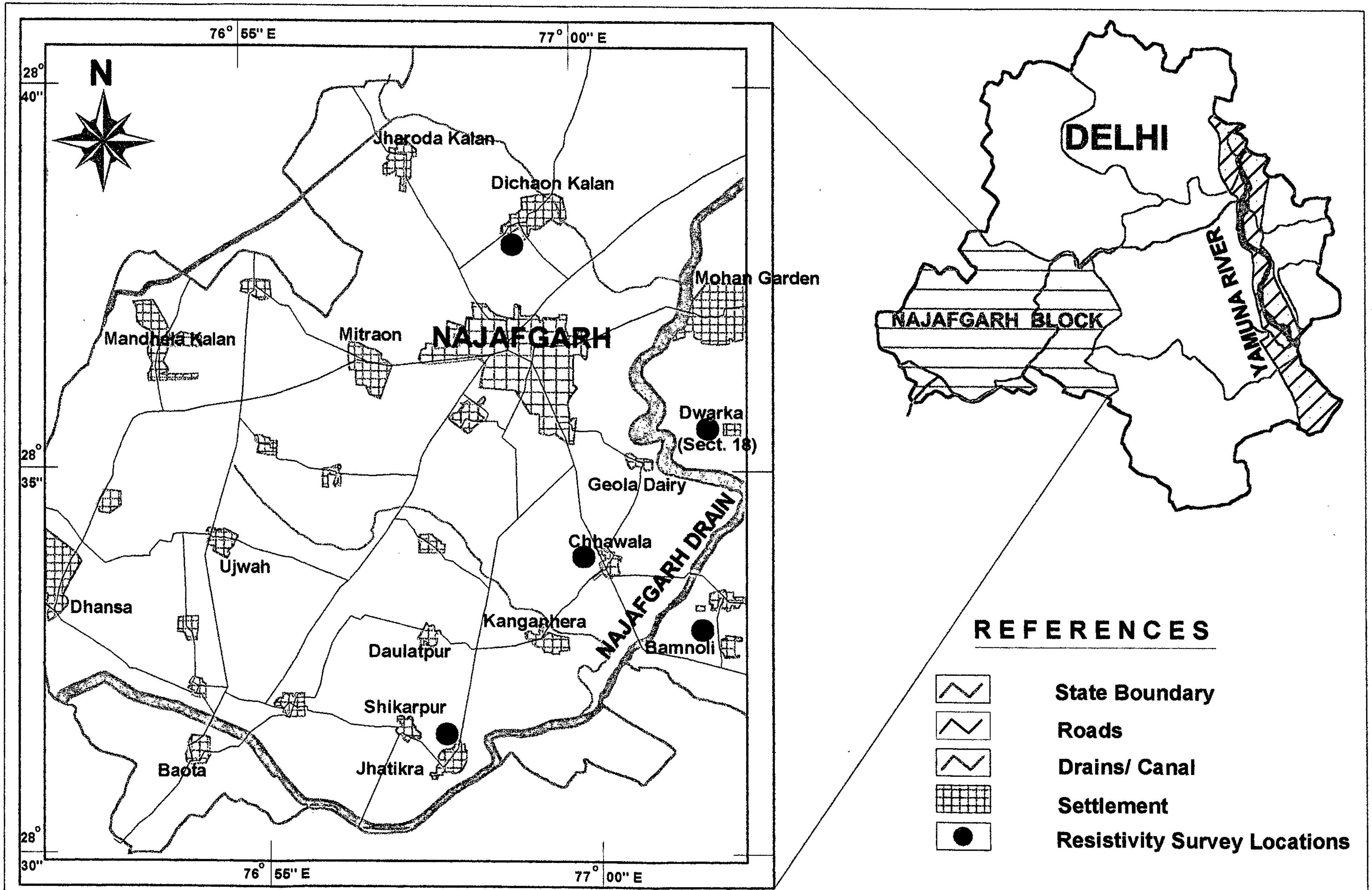


Fig.: 3.1 Map of the Study Area showing Resistivity Survey Locations

The Quartzite ridge constitutes northernmost extension of the Aravalli in the form of two ridges: i.e., Sohna ridge in Haryana, nearly 45km away from Delhi and west of it is Harachandrapur ridge also known as Delhi ridge. The Aravalli Mountains constitute remnants of Pre-Cambrian times whereas Thar desert and alluvium are Quaternary features formed by aeolian and alluvial processes.

The four-fold classification of Precambrian rocks of Aravalli ranges (Heron, 1953) envisages the geological evolution of the terrain through 3 major orogenic cycles now represented by:- (Gupta et.al., 1980).

- Banded gneissic complex older than 2500 Ma.
- Mewar gneiss
- Aravalli supergroup between 2500-200Ma.
- Delhi super group 200-140Ma

Although there are certain revisions in the local stratigraphic sequence and regarding correlation due to latter investigations, the sequence remains the basic frame of reference (Bhanumurty et. al., 1978, Choudhary et.al., 1984; Roy,1988).

In Haryana and Delhi region the rocks are exposed as NE-SW trending strike ridges, amidst the alluvial and Aeolian cover. Both ridges Sohna and Harachandrapur consist of thickly bedded quartzite with minor schist (Shco Prasade, et.al.1993; Awasthi and Prasad, 1992).

In the south Delhi and adjacent parts of Haryana the country rock i.e., Alwar quartzite of Delhi supergroup has been intruded by Pegmatite's and Quartz veins representing the acid igneous activity of post Delhi age (Heron, 1935; Tyagi, 1980). The minor Pegmatite's occurring as dyke swarms and vein quartz in this region are the evidences of hydrothermal activity (Tyagi, 1980).

The Delhi city is the last spur thrown out by the Aravalli towards the plains of northern India. The ridge reaches near the bank of Yamuna River at Wazirabad village, and runs parallel to the river encircling the walled city. It extends towards the western parts of New-Delhi and further extends towards the Qutub and Mehrauli where it throws out numerous branches some of which extends towards Gurgaon district and other push eastwards again towards the Yamuna river. The southern part near Mehrauli and Tughaquabad is called Kohi. It is a rock region surrounding the hill outgrowth.

The alluvial deposits of Quaternary age are mainly composed of unconsolidated clay, silt and sand with varying proportions of gravel and kankar. The Alluvial plain is further divided into: younger alluvium and older alluvium.

Younger alluvium belongs to the recent age and deposited in the flood plains of Yamuna river and also along the banks of major streams flowing from the hills. These sediments range in texture from clay/silt mixed with tiny mica flakes to medium/coarse sand and gravel. Absence of permanent vegetation (due to periodic flooding) and lack of kankars in general characterizes Younger alluvium.

Older alluvium are the sediments deposited as a result of past cycles of sedimentation of Pleistocene age and occur extensively in the alluvial plains within the territory of Delhi. This is composed of interbedded, lenticular and interfringing deposits of clay, silt and sand ranging in size from very fine to very coarse with occasional gravels. The kankar or secondary carbonates of lime occur with clay/silt deposits and sometimes as hard/compact pans. Older alluvium is predominantly clayey in nature in major part of territory except near closed alluvial basin of Chattarpur, where the alluvial formation is derived from the weathered Quartzite rocks.

3.4 SUBSURFACE CONFIGURATION

The nature of bedrock topography is rendered uneven due to existence of subsurface ridges. The thickness of alluvium overlying the quartzite's increases away from the outcrops. The thickness of alluvium is 300m and more in most parts of Najafgarh, Khanjwala and Alipur blocks, while in the southeastern parts of Najafgarh block, the thickness ranges from 50m to 300m. In the city block, west of the ridge, the alluvium thickness increases away from the ridge to 300m or more. East of the ridge in the areas upto river Yamuna, the alluvium thickness is comparatively less to about 165m. East of the Yamuna in parts of city and Shahdra blocks, the thickness ranges between 48m and 240m. In the Chattarpur basin of Mehrauli block, the alluvial thickness varies from a few meters near the periphery to 115m around Satbari bund.

Table: 3.1 Description Of Geological and Geomorphological Map.

S.no	Geomorphic unit	Lithostratigraphy	Brief Description
1.	Delhi Ridge	Quartzite, Pegmatite	Northeast orientation, the ridge is the oldest formation in Delhi composed of Quartzite, Pegmatite and their weathered products.
2.	Older Alluvium	Older Alluvium	Flat to gently undulating plain of large areal extent formed by river deposition. Older refers to early cycle of deposition.

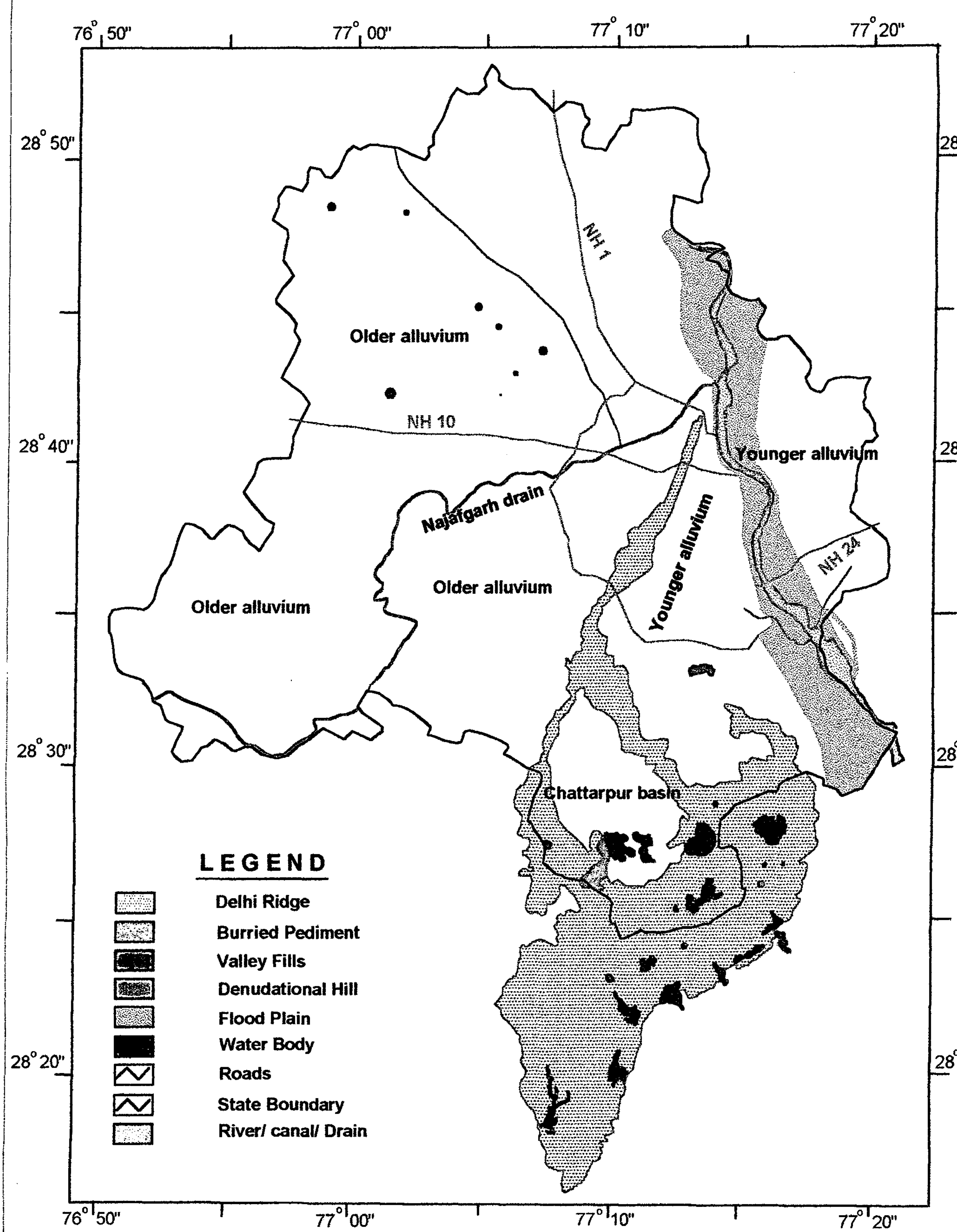


Fig.: 3.2 Geology and Geomorphological Map of Delhi

3.	Younger Alluvium	Alluvium	Flat to gently undulating plain of large areal extent formed by river deposition. Younger refers to later cycle of Deposition.
4.	Flood Plain	Alluvium	Relatively smooth land adjacent to river Yamuna, covered by water annually when the river overflows its bank.
5.	Valley fills	Kohi	Unconsolidated sediments of Delhi ridge deposited in the older valley due to erosion from elevated areas.
6.	Buried pediments	Delhi Ridge	5 to 20 meter of consolidated sediment deposit in the depressed areas of Delhi Ridge.
8.	Denudational Hills	Delhi Ridge	Weathered Ferruginous/ Quartzite reef with occasional presence of Pegmatite.

3.5 GROUND WATER SITUATION:

Delhi, despite its limited areal extent has diversified geological and topographic setup giving rise to different groundwater situations in different parts. The prevalent rock formations are widely varied in composition and structure ranging in age from Pre-Cambrian to recent which controls occurrence and movement of groundwater. The varied landforms like Ridge areas; alluvial plains of western Delhi, closed Chattarpur basins and flood plains of river Yamuna are significant control to occurrence and movement of groundwater.

The high relief areas of Delhi ridge with steeper topographic slopes and characteristic quartzite formation provides high runoff and less scope for rainwater infiltration. The inherent inhomogenity and low permeability of these hard rock formations further create a complex situation for occurrence and movement of groundwater.

Groundwater in the Delhi region occurs both in unconsolidated Quaternary alluvium and in quartzites occasionally intercalated with schists. The alluvium mainly consists of beds of clay, sand and gravel. At some locations there are impure calcareous matter in the form of irregular concretions, locally known as 'kankar', with abundance of as high as 30% (Wadia, 1981). A large part of the area has alkaline and saline soils. The alkaline soils contain sodium bicarbonate and carbonate among the soluble salts, while the saline soils are impregnated with sodium chloride and sulphates as the main soluble salts. The primary source of groundwater is rainfall during the southwest monsoon (July-September). Groundwater in deeper aquifers (>40m depth) is mostly recharged through leakage from the upper unconfined aquifer and partly from lateral groundwater flow from the north and southwest. Throughout the area, among the clay minerals in the alluvium formations abundance of Illite is 70-80 % (Vasudev Rao and Chatterjee, 1972). Smecite is mostly present in the western and northwestern parts of the region.

The alluvial tracts occupying larger parts constitute the potential groundwater reservoir in the territory. The characteristic and potential of groundwater reservoir, groundwater movement and occurrence show a distinct variation even in the alluvial aquifer due to their manner of deposition. The aquifers in western alluvial plains of the territory are distinct from the aquifer of Chattarpur basin and those occurring in Yamnua flood plains. The variation of quality as well as quality of groundwater in space as well as depth adds another dimension to the complex groundwater situation in the territory.

In the Yamuna flood plains and the Chattarpur basin, the shallow fresh water aquifers are available within depth range of 40-50m, behaving as a single unconfined aquifer system. In western part of Delhi i.e., in Khanjawala and Najafgarh blocks, semiconfined and confined aquifers occur at greater depth. The data from CGWB depicts the following groundwater information (table: 3.2).

Table: 3.2 Ground water data for different formations in Delhi.

Nature of formation	Depth domain (mbgl)	Well discharge m^3/hr (gph)	Draw down (m)	Transmissivity
Alluvium	30-50m	18-135 (4000 to 30000)	2.0 - 24.0	130 - 403
Quartzite	50-150m	2-18 (500 to 4000)	1.5 - 30.0	5 - 135

Ground water in the Delhi region is mostly saline in all parts and moderately to high in some locations (Seth and Khanna, 1969; Das et al. 1988; Datta et al 1994). Erikson argued that the Delhi area alluvium, which was thoroughly washed by water about 20,000 years ago, during the pluvial period, could have hardly retained any saline deposits to cause high salinity. He had observed that dissolution of airborne salts from the Arabian Sea, which have accumulated since Pleistocene time resulted in an increase in salinity of groundwater. However the arguments of Erikson cannot explain salinity in deeper waters (> 40m depth), which are present below impervious clay beds. Other common explanations suggested for high salinity of groundwater in the Delhi region are possible presence of water of marine origin, higher rate of evaporation and non-flushing of water at greater depths.

Chapter IV MATERIALS AND METHODS

4.1 DATA AND INSTRUMENTS USED

Indian Remote Sensing satellite (IRS) - 1C is India's new generation remote sensing satellite which is one of the most advanced civilian earth satellite. It is Sun-synchronous satellite that is placed in the orbit at an altitude of 817 km and its repetivity time is 24 days. IRS-1C has three types of sensors (viz., PAN, LISS-III, WiFS) with spatial resolution of 5.8m, 23.5m and 188m respectively.

For the present study the following data was used:

- IRS- 1C, PAN single band data, having a resolution of 5.8m dated 11/2/97.
- IRS-1C, LISS-III, 4 Band digital data, having a resolution of 23.5m dated 10/4/1997.
- IRS-1B, LISS-II, 3 Band data, having a resolution of 36.25m dated 13/11/98.
- Toposheets: Survey of India toposheets no 53H/2 and 53D/14 at 1:50,000 scale.
- Eicher city map.
- DDR-2 Resistivity meter (IGIS).

4.2 METHODS

4.2.1 Image interpretation:

Image interpretation is defined as the act of examining images for the purpose of identifying objects and their significance. Image interpretation is infact a complete process of physical and psychological activities occurring in a sequence of time. The various aspects of image interpretation are

Detection – process of picking an object or element.

Recognition and identification – process of distinguishing an object.

Analysis – Process of resolving.

Classification – Process of identification and grouping.

Deduction - Process where references are drawn about the objects.

Idealization – process of drawing ideal or standard representation.

Techniques of Image Interpretation:

Visual interpretation:

Visual image interpretation is based on the 8 elements of photointerpretation, which are

1. Tone/ color – refers to relative shades of B/W images or color of FCC (False colored composite) images. Tone/ Color is a fundamental property of an image and conveys more information to an interpreter than any other interpretation elements.
2. Texture – texture refers to the frequency of tonal changes in an image.
3. Pattern – it relates to the spatial arrangement of the objects.
4. Shape - shape refers to the general form, configuration or outline of an individual object. Shape is one of the most single important factors for recognizing objects from images.
5. Size – The size of an object can be important tool for its identification.
6. Shadows – the shadow may enhance or reduce the capability of interpretation.

7. Site – location of objects in relation to other features may be helpful in the process of image interpretation.
8. Association – It is one of the most important tools in identification of the landforms.

Digital Image Processing:

Digital image processing involves the modification of the digital data for improving the image qualities with the aid of sofesticated tools like Computers. The process helps in maximizing clarity, sharpness, and details of features of interest towards information extraction. Image processing improves the interpretability of an image by enhancing the features of interest at the cost of remaining features.

Methods of Digital Image Processing:

1. Image reduction – selection of the areas of interest from the entire image.
2. Image magnification – increasing the scale for easy visual interpretation, this gives detailed information about the spectral reflectance or emittance characteristics of a small area.
3. Image enhancement – To improve the appearance of an image for human visual analysis or machine based analysis.
4. Contrast enhancement – To expand the original input brightness values to make use of the total dynamic range or sensitivity of the output services.
5. Ratioing – Minimises the environmental effects, which gives wrong perception of the object. It helps in distinguishing image features in multispectral data.
6. Principle component analysis – method of data compression by which the large data can be contained in less no of bands.

Information can be extracted from the digital data by the classification technique. Classification techniques depend on the spectral properties of various features covered in the scene and employ various types of spectral analysis.

The object of classification is to generate meaningful thematic maps with the help of the remotely sensed data. There are two methods for multispectral classification

Supervised classification:

In this method the analyst chooses some conventional (somewhat artificial) classes in a scene from prior knowledge. The interpreter also locates training sites on the image to identify the classes. Training sites are the areas representing each known land cover category that appears homogenous. Classification then starts with by statistical processing in which every pixel is compared with the various signatures and assigned to the class whose class comes closest. Few pixels in a scene do not match and remain unclassified.

Unsupervised classification:

In this technique, there is no need to train the computer algorithm. The image data are first classified by aggregating them into natural spectral cluster present in the scene. Then the analyst has to determine thematic class corresponding to each spectral cluster by comparing the classified image data to ground information.

4.2.2 Theory of Resistivity Method:

The basic principle behind electrical geophysical methods is that different geologic material have different electrical properties, layers in the subsurface can be identified on the basis of these properties. The methods used to measure the properties of geologic materials can be divided into two types: methods using applied currents, and those using naturally occurring currents. Those methods that used applied currents include electrical resistivity, induced polarization, and electromagnetic surveying. Methods that use naturally occurring current flow include telluric surveying, magneto telluric surveying, and self-potential.

Basic Electrical Theory

The principle of the electrical resistivity method is simple. A current flow is applied to the surface of the earth, and potential difference in the flow is measured. This gives us the resistivity of the geologic materials, which can in turn tell us what type of material we might be sampling. In electrical resistivity method, a battery providing the power source is connected through an ammeter to a resistor in a simple electric current. The battery supplies a potential difference from terminal to terminal, and this charge moving through the system is called current, and is written as $\mathbf{i=q/t}$. Where current equals charge per unit time. The current density is called **j**, and is equal to current per unit area. According to the Ohm's law current is directly proportional to voltage, and inversely proportional to resistance. But the measurement of resistivity is not so simple, as the resistance of a resistor is affected by length. For a medium with a given resitivity, it is equal to the measured resistance times area, divided by length.

$$\rho = \mathbf{R\,L/A}$$

where,

ρ is the resistivity, L is the length,

R is the resistance and A is the area.

Electrical resistivity of rocks:

Electrical resistivity is a physical quantity describing the ability of a substance to conduct electrical current. In fact, the easier electrical current is conducted through a substance, the higher is its conductivity and the lower its resistivity. There are two major ways in which electrical charges can be transported through rocks either by electrons (electronic conductivity) or by ions (electrolytic conductivity).

Except for some ore-type minerals, most of the rock forming minerals are very poor electronic conductors and neither are the mineral grains good electrolytic conductors. The resistivity of rocks is not fully dependent on mineral composition. The electricity is predominantly conducted by the ions of the fluid (generally water) present in pores, cracks and fissures and along grain boundaries. Hence the major factors determining the resistivity of a rock will be interconnected porosity, permeability, fluid saturation and resistivity of the fluid. Resistivity also varies according to the nature of geologic nature:

Homogenous geologic material:

When a current is applied to a body of homogeneous geologic material, a potential field is created. This potential field exists only in the subsurface, and not in the air, since air is an infinite resistor. The potential field is a source at one electrode and a sink at the other. The potential at any point in the field can be found with the equation:

Vp = i*(rho)/(2ã*r1) - i(rho)/(2ã*r2)

This equation is the main equation for electrical resistivity. In it's current form, this equation describes the potential field only for the two current electrodes. But while doing a resistivity survey, we use two potential electrodes also and then the equation can be written as:

Resistivity = 2(pi)V/i * (1/(1/r1-1/r2-1/r3+1/r4)

This equation is used more frequently in the resistivity surveys. The potential electrodes are used to normalize ground potential. The lines of current flow are always, drawn perpendicular to the potential lines. And the area between the flow lines need not be the same, but the current flow is same.

One Horizontal Interface:

For a single interface, the resitivity will either be higher or lower in the upper medium. If the resistivity is higher in the lower medium, the current flow lines will be bent toward the normal to the interface, spaced farther apart. Conversely if the medium below is of lower resistivity, the flow lines will be bent parallel to the interface, spaced closer together. Thus, if the resistivity in the lower layer is higher, more current will flow in the upper layer.

The values recorded in the field are *apparent resistivity* values. That is, they are not the true measure of resistivity in any one of the two mediums, but rather this value is product of both resitivity values. This is due to the fact that the current is not just flowing through one of the mediums, but both, and it is affected by both. As the electrodes are spaced farther and farther apart, more of the current flows to a deeper and deeper depth.

So in effect, at first when the electrodes are close together, *mostly* the upper layer resistivity is recorded. But when the electrodes are moved farther apart, the lower layer begin to get sampled more and more, as a larger percentage of the current passes through the lower layer.

Multiple Horizontal Interfaces

The method remains same for multiple layers. However, it becomes more complicated. In a simpler three layer case, if there is a low or high resistivity layer in the middle of two other layers, it is slightly easier to distinguish. The graphs of apparent resistivity for these cases clearly show the existence of a low or high resistivity middle layer, but the graphs for cases where the resistivity always increases or decreases is more difficult to determine.

Vertical Contacts

There are two procedures while mapping a vertical contact, one is the constant-spread approach, and the other is the expanding-spread approach. The constant-spread approach involves moving the entire electrode assembly across the vertical contact. In the expanding-spread method, one of the electrodes is moved back and gradually crosses the contact. In the case of both methods, the resistivity versus distance (or electrode spacing) has a slope with discontinuities as well as negative slopes.

Other Geometries

Two Vertical Contacts

In this case the curve contains the same sharp discontinuities and negative slopes as the single vertical contact, but in this case, there is a symmetrical second curve as well.

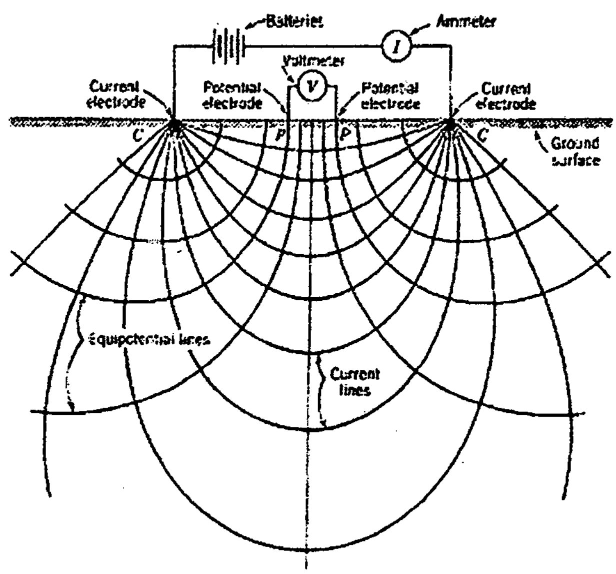


Fig.: 4.1 Electrical circuit for resistivity determination and electrical field for a homogenous subsurface stratum..

Hemispherical Structures

For this case, the curve is similar to the two vertical contact cases, since the hemisphere can be imagined as a two vertical contact case that doesn't extend as far down, and therefore is tempered by the material below. It will be a bilaterally symmetric curve with more rounded edges that the sharp discontinuities of the two contact graphs.

Dipping Interfaces

Dipping interfaces generally have resistivity graphs that are similar to the two vertical case, but are not bilaterally symmetric.

4.2.3 The Equipment Used For Electrical Resistivity

Ammeter, Voltmeter, 4 electrodes (two for source/sink, two for volt meter/potential), Connecting wire and Power source (DC or AC, batteries in series or motor-driven

Electrode Spacing

The arrangement for current electrodes and potential electrodes is variable. Over the years, many variations have been tried; however, only three are in popular usage:

Wenner Method

All electrodes equally spaced i.e., the potential electrodes located at the third points between the current electrodes. The apparent resistivity is given by the ratio of voltage to current times a spacing factor. For Wenner arrangement the apparent resistivity is

$$p = 2\pi a.V/I$$

where,

p is the apparent resistivity

a is the distance between the adjacent electrodes

V is the Potential difference between Potential electrodes

I is the Current applied.

Advantages:

Equal spacing yield quick results

Less demand for instrument sensitivity

Data can be analyzed directly.

Disadvantages:

Susceptible to near-surface lateral variations.

All electrodes must be moved for new reading.

Schlumberger Method

In schlumberger arrangement, the potential electrodes are close together. The apparent resistivity is given by

$$p = \pi(L/2)-(b/2)/b.V/I$$

where,

L is the distance between current electrodes

b is the distance between potential electrode.

Theoretically, L>>b, but for practical application good results can be obtained if

L ≥ 5b (Compaigne Generale de Geophysique 1963).

Advantages:

Not all electrodes must be moved for each reading.

Disadvantages:

Data must be pre-analyzed.

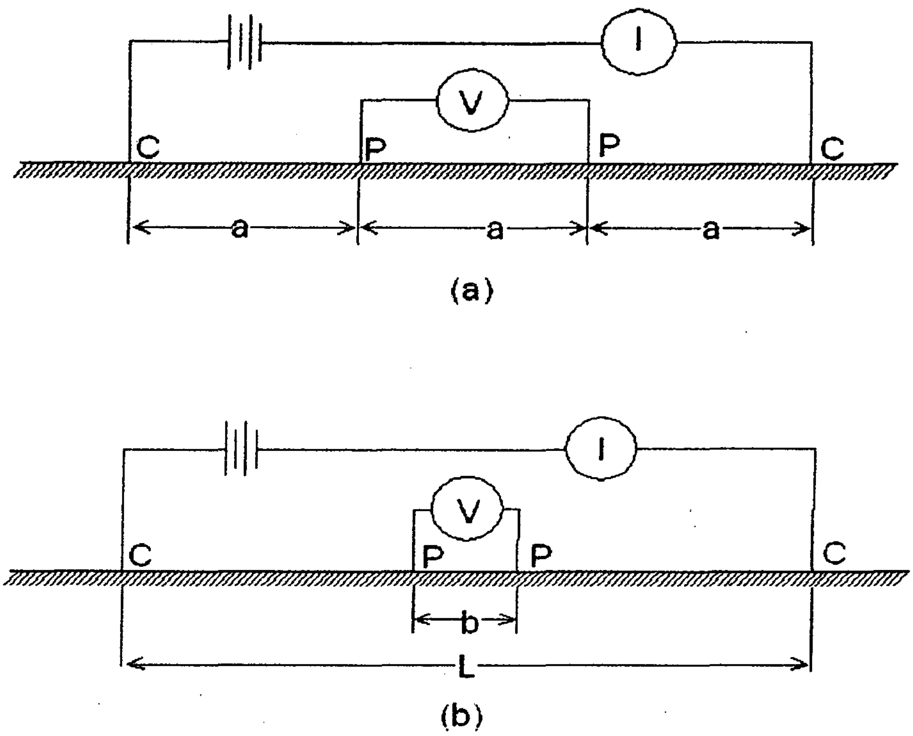


Fig. 4.2 (a) Wenner arrangement (b) Schlumberger arrangement

Dipole-Dipole Method

Current electrodes close together, and potential electrodes close together, but the two sets are relatively far apart.

For the present study direct electric current resistivity method using the Schlumberger arrangement of the electrode was followed with increasing electrode spacing. The data was recorded by the resistivity meter and that data was used for drawing the VES (vertical electrical sounding) using the FRES software.

Typical Resistivities of Geologic Material

Resistivity near surface material is heavily affected by groundwater, and water is a low resistivity material. In general finer grained sediments have low resitivities, and bedrock has high resitivities. Resistivity values for different rocktypes are shown in table: 4.1

Resistivities are reduced by:

- Increasing porosity.
- Increasing ion content of groundwater.
- Increasing content of clay.
- Decreasing grain size.

Table: 4.1 Velocity and electric resistivity values for several rock types (Duprat 1991).

Sl.no.	Lithology	Resistivity (Ω)	Velocity m/s
1.	Silt	10-100	750
2.	Sand - Gravel	300 – 8000	900 - 1100
3.	Freshwater sand	50 –100	
4.	Argillaceous sand	25 – 50	1600 - 1800
5.	Salt-water sand	0.4 - 1.3	
6.	Pebble aquifer	100 to several hundred	1700 - 2000
7.	Limestone	80 to several hundred	3000
8.	Clay - marls	Several to 50	2000 - 2500

Chapter V RESULTS AND DISCUSSION

The purpose of interpreting geoelectrical field measurements is to determine the model, which best represents, the geo-hydrologic section in terms of both geometry and resistivity. (Mazac et. al., 1987).

Geo-electric surveys using Vertical Electrical Soundings (VES) are well suited to the investigation of alluvial aquifers where various lithologic units often have large resistivity contrasts (Ayers J.F., 1989). Bavaji J.R. (1988) used the technique successfully in delineating the fresh saline water interface in Bhatinda district of Punjab. Bavaji has correlated the VES data with that of electrical logging and found that the results from electrical logging and VES match perfectly.

Profiling is the most commonly used technique in pollution studies (Kelly, 1985) and under favorable conditions the extent and degree of pollution can be mapped. By repeating measurement it is possible to monitor pollutant movement and changes in concentration. Because of the lack of theoretical models profiling results are normally interpreted qualitatively. Profiling results can be interpreted quantitatively if study is supported by vertical electrical sounding. Vertical electrical sounding VES is the most accurate method for defining conditions because it yields quantitative results. (i.e. the thickness and resistivities of geo-electric layers). A realistic picture can be obtained when it can be reasonably assumed that the geologic section is approximately horizontally layered and quasi one-dimensional.

To make the VES data more reliable, two equally important conditions must be recognized (Maskova and Mazac, 1985)

(a) It is necessary to start with a realistic geological model, because there is no method, which yields an unambiguous interpretation of an actual VES. This difficulty is caused by the presence of surface inhomogenities and limited sensivity of measuring instruments (Keofoed, 1979).

(b) Interpretation results depend on accurate and effective interpretation procedures, (Keofoed, 1979; Mooney, 1980). Computer used, which interpret VES curves automatically should be used with custom. Because, these programs yield mathematical accurate results, but do not lead to geologically realistic solutions.

In cases, where actual conditions differ substantially from the quasi one dimensional model, the normal interpretation procedures will lead to result which can differs substantially from reality (Maudry, 1984). In such cases, multi-dimensional modeling based on numerical methods to test the correctness of an interpretation, becomes necessary. The advantage of multi-dimensional modeling is that one can assess the information content of the usual one-dimensional interpretation procedures for realistic geo-electrical conditions. For example, a multilayered medium with a distinctly variable geometry and variable physical properties, i.e., conditions typical of a contaminated site.

Despite the advantages of multidimensional modeling resistivity methods were used based on one-dimensional interpretation procedures. One reason is the difficulty of time required for multi-dimensional modeling. A second reason is that the error in the observed values due to the unavoidable surface inhomogenities and instrumental effects can considerably outweigh the effects of inhomogenities at the greater depths.

The alluvial aquifers are best studied for the pollution purpose by the geophysical techniques, because in porous formation, the resistivity is controlled more by the water content and quality within the formation than by the rock resistivity. In aquifers composed of unconsolidated materials, the resistivity decreases with the degree of saturation and the salinity of the ground water. The clayey aquifers yield the saline water. Clay minerals conduct electric current through their matrix, therefore clayey formations tend to display lower resistivities than do permeable alluvial Aquifers. Therefore, it is easier to distinguish between the aquifer types and their water quality with the help of resistivity surveys.

5.1 Resistivity Study

The VES curve of Bamanauli shows variation in resistivity values from 13-15 ohm-m indicating a layer of clay and kankars, with some amount of silt. But after a distance of AB/2 the resistivity values goes upto 18 ohm-m indicating a layer of clay with sand and kankars. Then again the resistivity values goes down (Fig.: 5.1).

From VES curve of Dichaun, it can be seen that only in the topsoil of about 6m depth the resistivity value reaches to 10 ohm-m, indicating the presence of clay Kankars with fine sand. For the rest of the depth the resistivity remains well below 6 ohm-m. Thus the conditions have become more suitable for the presence of clayey horizon (Fig.: 5.2).

The graph of Dwarka shows that the resistivity value varies between 25-15 ohm-m, which indicates a zone of fresh water, because of the presence of more sand and Kankars. The resistivity value seldom falls below 10 ohm-m, which indicates that the groundwater aquifer system is more sandy, and that is why the groundwater in the area is fresh (Fig.: 5.3).

The graph of Jhatkira indicates that the initial resistively values are more than 20 ohm-m, but with the increasing depth, the resistivity goes down which indicates the presence saline water in the deep (Fig.: 5.4).

The VES curve of Rohini, it can be inferred that a maximum value of 10 ohm-m is observed just below the topsoil. Then after the curve becomes more undulating. This may be because Rohini area was used to be a landfill with the passage of time the material got filled and that may be a reason for the variations in the curve (Fig.: 5.5).

The VES curve of Narela depicts a good aquifer system consisting of resistivity values varying from 20 ohm-m to 100 ohm-m, which indicated a sandy aquifer, with almost no clay. But with the increasing depth, the characteristics of the aquifer has changed a lot and the proportion of clay has increased very much, putting down the values again to a level of 10 ohm-m and even less than that (Fig.: 5.6).

On inspection of the geoelectric data obtained from the VES location Chawla, it can be observed that the area has a overall resistivity value of 10ohm-m and further the resistivity values goes down with the depth. This indicates higher value of EC in the area, which in turn suggests the presence of higher amount of cations and anions in the water. The higher EC value means higher salinity (Fig.: 5.7). Interpretation of the VES curve of Chawla shows that the water quality deteriorates with the depth. The fact is also supported by the EC map of Delhi region, in which EC contours converges towards Chawla area indicating higher salinity (CGWB report). The slightly undulating nature of the curve below the 10 ohm-m indicates that there is some intercalation of Kankars, which is supported by the Lithology of the area.

The VES curves of the different places can be grouped into two categories. One having a value of more than 20 ohm-m in topsoil. The other group is having resistivity value of 10ohm-m or less. The place having the higher value of resistivities are near to Najafgarh drain. This means that the area near the Najafgarh drain are getting recharged due to lateral movement of groundwater and this can be the reason for relatively fresh water in Dwarka and Jhatkira than the Dichaun and Chawla..

The geoelectrical soundings have generally indicated 2 to 3 layers in alluvium with resistivity values ranging from 3 ohm-m and 30 ohm-m. The results of geoelectrical soundings correlate fairly with the borehole data.

From the comparative study of the resistivity with the borehole data, a fairly agreeable relationship between the resistivity and the nature of Alluvium has been established for the area and is shown below in table 5.1

TABLE 5.1 Resistivity values for various types of Alluvium

Resistivity Range	**Nature of Alluvium**
3-9 ohm-m	Clay and clay with Kankars.
10-19 ohm-m	Clay and Kankars with fine sand intercalation.
More than 20 ohm-m	Greater proportion of sandy layer with little clay.

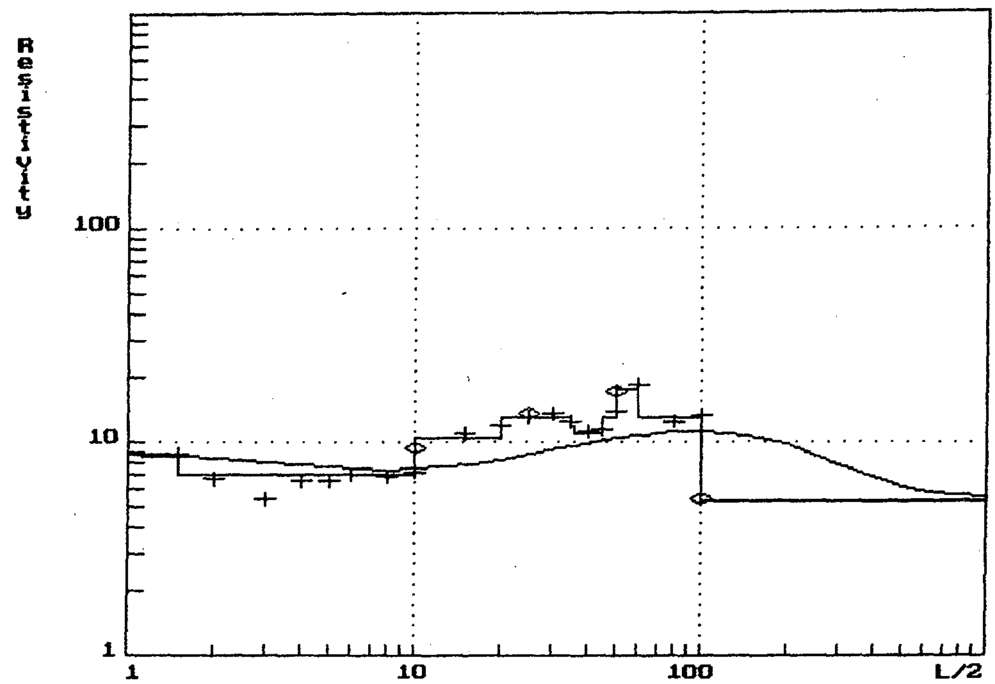


Fig.: 5.1 Vertical Electrical Sounding (VES) curve of Bamnauli.

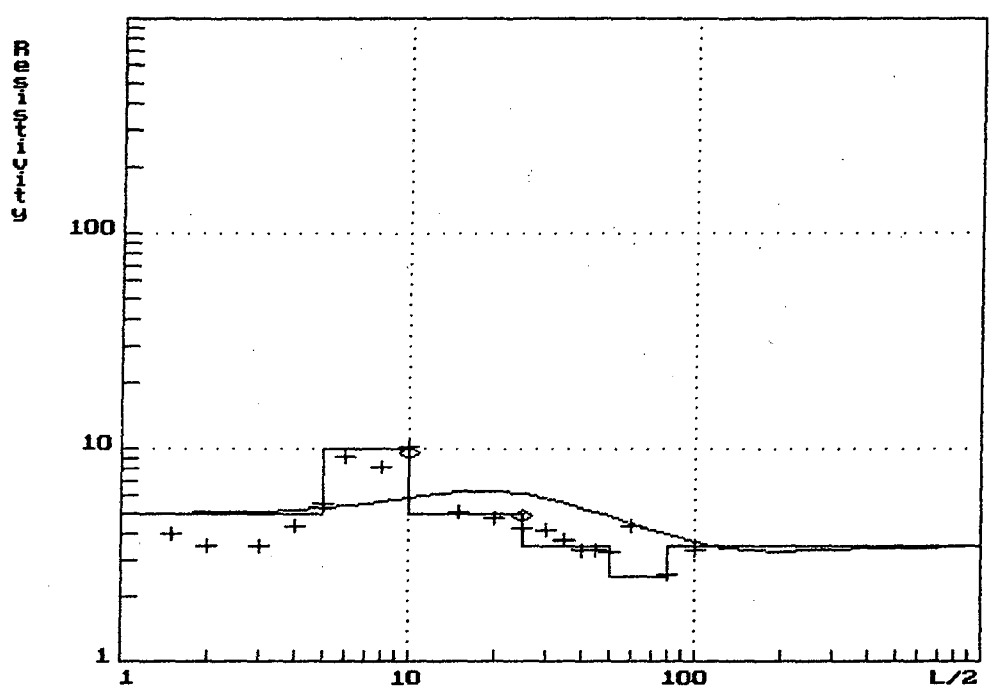


Fig.: 5.2 Vertical Electrical Sounding (VES) curve of Dichaun.

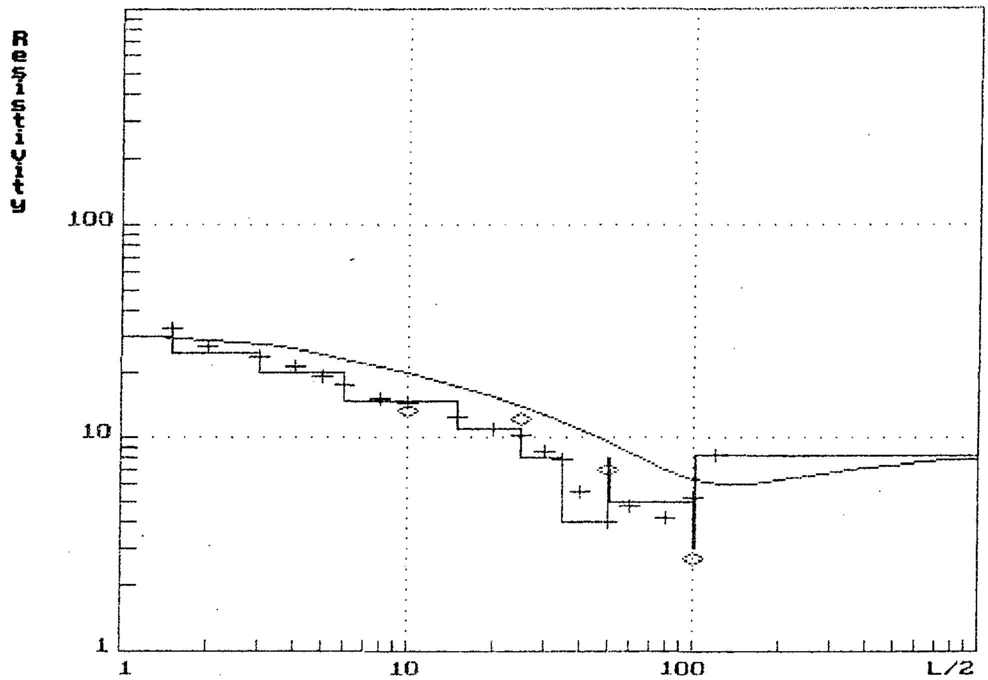


Fig.: 5.3 Vertical Electrical Sounding (VES) curve of Dwarka.

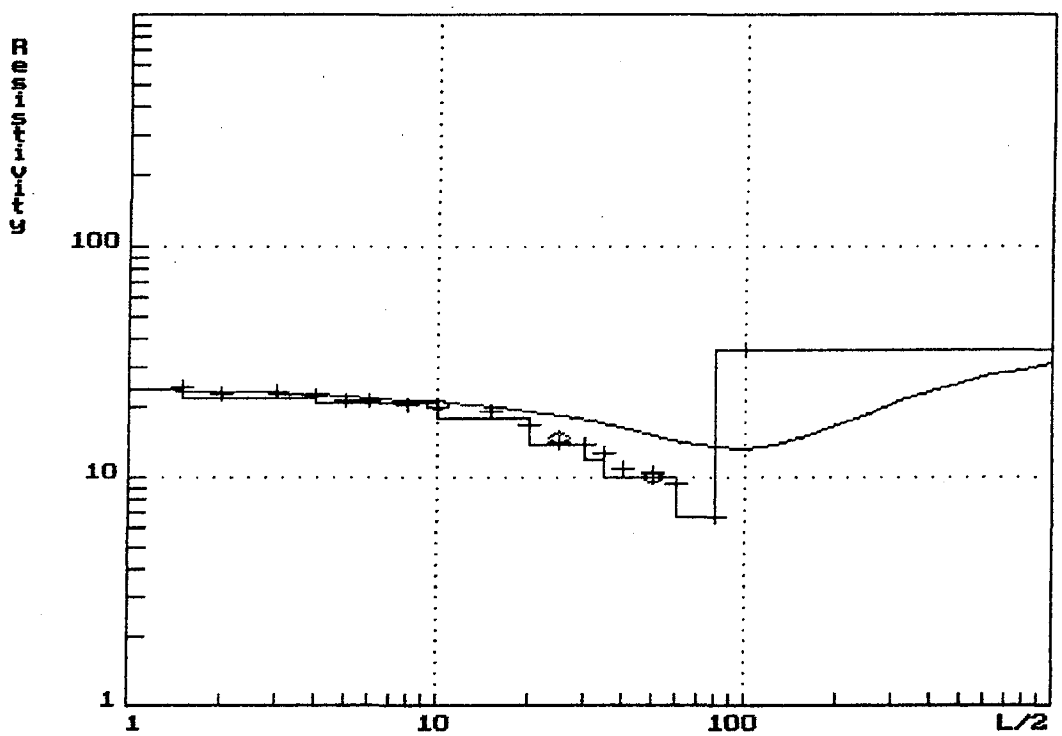


Fig.: 5.4 Vertical Electrical Sounding (VES) curve of Jhatkira.

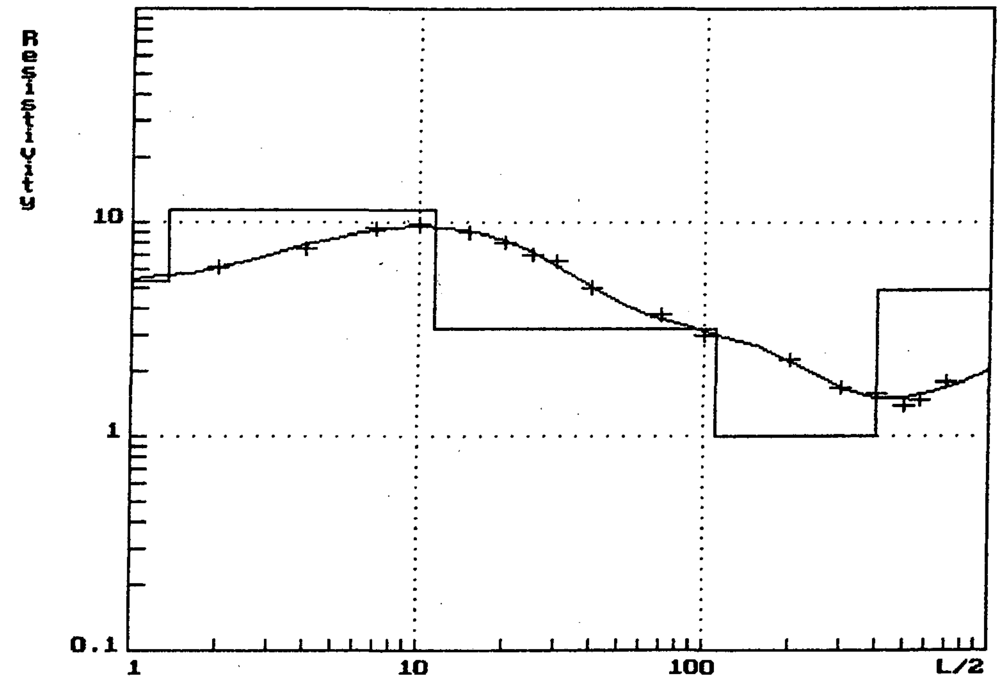


Fig.: 5.5 Vertical Electrical Sounding (VES) curve of Rohini.

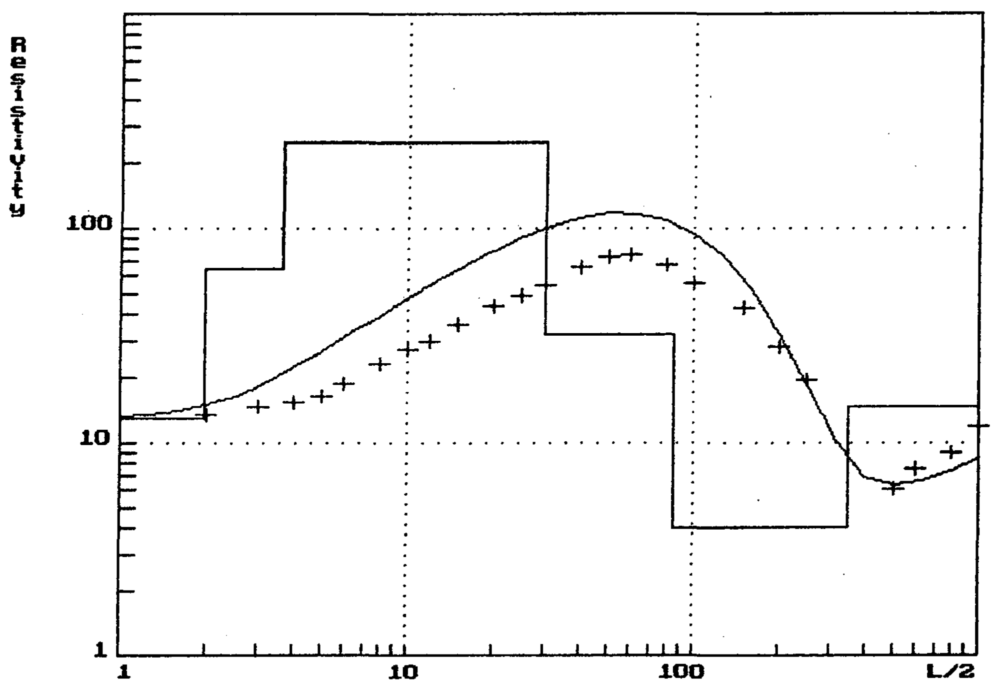


Fig.: 5.6 Vertical Electrical Sounding (VES) curve of Narela.

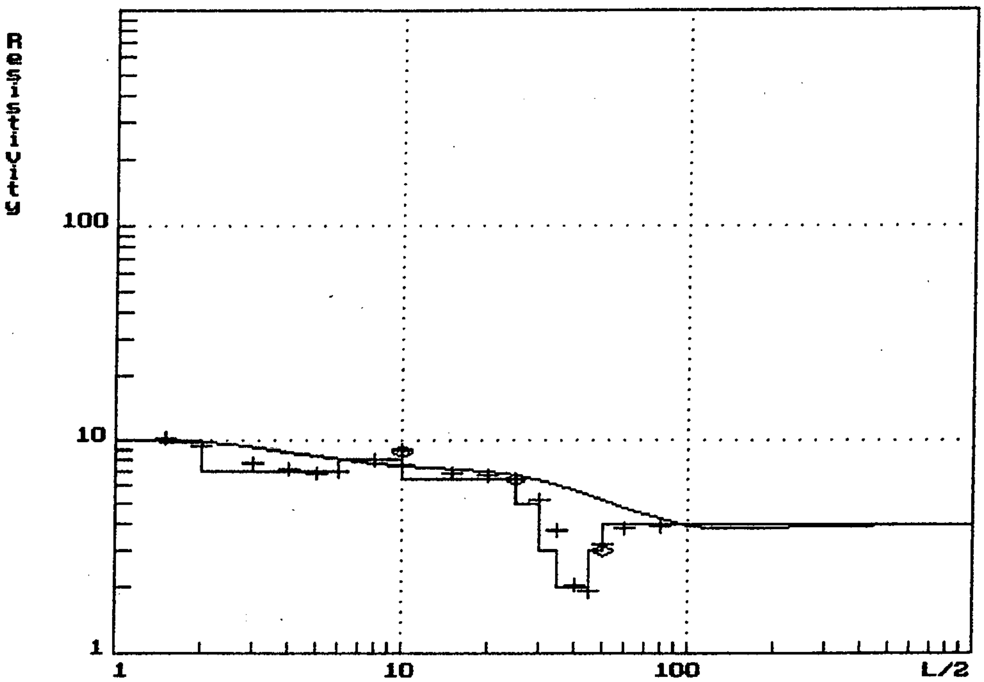
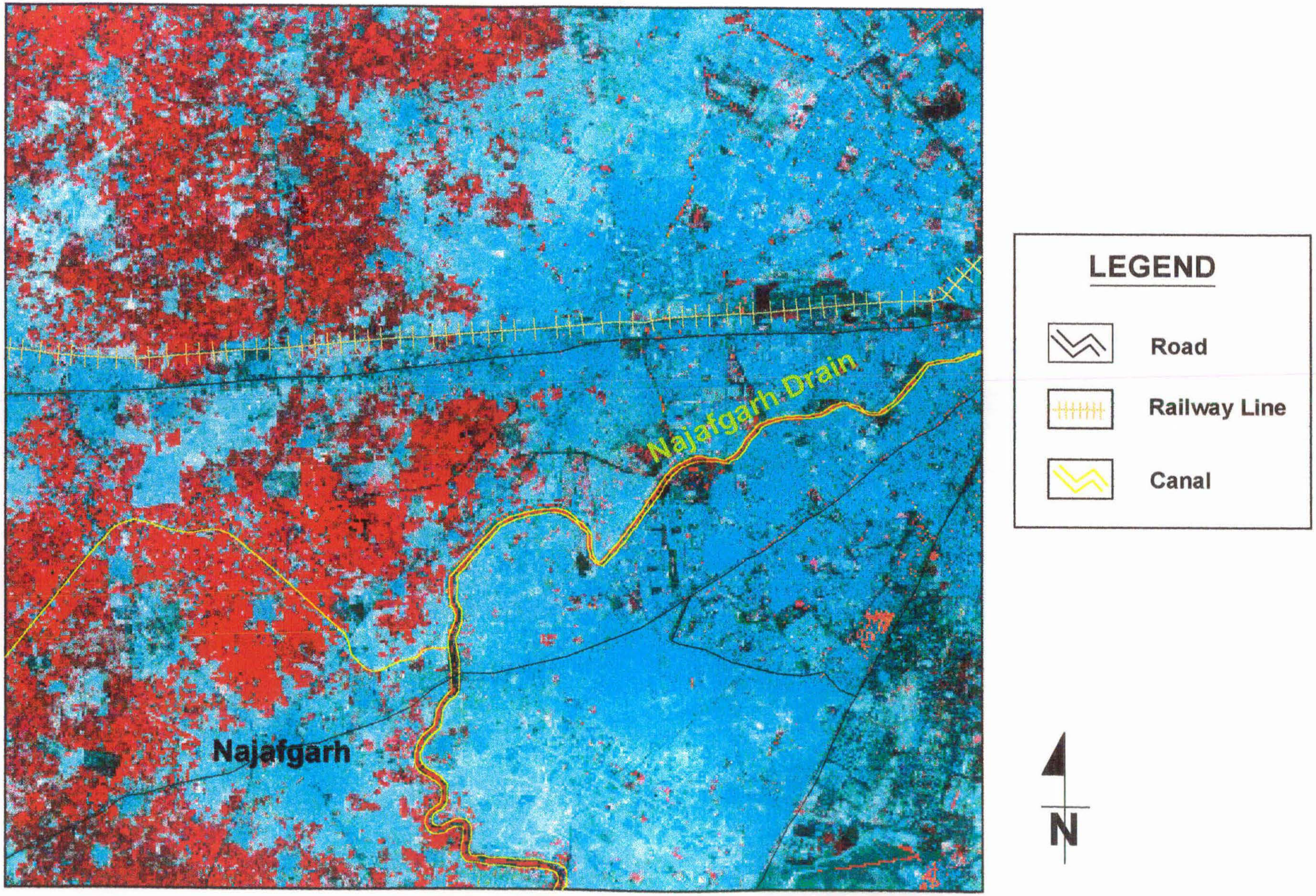


Fig.: 5.7 Vertical Electrical Sounding (VES) curve of Chawla.

5.2 Remote Sensing Study

It is believed that the characteristic of groundwater is reflected on the soil and vegetation of the surface above it. Hence, the characteristics of the groundwater at a particular area can be determined to an extent, by its surface manifestation in terms of the surface land use / land cover pattern. This is the basis on which, an attempt has been made to correlate the surface soil and vegetation status with the groundwater at that particular area. For this, land use / land cover maps of the study area have been prepared with the help of IRS-1C (LISS-III) data of June 2000 and Survey of India (SoI) topographic map of the study area. **Fig.: 5.8** shows the standard FCC (False Colour Composite) map of the study area collected from IRS-1C (LISS-III) sensor. This satellite data has been digitally processed and supervised

IRS-1C (LISS III) Standard FCC Image of the Study Area
(Taken in June 2000)



LAND USE/ LAND COVER MAP OF THE STUDY AREA

(Based on Supervised Classification of IRS 1C LISS III data of June 2000)

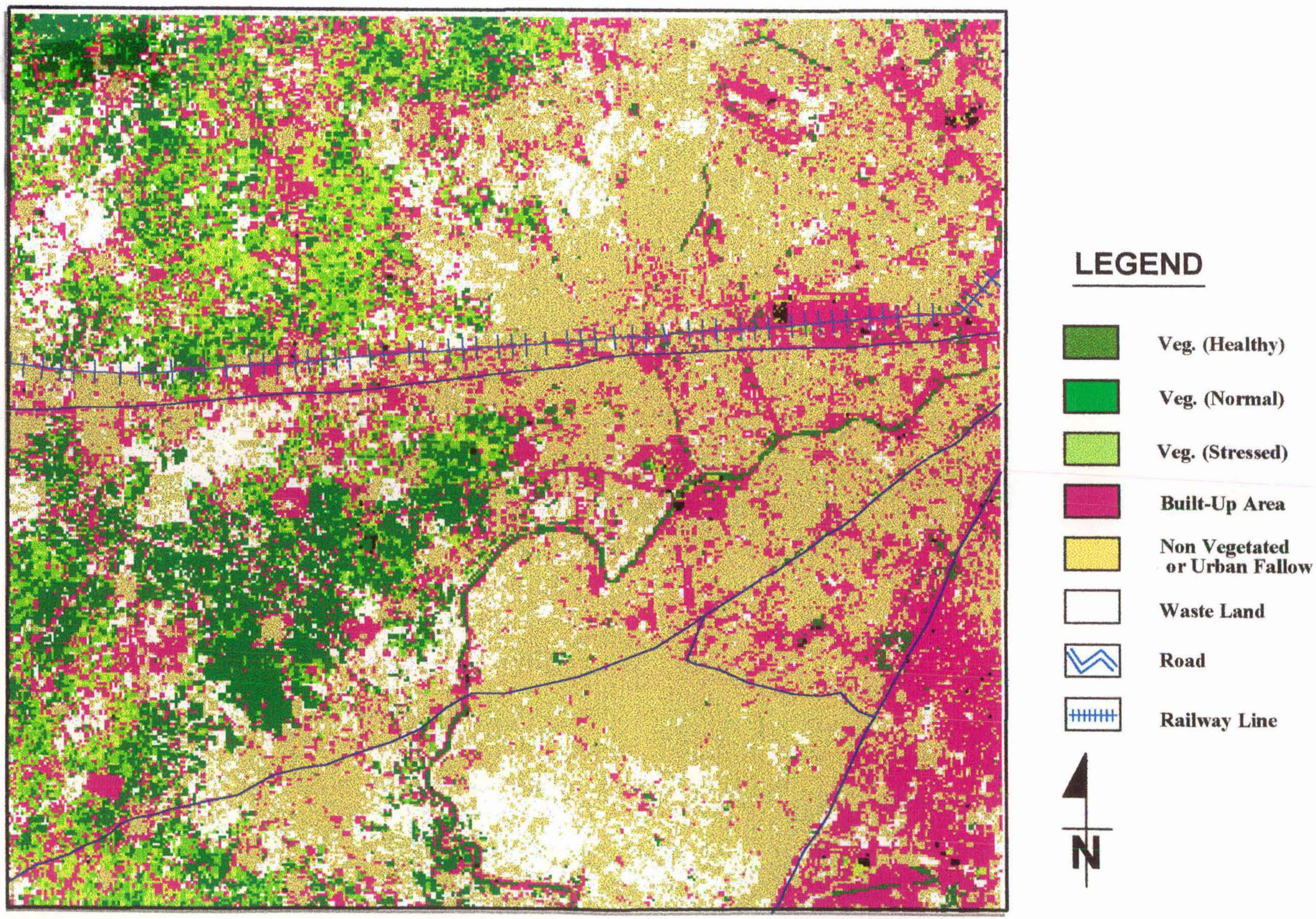


Fig.: 5.9

LAND USE/ LAND COVER MAP OF THE STUDY AREA
(Based on Unsupervised Classification of IRS 1C LISS III data of June 2000)

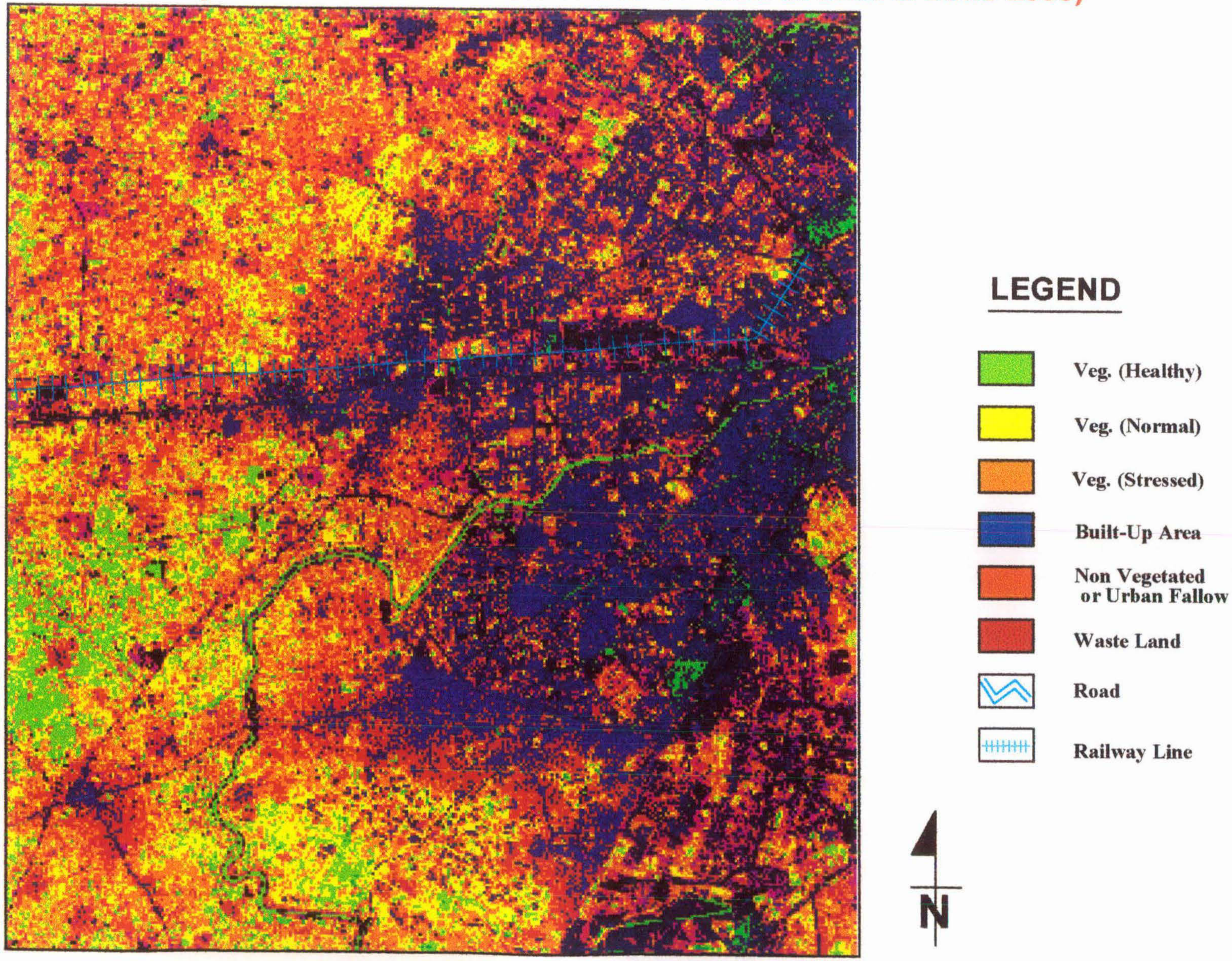


Fig.: 5.10

classification of the data using weighted average classification scheme has been made to prepare major land cover features of the area **(Fig.: 5.9).** Similarly, unsupervised classification of the satellite data is also carried out using clustered means method to prepare the possible landuse / land cover features of the study area **(Fig.: 5.10).** Also, spectral reflectance values of the resistivity sampling sites were calculated using IRS-1C (PAN) data with the help of Image Viewer software. The spectral reflectance values are then correlated with the topsoil resistivity values for each of the sampling sites. The results are tabulated in the table 5.2

TABLE: 5.2 Spectral reflectance and topsoil resistivity values of the sampling sites

Sl.No.	Location	Top soil Resistivity values	Spectral Reflectance
1.	Chawla	3 – 6 ohm-m	Low
2.	Dichaun	3- 9 ohm-m	Low
3.	Bamnauli	10 –15 ohm-m	Moderate
4.	Jhatikra	10 – 12 ohm-m	High
5.	Dwarka	10 –20 ohm-m	High

Table 5.2 indicates that Chawla and Dichaun areas, having low spectral reflectance values and lower topsoil resistivity values are underlained with saline groundwater. Similarly moderate to high spectral reflectance values and higher resistivity values for Bamnauli, Jhatikra and Dwarka areas suggest that those areas are having less

saline or fresh water. These results show a reasonably good correlation with that of the chemical analysis data of the groundwater samples collected from the resistivity survey sites (Tables: 5.3 and 5.4). (Source: CGWB report, 1999).

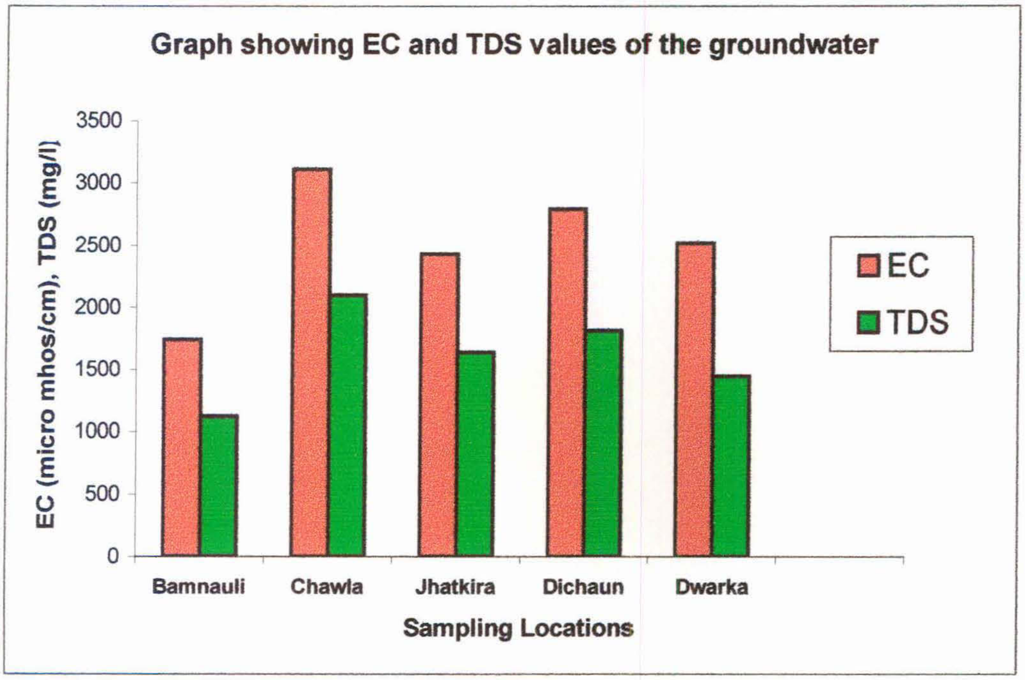
TABLE: 5.3 Major anion composition of the groundwater.

Location	EC	TDS	CO_3	HCO_3	Cl	SO_4	NO_3	F	PO_4
Bamnauli	1743	1122	Nil	1101	87	32	11	3.65	0.1
Chawla	3110	2100	Nil	406	658	400	130	1.84	0.04
Jhatkira	2430	1640	Nil	824	326	240	59	0.81	0.07
Dichaun	2790	1816	Nil	519	584	338	178	3.69	0.05
Dwarka	2520	1450	Nil	361	718	30	2	1.09	0.09

TABLE: 5.4 Major cation composition of the groundwater.

Location	EC	TDS	Ca	Mg	Na	K
Bamnauli	1743	1122	19	17	420	2.5
Chawla	3110	2100	18	136	345	6.5
Jhatkira	2430	1640	65	76	445	8.6
Dichaun	2790	1816	126	124	420	11
Dwarka	2520	1450	169	117	195	15

Fig: 5.11 Graph showing Electrical Conductivity, EC (in µ mhos/ cm), and Total Dissolved Solids, TDS (in mg/l) of the groundwater samples collected from the resistivity survey locations.



From this graph, it can be observed that the EC values as well as TDS values, which represent the total amount of ions in the groundwater, are higher at Chawla and Dichaun as compared to that at Bamnauli, Jhatkira and Dwarka. This represents low resistivity value at Chawla and Dichaun.

The land use and land cover map of the study area also shows more stressed vegetation at Chawla and Dichaun area, which is attributed to the saline groundwater.

CONCLUSION

The Electric Resistivity methods have proved it's utility in the groundwater studies. The methods are important for the qualitative as well as quantitative studies. The technique has been successfully used for the delineation of the saline water zones. The Geophysical survey can also be used in dealing with the problem of saline water encouragement in coastal water encroachment in coastal belts of the country etc. The results provided valuable information on the hydrological framework of the alluvial aquifers.

The combination of Remote sensing and electrical Resistivity can be immense importance in hydrological studies. The Remote sensing by virtue of its synoptic coverage, spectral and temporal attributes can be of great help in identifying the areas under stress.

Though the remote sensing is of limited use in groundwater studies. But the technique can provide the useful information through the indirect evidences for example by using the Vegetation anomaly or geochemical anomalies. The advantages like easy accessibility and the synoptic coverage of the remote areas of remote sensing supercedes the limitations of the remote sensing.

The VES survey of the area has indicated that in the study area major part of the alluvium column comprises of clayey material. The clay zones because of their impervious nature prevent both vertical as well as lateral movement of groundwater as a results of which the water remains saline in the semiarid areas.

Study of the area has indicated that the groundwater is saline through out the Najafgarh and only some regional variations can be seen which are also confined in the top layer.

The possible reason for the salinity is the presence of clayey horizon in the area, which accounts for the poor hydraulic conductivity of the aquifer.

The Electrical resistivity surveys could have been of great importance, if they would have been conducted in conjunction with the other geophysical methods such are electrical logging etc. Results from the surveys could have been more informative if the surveys were done in more systematic way i.e., using the profiling technique. But due to the lack of time it was not possible to analyze the whole area by resistivity surveys.

REFERENCES

Archie, G.E., (1942). The Electrical Resistivity Log as an aid in determining some reservoir characteristics. Trans. Am Ins. Min. Metall. And petr- Eng V. 146, pp 54-67.

Arcone, S.A., (1981). Some field studies of the correlation between electromagnetic and direct current measurements of ground resistivity, underground corrosion. Am-Soc-Terst. Mater., Spec. Tech- Publi. 741: 92-110.

Awasthi, S.C., and Prasad M. (1992) Palaeovolcanism in Sohna area, Gurgaon district, Haryana. Records Geol. Survey India. 115, 1-3.

Ayers, J.F., 1989. Conjunctive use of geophysical and geological data in the study of an alluvial aquifer. Ground Water, vol. 27, no. 5, pp. 625-632.

Baron, VA, Alfoldi L., Vekerdi Z, Galfi J, and Sheko A1 (1988) Investigation methods. Geology and the Environment, UNESCO, pp 37-54.

Bavaji J.R., (1988). Electrical resistivity technique for fresh saline interface demarcation in Bhatinda district, Punjab. Geophysics research bulletin, vol. 26, no. 1

Bhanumurty, Y. R., Dimri, D. B., Hassan, Y., (1978). Geophysical investigations for the geotechnical project of Delhi metropolitan area. Geol. Surv. India, Misc. Pub. No: 43, pp 35-43.

Bugg, S. F., and Lloyd, J.W., (1976) A study of fresh water lens configuration on the Caymen Islands using resistivity methods, Quaterly Jour. Engrng. Geol., v. 9, pp. 291 -302.

Cahyna, F., (1985). Dipole Electromagnetic profiling by EM-31 the hydrogeological survey. Proc-8th Conf. Geophys., Sect. S4, Ceske Budcejovice, 68 pp.

Cartwright, K.,and McComas, M.R.,(1968). Geophysical surveys in the vicinity ofsanitary landfills in Northerneastern Illinois, Ground Water, v. 6, no. 5, pp. 23-30.

CGWB Report, (1999) Status of groundwater quality and pollution aspects in NCT- Delhi.

Chandu, S. N. (1997). Geomorphological modeling through linear discriminant analysis for evaluation of groundwater potentiality – a case study from Jhansi district, UP. In Geographical Information Systems and Remote Sensing Ed. I. V. Muralikrishna. Allied Publ. Hyderabad. India. 376-385.

Choudhary, A.K; Gopalan, K; and Shastry, C.A., (1984). Present status of the Geochronology of the Precambrian rocks of Rajasthan. Technophysics, 105, 131-140.

Chudacek, S., Landa, I., Mazac, O. and Cahyna F., 1982. Detection of Agricultural pollution by Geolectric methods. Int. Symp. IAH, Mem. XVI (1) : 151-162.

Compaigne Generate de Geophysique, Master curve for electrical soundings, 2nd rev. ed., European Assoc. Exploration Geophysicists, The Hague, Netherlands, 49 pp., 1963.

Cox, A.S. and Saunders WR (1991) Application of Electromagnetic and Ground penetrating radar geophysical techniques for identifying zones of potential subsurface contamination Geonics Documents, Ottawa.

Cracknell, A.P. and Nirala, M. L. (1997). Remote sensing data in hydrological studies of the doon basin in Scotland, In. Geographical Information Systems and Remote Sensing Application. Ed. I. V. Muralikrishna. Allied Publ. Hyderabad. India. 361-366.

Dakhnov, V.N., (1955) Electrical Investigation of oil and Gas deposits. Gostroptekhizalat, Moscow, 497 pp. (in Russian)

Das, Brijraj, K., Kakar, Y.P., Moser, H. and Stichler, W. (1988). Deuterium and Oxygen-18 studies in groundwater of the Delhi area, India. Jour. Hydrol.,v.98, pp.133-146.

Datta, P.S., Bhattacharya, S.K. and Tyagi, S.K. (1994). Assessment of groundwater flow conditions and hydrodynamic zones in pheratic aquifers of Delhi area using Oxygen - 18. Proc. Intn. Workshop on "Groundwater Monitoring and recharge in semi-arid areas", Hyderabad. IAH/UNESCO Publn. S IV, pp.12-24.

Dobrin, M.B., (1976). Introduction to Geophysical prospecting, 3rd edition McGraw Hill, New York, 630 pp.,

Drury, S. A., (1986). Remote sensing of geological structures in temperate agricultural terrain. Geol. Mag. 123: 113-121.

Duprat, A., (1991) Geophysics applied to water exploration, CGG Technical series, Paris.

Ebraheem, A.M., M.W. Hamburger, E.R. Bayless and N-C. Krothe, (1990), Application of Earth Resistivity methods to study ground water contamination at the wheat land reclamation site, southwestern Indiana: Ground water v-28, no.3, p. 361-368.

Erikson, E. (1976). The distribution of salinity in groundwater of the Delhi region and recharge rates of groundwater. In: Interpretation of Environmental isotope and hydrochemical data in groundwater hydrology, International Atomic Energy Agency, Vienna, pp.171-177.

Griffith, D.H. and King, R.F., (1965). Applied Geophysics for Engineers and Geologists, Perganeon, Oxford, 223 pp.

Grinbaum, I.I., (1965). Determination of Filteration properties of Rocks by Geophysical Methods. Nedra, Moscow, 186 pp.

Gupta, S.N; Arora, Y.K., Mathur, R.K; Iqbaluddin, Prasad, B; Sahai, T.N. and Sharma, S.P. (1980). Lithostratigraphic map of the Aravalli region and NE Gujarat. Published by Geological Survey of India.

Hackbrath, D. A., (1971). Field study of subsurface spent sulfite liquor movement using earth resistivity measurements, Ground Water, v. 9, no. 3, pp. 11-16.

Halevy, E., Moser, H. and Zuber, A., (1967). Borehole dilution techniques: A critical review. Isotopes in Hydrology, IAEA Vienna, p. 531-564.

Hatherton, T., et al., (1966) Geophysical methods in Geothermal prospecting in New Zealand, Bull. Volcanol., v. 29, pp. 485 - 498.

Heron, A.M. (1935) Synopsis of the previndhyan geology of Rajputana. Trans. Nat. Inst. Sci. India, 1: 17-33.

Heron, A.M; (1953). The Geology of Central Rajputana, Mem Geol. Surv. Indra 79: 389 p.

Kashkovsky, G.N., Fomenko VI and Sokolovs Kaya LA (1989) Methods of Hydrogeological & Geotechnical forecasting. Geology and the Environment, UNESCO, pp 76-84.

Keller, G.V., (1979). Resistivity surveys and Engineering problems, Geophysical methods in Geotechnical Engineering. ASCE Natl. Conv., pp.1-50.

Keller,G.V. and Frischknecht, F.L., (1966). Electricals in Geophysical prospecting. Pergamon, New York, N.Y., 517 pp.

Kelly, W. E., (1985). Surface geoelectrics for detecting and monitoring ground-water pollution. 2nd Ann. Geotech. Semin., Omaha, Nebr.

Kelly, W.E. (1976), Geoelectric sounding for delineating Ground water Contamination: Groundwater, V-14, no1, p.6-10.

Kelly, W.E. (1977), Geoelectric sounding for estimating aquifer conductivity, Ground Water, v 15, pp. 420-425.

Kelly, W.E., Powers, M.A. and Virgadamo, P.P. (1983). Ground water Pollution: Assessment and Control. Proc. Natl-Conf. Environment Eng., ASCE, Boulder, Colo., pp. 556-560.

Keofoed, O., (1979).Geosounding principles, 1, Resistivity Sounding Measurements. Elsevier scientific publishing co., New York. 276 pp.

Klefstad, G., et al., (1975). Limitations of the electrical resistivity method in landfill investigations, Ground Water, v. 13, pp. 418-427.

Klimas and shleinius S (1994) Urban Hydrogeology. Problems of subsurface research, utilization and protection in Lithuania. Proceedings. Vilnius-pp 122-123.

Komatina M (1990) Ground water protection, hydrogeological investigation III. Applied Hydrogeology. pp 237-387 Geczavod, Beograd.

Kosinki, W-K. , (1981). Geoelectric soundings for predicting aquifer properties. Ground water, 19 (2): 163 – 171.

Kouranne, L.K. and Lahermo p (1989) General methods to identify and measure the impact of mining on the environment. Geology and the Environment, UNESCO, pp55-59.

Mares, S., Karous, M., Landa, I., Mazac, O., Muller, K- and Mullerova, J., (1983). Geophysical methods in hydrogeology and engineering geology SNTL, Praha, 198 pp. (in Czech).

Maskova and Mazac (1985). Increased information capacity of vertical electrical sounding. Proc. Int. Symp. Hornicka Pribram, Sect. Math. Methods Geol., Pribram.

Mazac, O. and Landa., (1983). Applicability of surface geophysical methods in determining migration parameters. Methodol. Man., Geofond, Prague, 32 pp. (in crech).

Mazac, O., Kelly, W.E. and Land, I., (1985). A hydrogeophysical model for relations between electrical and hydraulic properties of Aquifer. J. Hydrol., 79 : 1-19.

Mazac, O., Landa, I.., and Skuthan., (1978). Complex of Geophysical and Hydrogeological methods for construction of prognostic maps of contamination. Proc- 22nd Int. Geophys. Symp., Prague, pp-233-252.

Mazal, O, and Land, I., (1978) a. The Application of vertical Electrical sounding in treating problems of Ground water contamination by petroleum hydrocarbons. Proc. Int syup. Ground water Pollut. Oil Hydrocarbons, Prague, pp. 351-361.

Mazzac, O., W.E. Kelly and I. Landa, (1987), Surface geoelectrics for Groundwater pollution and protection studies: Journal of Hydrology, V. 93 no.3 p. 277-294.

Mc Neill, J.D., (1980). Electromagnetic terrain conductivity measurements at low induction numbers. Geonics Tech. Note TN-6, 15 pp.

Merkel, R.H. (1972). The use of Resistivity techniques to delineatge acid mine drainage in ground water: Ground water, V.10, no.5, and p.38-42.

Mikalauskas, V.V., (1976) Ground water protection in Lithuawa Vilnius: Mokislas. 112 pp (in Russian)

Mooney, H.M., (1980). Handbook of engineering Geophysics, vol. 2: Electrical resistivity. Bison instruments, Minneapolis, Minn.

Morris, D. B., The application of resistivity methods to groundwater exploration of alluvial basins in semi-arid areas, Jour. Instn. Water Engrs., v.18, pp. 59-65, 1964

Mukherjee, S., (1988). Groundwater pollution - An environment hazard. Proc. Nat. Sem. on advances in groundwater hydrology and management of Irrigated lands, February 25, SVRCET, Surat, pp. 176 - 177.

Mukherjee, S., (1991). Use of Remote sensing techniques in detection of groundwater salinity in a part of Hamirpur district, Uttar - Pradesh. Proc. International geological correlation programme 264, Remote sensing spectral properties. December 2 - 12, Pune, India pp 48.

Mukherjee, S., (1995). Application of remote sensing techniques in evaluation of groundwater pollution. Chapter - 16, pp 230 - 239. " Remote sensing in Geography Ed. S.M. Rashid, Manak publications. New- Delhi.

Mukherjee, S., (1996). Targetting saline aquifer by Remote sensing and Geophysical methods in a part of Hamirpur- Kanpur, India. Hydrology Journal. Vol. xix (1) pp 53-64.

Mukherjee, S., and Sarin, V., (1990). Targetting potential groundwater sites in parts of Jhansi district, Uttar Pradesh by using Satellite Remote sensing techniques. Proc. AIS on GWIMGT, Dec. 11 -12, C.G.W.B. Lucknow.

Mukherjee, S., and Sarin, V., (1991). Groundwater appraisal report, Hamirpur district, Uttar-Pradesh (based on Remote sensing and Geophysical techniques) unpublished, Tech. Report. URSAC.

Muudry, E., (1984). Geoelectricaal model calculationsfor two dimensional resistivity distribution. Geophys. Prosp., 32 (1) : 124 -131.

Nirei H, Sath K, Furunok and Sujuki Y (1992) Geopollution in case of volatile chlorinated organic compounds. Proceedings of 29th IGC; Kyoto, Japan, pp 1-5.

Page, L. M., (1968). Use of the electrical resistivity method for investigating geologic and hydrogeologic conditions in Santa Clara country, California, Groundwater, v. 6, no. 5, pp.31-40

Roy, A.B. (1988) Stratigraphic and tectonic framework of the Aravalli mountain range. In A.B. Roy (Ed.) Precambrian of the Aravalli mountain, Rajasthan, India. Memoir of Geol. Soc. India-48: 49-54.

Sabiens, F. F. Jr. (1997). Remote sensing: Principles and Interpretation. (3rd ed) W.H. Freeman and Co., New York. 495p.

Seth, N.N and Khanna,, S.P (1969). A note on groundwater conditions in Delhi Area. Geological survey of India Misc. Publn. No. 14, part III, pp. 101-110.

Sharapanov, N.N., 1974. Methodology of Geophysical Investigation for Hydrogeological Mapping for sand Improvement purposes. Nedras, Moscow (in Russain).

Shco Prasead Verma, K.P; Singh, R. and Powar M.M (1993) Second Generation mapping and geochemical mapping of the rocks of Delhi super group in Haryana. Records of Geol. Survey, India, 125: 69-72.

Shestakova, V.M. and Orlova MS (1984) Gidrogeologia, M.G.U. pp 283-303 MGU, Moscow.

Skuthan, B., Mazac, O. and Land, I., 1986. The importance of Geophysical methods for protecting Ground waters from Agricultural pollution. Proc. J Geol Sci, Sect. App. Geophysics.

Sloggett, D. R. and McGeachy, C., (1986). EARTHSCAN- A range of remote sensing systems. Symp. On Remote Sensing for resources development and environmental management/ Enschede: 167 – 171.

Stollar, R.L; and P. Roux, (1975), Earth Resistivity surveys – a method for defining Ground water contamination: Groundwater, V.13, no.2, p. 145-150.

Svoma, J., (1978). Location and area measurement of rock and groundwater oil contamination by surface methods. Proc. Int. Sympt. Ground water pollut. Oil Hydrocarbons, Prague.

Touloukian, Y.S. and C.Y. Ho (Eds). (1981). Physical properties of rocks and minerals. McGraw-Hill/ CINDAS Data Series on Material properties. II-2 548 pp.

Tyagi, A. (1980) Mineralogical and Geochemical changes leading to the formation of clay deposits in the Mehrauli Area, South Delhi. Ph.D. thesis, Delhi- University.

Vinegar, H.J. and M.H. Waxman. 1984. Induced Polarized of shaly lands. Geophysics V.49, pp. 1267-1287.

Ward, S.H. (1967). Conduction of electricity in rocks. In Mining Geophysics. Societies of Exploration Geophysicists V.2, pp 198-223.

Warner, D.L, (1969). Preliminary field studies using earth resistivity measurements for delineating zones of contaminated Ground water: Groundwater, V.7, no.1, and p.9-16.

Zohdy, A.A.R., G.P. Eaton, and D.R. Mabey, (1974). Application of surface geophysics to Groundwater investigations; in techniques of water resources investigations; US, Geological survey, Books 2, Chapter D1, 116 p.