CHAPTER 2

PRINCIPLE AND THEORY

This chapter concerns principles and theories of electrical resistivity and very low frequency electromagnetic methods. Both techniques depend upon the electrical properties of rocks and minerals. The most common interest in this study is the electrical resistivity of leachate, or contaminated groundwater. Some hydrochemical parameters (chloride and total dissolved solids) may be used to indicate the apparent resistivity value. Resistivity survey data can be obtained from different field procedures, different electrode configurations and different conceptual resistivity models at landfill sites. VLF data can be interpreted in terms of apparent resistivity by transforming, or filtering, to current density values. The applications of both methods at the landfill site are explained in the last parts of this chapter.

2.1 Electrical resistivity method

The purpose of electrical resistivity surveys is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements the true resistivity of the subsurface can be estimated. The ground resistivity is related to various geological parameters, such as the mineral and fluid content, porosity and degree of water saturation in the rocks. Typical resistivity values for different types of subsurface materials and the geology of the area surveyed are illustrated in Table 2.1. Electrical resistivity surveys have been used for many decades in hydrogeological, mining, and geotechnical investigations. More recently, they has been used for environmental surveys.

Table 2.1 Resistivities of some common rocks and other materials.

(modified from Loke, 1999 and Vogelsang, 1995).

MATERIAL	RESISTIVITY (OHM-M)
Igneous and Metamorphic Rocks	
Granite	$5\times10^{3}-10^{6}$
Basalt	$10^{3}-10^{6}$
Slate	$6\times10^{2}-4\times10^{7}$
Marble	$10^{2}-2.5\times10^{8}$
Quartzite	$10^{2}-2\times10^{8}$
Sedimentary Rocks	
Sandstone	$8 - 4\times10^{3}$
Shale	$20 - 2\times10^{3}$
Limestone	$50- 4\times10^{2}$
Soils and Water	
Clay	1-100
Alluvium	10-800
Groundwater (fresh)	10-100
Sea water	0.2
Chemicals	
Iron	9.07×10^{-8}
0.01 M Potassium chloride	0.71
0.01 M Sodium chloride	0.84
0.01 M acetic acid	6.13
Xylene	7×10^{16}
Deposited Refuse	
Domestic garbage	12-30
Industrial mud	40-200
Scrap metal	1-12
Wastepaper (wet)	70-180
Contaminant plume	1-10
Used oil	150-700
Cleaning clothes and materials	30-200

Resistivity measurements are normally made by injecting current into the ground through two current electrodes (C1 and C2 in Figure 2.1) and measuring the resulting voltage difference at two potential electrodes (P1 and P2). From the current, I, and voltage, V, values, an apparent resistivity, ρa, value is calculated.

$$\rho a = k\, V / I$$

where k is the geometric factor that depends on the arrangement of the four electrodes.

The calculated resistivity value is not the true resistivity of the subsurface. It is an apparent value that is the resistivity of a homogeneous ground that will give the same resistance value for the same electrode arrangement. The relationship between the apparent resistivity and the true resistivity is complex. To determine the true subsurface resistivity, an inversion of measured apparent resistivity values must be carried out using a computer program.

The arrangement of current electrodes and potential electrodes is variable. Over the years, many variations have been tried, however, only four are in popular use (Figure 2.1). These four are:

(1) Wenner array, all electrodes equally spaced.

(2) Schlumberger array, the current electrodes are spaced much farther apart than the potential electrodes.

(3) Pole-dipole (three-point) array, one of the current electrodes is fixed at a great distance from the other three.

(4) Dipole-dipole array, current electrodes close together and potential electrodes close together, but the two sets are relatively far apart.

There are two basic plans for field mapping with electrical resistivity. Conventional sounding surveys are normally used. In this method, the center point of the electrode array remains fixed, but the spacing between the electrodes is increased to obtain more information about the deeper sections of the subsurface.

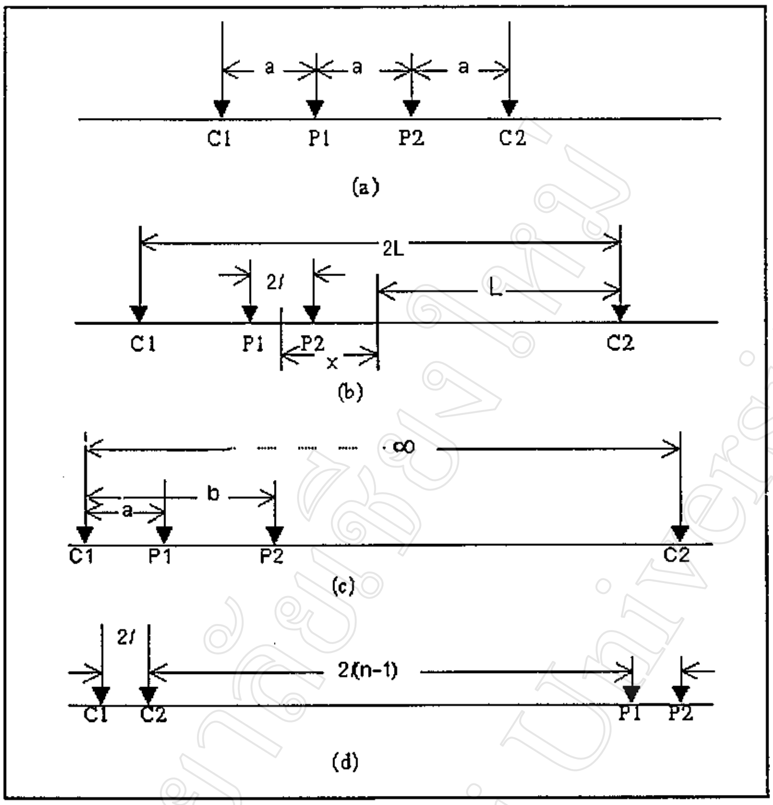


Figure 2.1 Electrode arrays in common use. (a) Wenner, (b) Schlumberger, (c) Pole-Dipole, (d) Dipole-Dipole (Telford *et al.*, 1990).

The measured apparent resistivity values are normally plotted on log-log graph paper. To interpret the data from such a survey, it is normally assumed that the subsurface consists of horizontal layers. In this case, the subsurface resistivity changes only with depth, but does not change in the horizontal direction. A one-dimensional model of the subsurface is used to interpret the measurements. Another classical survey technique is the profiling method. In this case the spacing between the electrodes remains fixed, but the entire array is moved along a straight line. This gives some information about lateral changes in subsurface resistivity. Interpretation of data from profiling surveys is mainly qualitative.

In many engineering and environmental studies, the subsurface geology is very complex and the resistivity can change rapidly over short distances. The one-dimension resistivity method might not be sufficiently accurate for such situations.

Two-dimension and even three-dimension electrical surveys are now practical commercial techniques as a result of the relatively recent development of multi-electrode resistivity surveying instruments and fast computer inversion software (Loke, 1995).

2.2 Very low frequency electromagnetic method

Very low frequency electromagnetic surveying is a continuous-wave (frequency domain) electromagnetic technique that utilises high power, low frequency radio transmissions as a source. Normally, this frequency is between 15 and 30 kilohertz. Their primary use is in communication with submerged submarines and for long-range radio positioning. Some of the most useful very low frequency transmitting stations are shown in Appendix B.

Sensed at a distance greater than a few tens of kilometers, electromagnetic transmissions act as plane waves propagating outwards horizontally. When these waves intersect a buried conductor they induce eddy currents that generate a secondary magnetic field concentric around the source of the currents. The strength of the eddy currents is greatest when the long axis of the conductor is oriented parallel to the direction of propagation, i.e., on a radial from the active transmitter. In this orientation the magnetic vector is acting tangentially.

Modern very low frequency electromagnetic instruments enable measurements to be carried out at a number of different frequencies in sequence in order to ensure optimum secondary field signal strength. However, the orientation of survey lines still has to be chosen to lie perpendicular to the expected orientation of targets. Figure 2.2 is a very simple schematic diagram that shows field induction caused by a fracture zone. Very low frequency electromagnetic surveys involve measuring the orientation (tilt-angle/dip-angle) of the vector summation of the primary (horizontal) and secondary magnetic field vectors. As the instrument passes perpendicularly over a vertical target the vector orientation changes from a maximum on one side to a minimum on the other side. The point at which the reading changes from positive to negative is termed the cross-over point and it lies directly above the conductor. If the conductor dips, then the anomaly shape will be distorted in either the positive or negative sense, depending on dip direction. The very low frequency electromagnetic method is primarily used in mineral exploration but has also been successfully applied in engineering and groundwater surveys to detect conductive fault zones and other sub-vertical conductors.

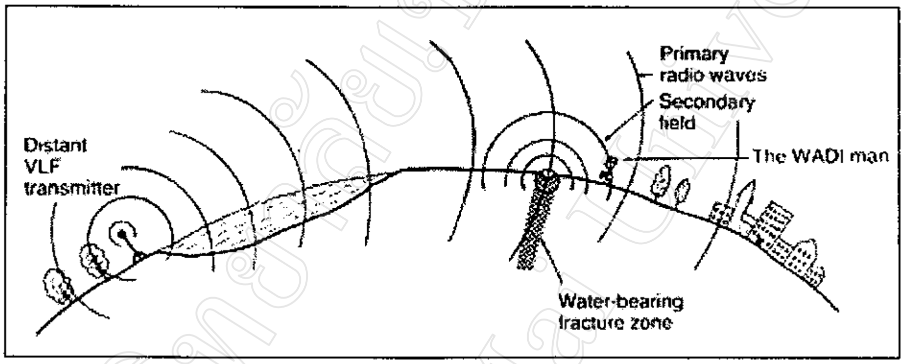


Figure 2.2 A schematic diagram of the VLF principle (WADI VLF instruction manual, 1991).

Data acquired during modern very low frequency electromagnetic surveys normally comprise at least three separate parameters of the secondary magnetic field, including the amplitude of the field and its quadrature (imaginary) and in-phase (real) components relative to the horizontal primary field. Results are presented as profiles against distance. Filtering of the real component, or dip-angle measurement, is often carried out in order to produce a maximum over the cross-over point (the point that lies directly over the anomaly), thus aiding interpretation. Advanced filtering of the real component of the secondary field can be used to produce a current density pseudosection. This provides an indication of current concentrations and their spatial distribution that approximately reflects the depth and location of sub-surface conductors.

2.3 The application of geophysical methods at hazardous wastes sites

There are three major areas for the application of geophysical methods at hazardous waste sites (Nielson, 1991). These are assessing hydrogeologic conditions, detecting and mapping contaminant plumes, and locating and mapping buried wastes and utilities.

2.3.1 Assessing hydrogeologic conditions

A variety of geophysical methods can be used to assess natural hydrogeologic conditions such as depth to bedrock, degree of weathering, and presence of sand and clay lenses, fracture zones, and buried relic stream channels. Accurately understanding the hydrogeologic conditions and anomalies can make the difference between success and failure in site characterization because these features will often control groundwater flow and contaminant transport.

2.3.2 Detecting and mapping contaminant plumes

A major objective of many site investigations is the detection and mapping of contaminant plumes. Geophysical methods can be employed in two ways to solve this problem. Some methods can be used for the direct detection of contaminants. In cases in which the contaminant can not be detected directly, geophysical methods can be used to assess the detailed hydrogeologic conditions that control groundwater flow. Then, the location of the contaminants can be estimated and the groundwater and contaminant flow pathways can be identified.

2.3.3 Locating and mapping buried wastes and utilities

Geophysical methods can also be used to locate and map the areal extent, and sometimes the depth, of buried wastes in trenches and landfills. There are methods that can also be employed to detect buried drums, tanks, and utility lines. In many cases, the trenches associated with buried pipes and utilities will be of interest because they form a permeable pathway for contaminant migration.

2.4 The application of resistivity survey at landfill sites

An objective of many site investigations is the location and mapping of inorganic or organic contaminant plumes. Inorganic contaminants from landfills, as well as salt brines, acid spills, and natural salt-water intrusion, are detectable by electrical methods because of their high values of specific conductance. For example, electromagnetic profiling measurements will often allow the detection and lateral mapping of landfill leachate or inorganic chemical spills. Sounding measurements with resisitivity or time domain electromagnetic can provide the vertical extent of inorganics plumes. Time series measurements can be made to map the changes in lateral and vertical movement of inorganic contaminants over time. Even measurements of subtle changes in soil salinity can rapidly be made. Hydrocarbons or other organic chemical contaminants are not generally detectable by geophysical methods at the typical parts per million and parts per billion levels of regulatory concern. Furthermore, highly water soluble organics, such as alcohol, are not detected by geophysical methods even at much higher concentrations.

Of the several non-invasive geophysical methods used in landfill studies, the electrical and electromagnetic methods are the most popular owing to their inherent ability to detect changes related to variations in fluid content, chemical composition, and temperature in the subsurface. Since the presence of saline fluids in the ground enhances its ability to conduct electrical current, it is possible to locate a contaminant plume by measuring the resistivity distribution in the subsurface.

In order to understand how the attendant processes in landfill environments can influence geoelectrical measurements, it is instructive to examine the consistent features of models derived from geological, geotechnical, biological, and biogeochemical observations on landfills (plus other contaminated lands) and rock weathering so that these features can be adopted as the basic building blocks for any geoelectrical model for landfill sites.

2.4.1 Nature and characteristics of anthropogenic deposits

Landfill deposits are characterised by complex material composition. The deposits may be mixtures of domestic and industrial wastes, soils, and exhumed geological materials. The wastes in old landfill sites may not be as well compacted as in modern regulated landfill practice and will, thus, have substantial internal permeability. They will, in general, consist of degradable and nondegradable materials, such as food and garden wastes, ashes, paper, textiles, plastics, metals, building waste, mill tailings, and organic liquids, but it is their chemical composition (Table 2.2) that is important when assessing their potential for groundwater pollution.

Some of the common industrial wastes are listed in Table 2.2. Many of these wastes ultimately find their resting places in landfill sites. Methylene, chloride, trichloroethylene, toluene, and m-xylene are among the hazardous organic compounds most commonly found in landfill sites. Since landfills are a complex mixture of anthropogenic deposits, their physical properties would show a wide range of variation. For example, the published resistivity of solid waste and contaminated substrate ranges from 1.5 to 20 ohm-meters with the associated leachate being highly conductive.

2.4.2 Physico-chemical and microbial weathering

The composition of a leachate will change as the refuse in the landfill ages. In general, the leachate from a young landfill may be characterised by high levels of organic acids, ammonia and total dissolved solids, but as much of the biodegradable mass is

Table 2.2 Some industrial wastes commonly buried in landfill sites (Meju, 2000).

Source	**Type of waste**	**Approximate composition**
Food and food products		
Additives	Trimmings	Organics and acids
Grain mills	Residues	
Meat / fish	Sludges	
Paper and paper products	Sludges, pulping sludges	Sulphates, organics, soaps, mercaptans
Soaps, detergents	Sludges	Surfactants, polyphosphates, aluminium–copper–oxides
Textile products: silk, cotton, wool, synthetics	Sludges	Acids, alkalis, metallic salts, solvents
Leather products	Sludges	Chrome salts, oils, dyes
Wood and wood products	Sludges, residues / mill tailings	Solvents, preservatives
Paints, varnishes	Sludges	Metallic salts, toxic liquids
Energy and petroleum coal, nuclear and petroleum refining	Sludges, residues, cindered coking, fly ash	Hydrocarbons, acids, metallic salts, radioactive materials
Metals, fabricated / scrap metals	Sludges, slag, slime, tailings scrap heap	Sulphur, chlorides, phenols, PCBs, oils, grease, chrome, alkalis, acids, metallic salts
Mining / mineral processing	Sludges, mine tailings	Acids, cynanide, metallic salts
Chemicals, fertilizer	Sludges	Sulphuric acids, organo-phosphates, copper sulphate, mercury arsenates

broken down with time, the concentrations of these parameters will decrease in the leachate produced from the ageing landfill (Table 2.3) .The leachate may contain toxic or hazardous substances in solid or gaseous forms and these might show up as high concentrations of chloride, iron, and zinc ions. Those elements with high ionic mobility generally have the highest concentration while those having low ionic mobility usually have the lowest concentration in leachates (Meju, 2000). The transport of leachate through the landfill is slow, unsteady, non-uniform, and sometimes discontinuous depending on the degree of compaction of the fill and seasonal changes in water supply to the system.

Table 2.3 Typical changes in leachate concentrations with age of refuse (Meju, 2000).

Parameter	**Age of refuse**			
	0–5 years	5–10 years	10–20 years	>20 years
TDS	10,000–25,000	5,000–10,000	2,000–5,000	<1,000
pH	5–6	6–7	7–7.5	7.5
BOD	10,000–25,000	1,000–4,000	50–100	<50
COD	15,000–40,000	10,000–20,000	1,000–5,000	<1,000
Ammoniacal Nitrogen	500–1,500	300–500	50–200	<30
Total Phosphorus	100–300	10–100		<10
Chloride	1,000–3000	500–2,000	100–500	<100
Sulphate	500–2,000	200–1,000	50–200	<50
Calcium	2,000–4,000	500–2,000	300–500	<500
Sodium + potassium	2,000–4,000	500–1,500	100–500	<100
Magnesium + iron	500–1,500	500–1,000	100–500	<100
Zinc + aluminium	100–200	50–100	10–50	<10
Alkalinity	10,000–15,000	1,000–6,000	500–2,000	<500

* All quantities are in mg / l (except pH in standard units).

Within the landfill, this liquid may collect in various areas, e.g., perched saturated zones or mounds at the bottom of the landfill. This leachate starts seeping as soon as enough hydrostatic head is developed. On passing through the base of the landfill, metal ions in solution may be removed from the aqueous phase by ion exchange, apsorption or precipitation onto the substrate, especially if the substrate is clayey. However, organic carbon in colloidal form in the leachate often has higher cation exchange capacity than clay and can absorb high concentrations of metal ions from solution, as can some inorganic colloids which form under certain chemical conditions. Metal ions absorbed preferentially onto the surface of colloidal particles may, thus, bypass the natural attenuation processses as the leachate seeps into the substrate. Within the substrate, the leachate mixes with groundwater, forming a leachate plume. Initially, on entering an anaerobic groundwater system, the organic material in the leachate is slowly biodegraded to form more acids that, in turn, may react with aquifer materials and cause changes in the fluid chemistry near the water table. In this deoxygenated environment, inorganic materials in the leachate, e.g., iron, and manganese may be dissolved in the groundwater. The dispersing leachate extends laterally and vertically as it sinks towards the bottom of the substrate, thus forming a three-dimension contaminant plume that may be steeply dipping (Figure 2.3). The amount of groundwater contamination resulting from this invasion will depend on the hydrogeology of the area and the attenuation capacity of the substrate. It may be effectively diluted and dispersed by groundwater in highly permeable formations that have high flow rates. Given enough time in less permeable formations, or with slowly moving groundwater, the plume laden with inorganic salts may enhance the mineralisation of groundwater. Since it is a moving and continuously evolving three-dimensional feature, the plume will in time be dispersed over a sizeable area, possibly with distinct compositional zonations.

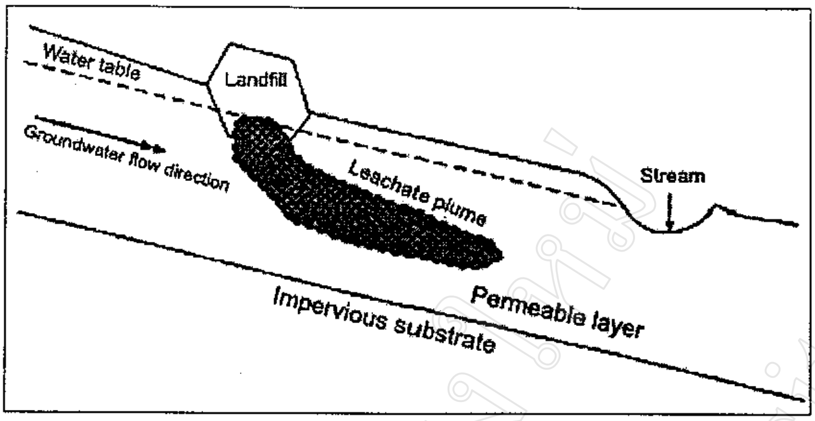


Figure 2.3 Geometry of a typical three-dimensional contaminant plume migrating downgradient from a landfill site (Meju, 2000).

2.4.3 Conceptual resistivity model

A conceptual resistivity model can be developed in line with the above biogeomorphic and hydrochemical considerations since the observable geoelectrical response of landfill sites and environs will vary in relation to significant changes in the chemistry of subsurface pore fluids. Surface layers of refuse may experience rapid aerobic decomposition while the bulk of the waste at depth may have only been partially decomposed under anaerobic conditions, thus leading to different physical properties. For a leachate-generating landfill in contact with granular substrate, the interactions between the invading leachate and substrate material may cause geochemical alterations of substrate depending on its buffering and cation exchange capacities. Accordingly, several zones are recognised in the generalised conceptual model shown in Figure 2.4. The top soil and clay cap, i.e., zones 1 and 2, form the uppermost confining layers. The resistivity of the top soil will vary from region to region and with the season but the usually 0.3 to 1 meter thick clay cap will, in general, be relatively conductive. Landfill sites are notorious for high levels of soil gas, principally methane and carbon dioxide. Fractured clay caps would allow gas migration. The geoelectrical signatures of zones 1 and 2 will be affected by seasonal changes. In wet seasons, infiltrating water may drive out gas, thus lowering the bulk resistivity. Conversely, rising vapours in the dry periods will drive out soil moisture, causing an increase in bulk resistivity. The degree to which these changes are detectable will depend on the nature of the materials in zones 1 and 2. For instance, the influx of gas into pore spaces in some clays may cause appreciable resistivity increases if water or leachate is displaced. This would not occure in a highly resistive, dry, sandy topmost layer. If the cover materials are iron-rich, the rising methane and sulphur dioxide in landfills may cause the formation of a pyritic geochemical alteration halo. This halo would be similar to that formed over fractured hydrocarbon accumulations overlain by iron-rich sediments or redbeds. Such a halo might be detectable by three-dimension or time-lapse geoelectrical surveys.

The clay cap is underlain by a zone of pervasive leaching of refuse and residual products, i.e., zone 3 in Figure 2.4. This is the top part of the landfill waste where oxygen and bacterial supply are abundant and will, thus, decompose quicker than the deeper parts. The bulk resistivity of this oxidized zone will show a relative increase with time as the organics for microbial degradation become depleted in supply, the oxidation of inorganics tends towards completion, and much of the soluble elements are removed. The leaching of clay minerals from the original landfill-soil mixture would leave behind the non-degradable fill material and siliceous geomaterial. This residual material would have larger soil and rock grains and relatively higher resistivity than the parent landfill material. It may, thus, be relatively resistive in comparison with the clay cap and the underlying zone of incomplete refuse decomposition, i.e., zone 4. However, the rate of water flux through zone 3 will affect the zone's eventual resistivity characteristics. Fast water flows will cause higher resistivities and slow water flows will cause lower resistivities. Zone 4 occurs in the lower part of the waste deposit and is dominated by relatively immature leaching and will have relatively low bulk resistivities.

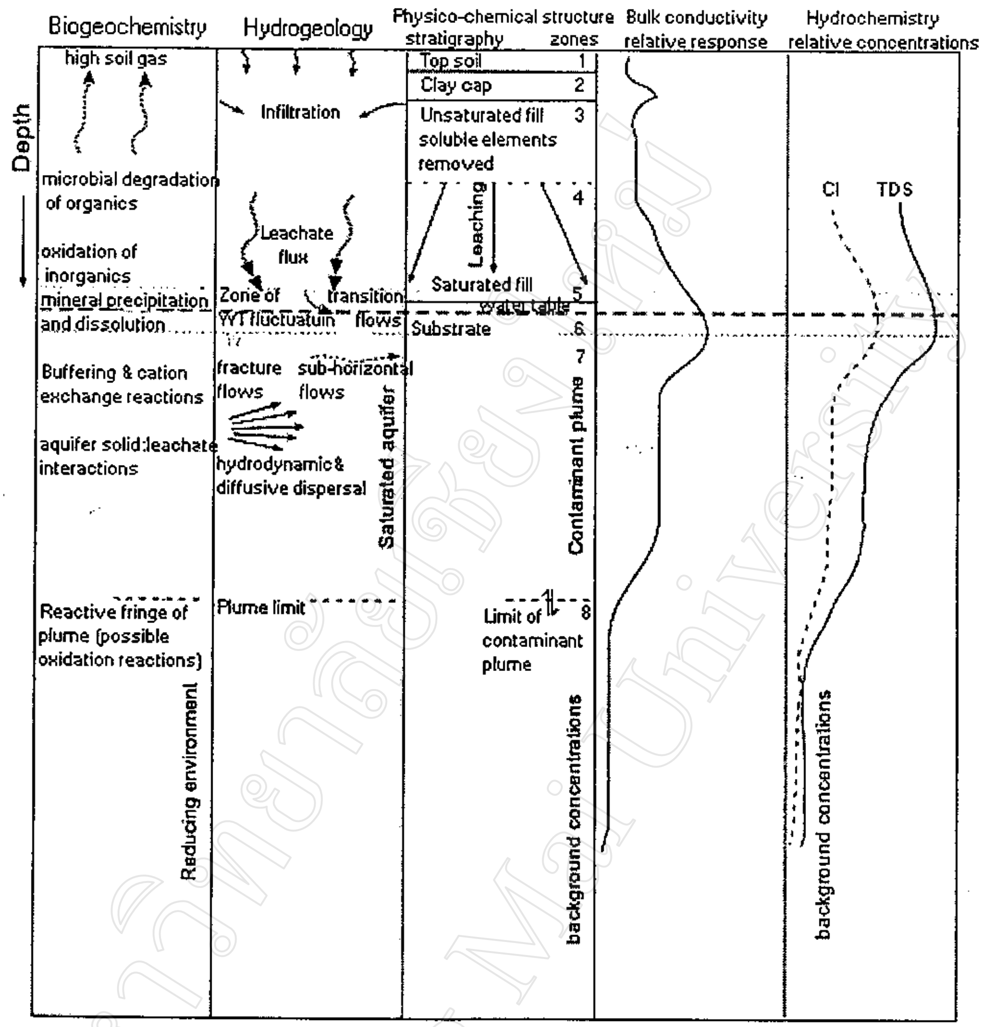


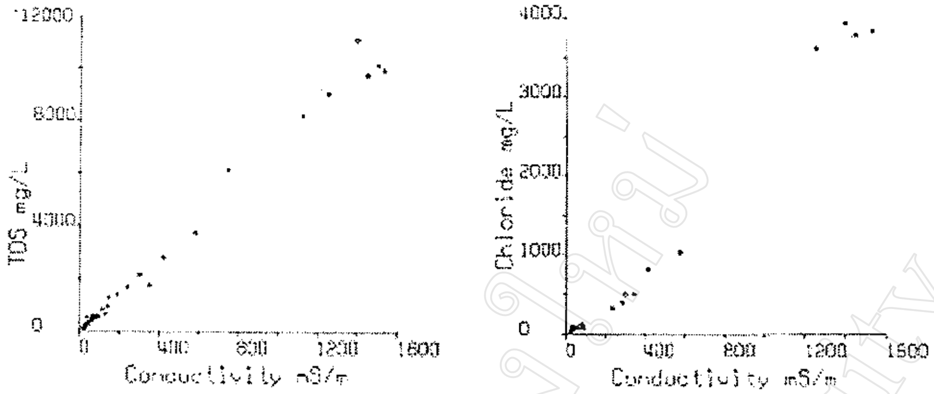
Figure. 2.4 A conceptual resistivity model for old landfill sites with leachate generation and migration into groundwater system in granular substrate and environs (Meju, 2000).

For a landfill resting on highly impermeable substrate, leachate mounding may occur in the basal part of the waste deposits and will render these basal part the most electrically conductive part of the entire landfilled section. However, if a landfill rests directly on a relatively permeable substrate saturated with groundwater, fluctuations in the water table may occur within a section that encompasses the basal part of the landfill zone 5 and the uppermost part of the substrate zone 6 as shown in Figure 2.4. The mineral salts and organic material leached from the fill materials will be deposited near the water table, depending on the local hydrogeological and Eh–pH conditions.

This deposition will be analogous to supergene enrichment of metallic sulphide minerals and chemical weathering of soils/rocks. It will cause an increase in total dissolved solids, which in turn, will cause an increase in electrical conductivity and other chemical parameters in the pore water. Due to water table fluctuations, the zone of deposition, or mineral enrichment, may extend from the basal part of the landfill into the upper part of the subjacent geological formation or may lie well beneath the base of the landfill, depending on the permeability, fluid saturation, groundwater flow, and dispersion characteristics of the substrate and the mobilities of the ions in solution. Below the water table, the leachate mixes with groundwater and reacts with substrate material, forming a relatively conductive plume, zone 7. Beyond the plume, the uninvaded substrate, zone 8, will have total dissolved solids and conductivity values intrinsic to the natural medium, i.e., background concentrations .

2.4.4 Relationship between geoelectrically important hydrochemical parameters

Electrical conductivity is usually taken as a measure of the total dissolved salts in groundwater by hydrogeochemists, whereas chloride content is used as a conservative leachate indicator parameter in water sample studies since, apart from dilution, it undergoes very little chemical or biological change in the groundwater system. To describe the relationship between groundwater conductivity and total dissolved solids and chloride content in the plume emanating from the landfill, data are shown graphically in Figures 2.5(a) and 2.5(b). There is an almost linear relationship between conductivity and total dissolved solids in Figure 2.5(a) and between conductivity and chloride content in Figure 2.5(b).



(a) (b)

Figure 2.5 (a) Relationship between fluid conductivity and total dissolved solids. (b) Relationship between conductivity and chloride concentration (Meju, 2000).

2.5 The application of a very low frequency electromagnetic survey at landfill sites

Electromagnetic surveys are especially adapted to mapping lateral difference of resistivity or conductivity. Possible targets are the borders of waste dumps, singular objects, and steep dipping structures, such as faults, fracture zones, and crevices, that may guide contaminated leachates.

Very low frequency electromagnetic survey results are comparable to those of resistivity mapping. However, very low frequency electromagnetic methods progress faster and cost less because there are no electrodes to be grounded. The evaluation is nevertheless more complicated, since instead of the simple Ohm's law, the complex formulae of Maxwell have to be used. Very low frequency electromagnetic survey is well geared to detect buried hazardous waste quickly and accurately, even under an extended area. However, the method has some disadvantages, the most important of which is its limited depth of penetration. In clay-bearing rocks with resistivities of less than 30 ohm-m, only a depth of approximately 15 meters can be reached. Apart from that, the nearly homogeneous field often omits small random structures, which are the common electromagnetic targets in hazardous dump sites.