TROUBLED WATERS: ENVIRONMENTAL APPLICATIONS OF ELECTRICAL AND ELECTROMAGNETIC METHODS

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Abstract. The relatively new subdiscipline of environmental geophysics has grown enormously in the last five years. The size and diversity of the field, and the associated literature, is such that it is extremely difficult to keep up with even a small portion of the field. Electrical and electromagnetic (E & EM) methods, including ground penetrating radar and time-domain reflectometry, play a central role in environmental geophysics. One reason for the utility of E & EM methods in groundwater studies is the similarity in the way that current flow and fluid flow depend on the connectivity and geometry of the pores in soils and rocks. Another reason is the influence of the pore water quality on the geophysical response. More than any other geophysical technique, E & EM methods are directly affected by the presence of conductive pore fluids in the subsurface, such as leachates from landfill sites and sea water invading a coastal groundwater supply that has been placed under stress because of population expansion. The chloride ion is one of the most electrically active of the naturally-occurring ions, and allows us to detect sea water incursion; leachates from landfill sites contain the by-products of organic decay, such as acetic acid, which are generally less conductive than chloride, but nonetheless enhance the pore water and formation electrical conductivities. Landfill leachate plumes are thus easily mapped. The shallow subsurface electrical and dielectric properties exhibit hysteresis due to seasonal changes in water content; the physical properties will be different for the same degree of saturation, depending on whether the water level is rising or falling. Topographic effects are also important; an empirical correction method works well to remove a background trend in the conductivity due to changes in elevation. Heterogeneity and anisotropy of the electric properties may be related to similar effects in the hydraulic properties. New technology and the adaptation of existing technology has lead to the development of fresh instruments, such as electrode arrays towed across the ground, resistivity logging while drilling, fast-rise time TEM, NMR combined with TEM, electric quadripole, et cetera. The applications of E & EM methods cover a wide range of geographic areas and groundwater problems, but have had particularly wide use for groundwater exploration in arid and semi-arid regions, for mapping and monitoring salt-water incursion in susceptible aquifers, and for mapping and monitoring contaminants.

1. Introduction

What is "environmental geophysics", and what place do electrical and electromagnetic (E & EM) methods have in this relatively new, and growing, field of endeavour? The variety of answers to the first question will be almost as great in number as the number of geophysicists who have become active in the field, and there have been some previous attempts to define what is meant by environmental geophysics (e.g., Greenhouse, 1991; Steeples, 1991; Won, 1992). My personal answer is that it concerns any use of geophysics in the near-surface, hence the use of the term "near-surface geophysics" has been growing so that a wide range of such applications may be embraced. That vague answer gives us,

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perhaps, the greatest flexibility. In some applications, the "near-surface" may be only the upper few metres, e.g. in archaeology, engineering and soil science; in other applications, the "near-surface" may be the top 200 metres, e.g. in studies of groundwater resource quantity and quality. Yet other applications include the scales between, e.g. mapping and monitoring of leachates from landfill sites. I, like most "near-surface" geophysicists, work on applications in most of these fields; most of us would therefore prefer to choose a definition that would include most of those applications. The majority of people, however, would probably expect the growing subdiscipline of environmental geophysics to be concerned primarily with the mapping and monitoring of a pollutant that may constitute a threat of some kind to the general populace. By "pollutant", I mean any substance that may cause a degradation of the quality of life, in particular the loss of a groundwater supply. This definition thus includes sea water incursion into a coastal ground water source. I will try to restrict my discussion to the narrower aspects of mapping and monitoring "pollution" from a variety of sources, all of which may threaten the water supply. We cannot, however, evaluate the threat to a groundwater supply without, first of all, knowing the structure and extent of the groundwater resources and possible groundwater flow paths. I will thus include the more general aspects of groundwater exploration.

This is still a daunting task. A search through one on-line literature data base yielded 1385 references for the period from 1988 to 1993 alone, for topics that related to the application of E & EM methods, including radar and time-domain reflectometry, to problems in groundwater studies, salt-water incursion, hydrogeology, and waste disposal. While this is a substantial number of references, it is only a fraction of the number of publications on E & EM methods generally. A search through the previous 200 years, from 1785 to 1987, yielded 1872 references, only 10 of which were published in the period before 1960. The oldest reference that fit the search criteria dated from 1940 (Johnston and Huberty), although references to an older study were located in a more traditional manner (Swartz, 1937, 1939). In contrast, 158 papers which fit the search criteria were found for the 1960–69 decade; almost 400 papers were found for the 1970–79 decade. This review will, of necessity, not cover all of the international literature, but will focus on some of the more accessible journals and reports, with a few additional reports included. Oddly, some previous reviews of environmental, engineering and groundwater geophysics had little, if any, coverage of E & EM methods. A special issue of *Geophysics* on engineering and groundwater geophysics (Romig, 1986) was entirely composed of papers about seismic applications, and a prior review article on geotechnical and groundwater geophysics (Dobecki and Romig, 1985) had only a small section on E & EM methods. This lack of coverage has been rectified, at least in part, in recent years by the publication of the set of volumes edited by Ward (1990) and by Nabighian (1987, 1991), and through special issues of *Geoexploration* (Chapellier *et al.*, 1991) and the *Journal of Applied Geophysics* (Chapellier *et al.*, 1994).

Electrical and electromagnetic (E & EM) methods, including ground penetrating radar (GPR) and time-domain reflectometry (TDR) since they involve the propagation of high-frequency EM wave energy, have the advantage of being widely available, fast and efficient methods. The purpose of this review is to discuss some of the E & EM techniques that may be specific to environmental geophysics (or some of the modifications that have been made to adapt E & EM methodology to environmental studies), to outline the background to the use of E & EM methods in environmental geophysics, and to mention some of the problems that may be faced in studies of the near-surface. This review is not exhaustive; the field is expanding too rapidly, and the literature is too diffuse to cover adequately in a single review. Instead, I will try to incorporate some of what I consider to be the major points. Most of the material here is not new, but is worth repeating in a different context – that of shallow geophysical surveying for environmental applications. Downhole E & EM logging is often a part of an environmental geophysical survey; there may a small degree of overlap between this review and that of Spies which deals with borehole applications (this volume). I will, however, concentrate on the environmental applications of E & EM borehole logging.

Before continuing, I should describe one problem that is encountered whenever the burgeoning field of environmental geophysics is reviewed, a problem hinted at earlier: the literature is widely scattered, so much so that it is almost impossible to have seen even a fraction of the publications on environmental geophysics in the last five years, let alone to have read them. Few geophysical texts mention environmental applications, though there are notable exceptions, such as Milsom (1989). None of the more traditional geophysical references, such as Sheriff (1991) or Telford *et al.* (1990), include any mention of environmental or groundwater geophysics. A number of hydrogeology texts mention geophysical methods, primarily resistivity and occasionally seismic refraction, but are often dated by the time they appear in print; a notable exception was Fried (1975) which covered the use of resistivity methods for mapping and monitoring groundwater contamination, and included a special appendix devoted to a description of the basic principles of resistivity methods. Some groundwater monographs, such as the one by Davis and Thornhill (1985), do not mention geophysics at all. More recent ones are somewhat better (e.g., Benson, 1990; in Nielsen, 1990), but the coverage is normally still slim. There isn't any one journal, or set of journals, that can be said to cover the subject area; there are simply too many people, both geophysicists and non-geophysicists, who are using geophysical methods, generally, and E & EM methods, specifically. The publications of which I am aware include the more "traditional" geophysical journals and monographs, such as *Geophysics*, *Geophysical Prospecting*, the *Journal of Applied Geophysics* (formerly *Geoexploration*), the *Journal of Geophysical Research*, *Geophysical Research Letters*, the more "environmental" annual *Symposium on Applications of Geophysics to Environmental and Engineering Problems (SAGEEP)*, and the excellent set of volumes edited by Ward (1990), particularly the reviews of electrical and EM methods by Ward and by

McNeill, respectively. Frishknecht *et al.* (1991) also provide an extensive review of shallow EM methods, including a brief mention of and substantial reference list for environmental applications. It is not my intention to try to replace those reviews, but rather to supplement them, and perhaps provide a different perspective. I also cannot adequately cover the subject of hydrogeology, but refer the reader to such standard texts as Freeze and Cherry (1979) or Domenico and Schwartz (1990). Reports of geophysical studies can be found in many if not most of the hydrology, hydrogeology and engineering geology journals and monographs, such as *Water Resources Research*, *Ground Water*, *Ground Water Management*, *Ground Water Monitoring and Remediation*, *Journal of Hydrology*, *Engineering Geology*, the *Quarterly Journal of Engineering Geology*, the numerous national journals of hydrology and hydrogeology, including a number of the journals of the American Societies of Civil and Mechanical Engineering (ASCE and ASME), and other more general environmental journals and trade publications. Some papers of geophysical interest appear in soil science publications, such as the *Proceedings of the Soil Science Society of America*, the *Soil Science Society of America Journal* and *Soil Science*. EM techniques, including ground penetrating radar and time-domain reflectometry, are prominent in the geophysical papers in the soil science literature, since soil scientists are concerned with the determination of the magnitude and extent of soil salinity and soil moisture. Other relevant papers appear from time to time in other, more general, earth science journals, too numerous to list, although I will mention *Science*, *Nature*, *Geology*, and the Geological Society of America Special Papers. Scanning the above list, one can readily grasp the difficulty in putting together a comprehensive list of recent papers in the field, but I have tried to give an impression of the journals that should be scanned regularly in any search for new papers.

One last introductory note on terminology should be made. The terms "dielectric permittivity" and "dielectric coefficient" are used rather than the phrase "dielectric constant"; the reason is simply that the dielectric "constant" is not constant, and is thus a misnomer. Some will argue that the dielectric properties are constant over a wide range of frequencies for a given set of material properties, e.g. for a given water content. I would respond that the same is true for the resistivity and the acoustic velocity, and we do not pretend that these parameters are "constant". If we alter the water content then the dielectric properties change. I will thus use the terms dielectric permittivity and dielectric coefficient throughout.

2. Physical and Chemical Properties in Electrical and EM Methods

2.1. HYDROGEOLOGICAL PARAMETERS AND ELECTRICAL PROPERTIES

A large proportion of the world's water supply comes from groundwater. Connections between the electrical properties and the hydraulic properties, such as the permeability, have long been proposed (e.g., Archie, 1942; Schopper, 1966, 1967; Wong *et al.*, 1984), but the search for a definitive relationship, or set of relationships, remains elusive. Any such relationships are often found to be only locally applicable. Many if not most of us still believe, however, that there should be a link, for simple physical reasons: the paths followed by fluid flow should be the same as the paths followed by electric current flow, with much the same requirements of good path connectivity, and with similar effects arising from restricted flow through small pore spaces. Clay-rich materials must, of course, be considered separately, since the nature of clay minerals gives them high porosity and enhanced electrical conductivity, yet low permeability. The complex nature of pore space and its relationship to the electrical and hydraulic properties has come under scrutiny over the years (e.g., Ruffet *et al.*, 1991; Wong *et al.*, 1984).

The hydrogeology of the subsurface can be divided into two realms (Figure 1): the *vadose* zone, which is unsaturated and where the water table will rise and fall with the seasons, and the *phreatic* or saturated zone, which lies below the water table and is thus in principle 100% saturated for 100% of the time. The grain size has a major influence on the hydrogeology. Sands and gravels are relatively porous and permeable, that is they allow fluid to flow more easily through the formation. Silts and clays, conversely, while perhaps high in water content, are nonetheless relatively impermeable to flow; that is silt and clay layers act to retard the flow of fluid. Sands and gravels thus act as *aquifers* (water supplies and conduits), whereas silts and clays serve as protective *aquitards* which retard fluid flow. Aquifers are *confined* if they are enclosed above and below by aquitards, or *unconfined* if they are open to flow from the surface. After a period of rainfall, a water layer may become trapped or *perched* above a shallow relatively impermeable clay aquitard, even though the formations below the clay remain relatively dry. The aquifers and aquitards can be complex in form, full of channels, heterogeneities, and structures of various scales. There are a variety of parameters that can be used to characterise the hydrology of a formation (e.g., Freeze and Cherry, 1979; Domenico and Schwartz, 1990). The most widely known is probably the permeability, with units of m^2, which is used as a measure of how open the medium is to fluid flow. Other parameters that normally appear include: the hydraulic head, in m, is related to the water table elevation; the hydraulic conductivity, in $m\ s^{-1}$ or $m\ d^{-1}$; the transmissivity, in units of $m^2\ s^{-1}$ or $m^2\ d^{-1}$ (square metres per day), is the product of the hydraulic conductivity and the thickness of the aquifer; the storage or storativity, in m^{-1}, is a measure of the degree to which an aquifer can store and supply water; the discharge, seepage or flow rate from a water well or in a subsurface path, in $m^3\ d^{-1}$ or $m^3\ s^{-1}$; or the (linear) velocity of flow in a subsurface formation, in $m\ s^{-1}$ or $m\ d^{-1}$. The last quantity is mostly used when talking about the movement of the leading edge of a pollutant away from a source or contamination. Often we can only determine some combination of hydrological parameters, the product of transmissivity and storativity for example. Some of the parameters depend on the fluid involved, such as the hydraulic conductivity which is specifically for

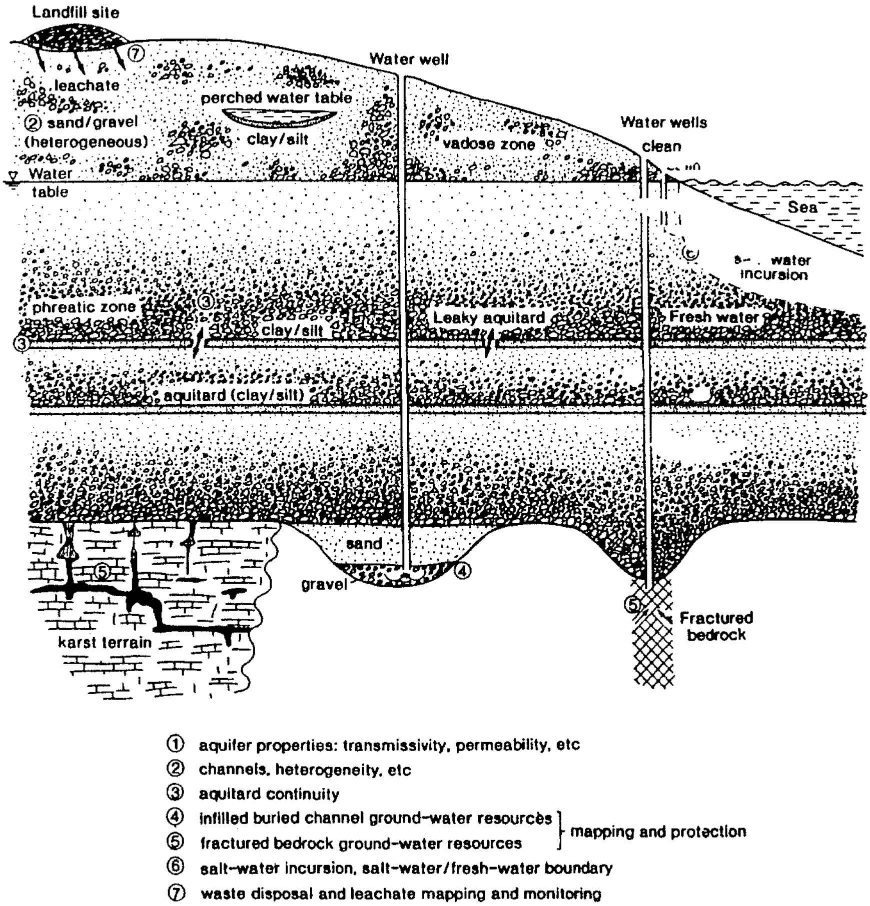


Figure 1. An overview of some of the hydrogeological and environmental elements with which environmental geophysics must deal. Groundwater resources must first be identified, such as the delineation of sand aquifer/clay aquitard sequences, their hydraulic properties, heterogeneity and continuity. Aquitards serve to protect groundwater supplies and their continuity (3) is particularly important. The water resources may be contained in buried channels (4) or fractured bedrock (5). The groundwater resources may be near a marine coast, and thus be susceptible to salt-water incursion if the water supply is drawn out too quickly (6); alternatively, the water supply may be shallow, and thus in danger from leached water (leachate) from landfill sites (7).

water, whereas the permeability is a property of the medium and is independent of the fluid properties. In earlier references (e.g., Archie, 1942; Schopper, 1966, 1967), the electrical properties were examined as possible proxy measures for the permeability. In more recent work, the relationships have been studied between the resistivity and more site-specific properties such as the hydraulic conductivity (e.g., Duran and Magnusson, 1984) and the transmissivity (e.g., Ponzini *et al.*, 1984; Ritzi and Andolsek, 1992).

Landfill sites are artificial hydrogeological systems; older landfills were simply holes in the ground, often inactive quarries, into which diverse types of rubbish were dumped. Newer "sanitary" landfills are carefully controlled; both the kinds of material and the operation of the landfill are now more carefully regulated in most countries of the world. Hazardous materials are either taken to more secure "permanent" hazardous waste disposal sites, or are disposed of in small amounts, a process known as *dilution* or *co-disposal.* The manner used to dispose of rubbish has also changed; modern landfills usually have a layer of clay, albeit often thin, at the base, and each days rubbish is covered with soil to minimise airborne contamination and vermin. Much of the concern in environmental surveys is to map and monitor the pore water flowing from landfill sites, both old and new. Both surface and subsurface water can infiltrate the landfill, and dissolve or *leach* mobile constituents from the discarded materials. The *leachate* can be a health hazard, depending on the nature and concentration of chemicals involved.

Geophysical surveys can be used, at least in part, to aid in the characterization of groundwater systems, both qualitatively, e.g. as confined vs unconfined, fractured rock vs buried channel, etc. (Figure 1), and quantitatively, e.g. transmissivity, hydraulic conductivity, etc. The positions of both permanent and perched water tables are needed, and, of course, the water quality is a central parameter. Mapping and monitoring both of landfill leachates and of salt-water invasion of aquifers are necessary to protect the water resources (Figure 1). E & EM methods are useful in all of these applications because of the influence that clay and water have on the electrical properties.

2.2. INFLUENCE OF PORE WATER AND CLAY CONTENT

2.2.1. *General remarks*

Let us consider, then, the second part of the opening question: what part do electrical and EM methods have to play in environmental geophysics? There are two reasons for the potentially dominant position of E & EM methods. The first is that, simply, water and clay dominate the electrical properties of the subsurface, which in turn influence the E & EM response of the earth. While silts can behave as aquitards, they are leaky aquitards, allowing relatively "slow" water flow through the less permeable layers. In general, the higher the clay content, the better the aquitard will be for confining and protecting the aquifer. Clay layers tend to be more conductive, because of the enhanced *cation exchange capacity* (CEC) of clays. That is, clay minerals are hydrated, platy in structure, with large surface areas, and tend to exchange ions easily with surrounding pore waters; all of these factors tend to lead to an increase in the electrical conductivity, and E & EM methods can thus be used to delineate protective aquitards.

The second reason for the importance of E & EM methods is the influence of ions, which will be present in varying amounts in the pore water. In some areas, the European Community to mention one, the pore fluid electrical conductivity is used

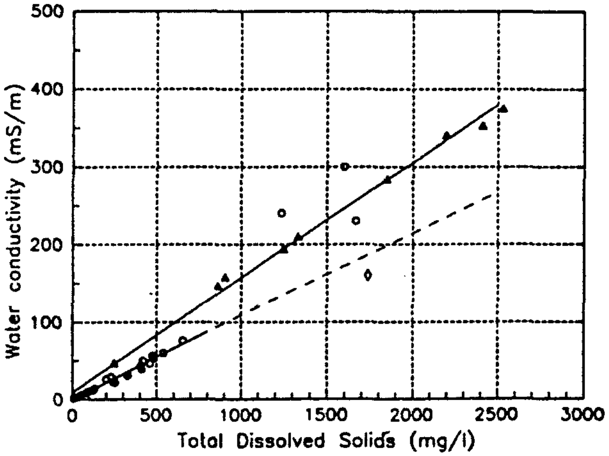


Figure 2. The pore water electrical conductivity (in mS/m) vs total dissolved solids (in mg/l) for a range of natural and landfill leachate waters, from Theimer *et al.* (1994). The solid circles are water samples taken from peatlands underlain by clays which in turn are underlain by carbonate rocks; the bicarbonate ion dominates the water chemistry. The open circles (lower left) are taken from uncontaminated "background" water samples adjacent to a landfill site near Christchurch (Smith, 1992), and the bicarbonate ion is also dominant. The solid triangles are water samples taken from a peatland that is underlain by marine clays, so that the water chemistry is dominated by NaCl; the chloride ion is approximately 1.5 times more conductive than a similar concentration of bicarbonate ion. The open circles and open diamond represent water samples taken from within the landfill site near Christchurch (Smith, 1992).

as a proxy for groundwater quality (e.g., Figure 2). The chloride ion, for example, is easily soluble in water, and is highly mobile. In coastal areas, the chloride ion acts as an indicator of sea-water incursion into an aquifer. Acetic acid is a common by-product of the decay of biological material, and is the source for much of the acidic smell that may be encountered at many landfill sites. While acetic acid is less electrically active in solution than the chloride ion, large quantities of acetic acid can be dissolved in water, and can thus be easily leached from a landfill site. We can think of the conductive ions present in leachate as an early warning system, so that we will start to look for the more hazardous substances that may appear, substances that will occur at much lower concentrations but which can be harmful even in small amounts. The chloride ion is highly mobile and easily dissolved, but is relatively innocuous when compared to other substances, such as benzene or carbon tetrachloride, which, while less easily dissolved or mobile, are much more hazardous to health.

Thus, E & EM techniques can be used to look for bounding clay layers which, we hope, are present to protect underlying groundwater supplies from some of the effects of human activities. Those same techniques can then be used to look for and monitor the spread of pollutants from landfill sites (Figure 1), since the mobile, electrically active ions are the first and fastest out of the rubbish dump. Similarly, if a coastal groundwater supply is overused, then sea water can be drawn into the water supply (Figure 1), and E & EM methods can again be used to map and monitor the extent of the groundwater contamination.

2.2.2. *Models of electric and dielectric properties*

The effects of water and clay have long been recognized (e.g., Keller, 1982, 1987; McNeill, 1990), and are summarised by McNeill (1990). The bulk electrical conductivity, σ, of saturated materials varies linearly with the pore water conductivity, σ_w, and with the effects due to the CEC of clay, σ_c. σ also depends on the porosity, ϕ, which is the fraction of the formation occupied by pore space. Overall, σ has the form (McNeill, 1990):

$$\sigma = \sigma_w \phi^n + \sigma_c, \tag{1}$$

where n is the "shape factor", a parameter that incorporates the effects of different grain sizes on the pore dimensions and hence on the electrical flow paths. Equation (1) is a modification of the formula that has been commonly called "Archie's law" (Archie, 1942). While various other formulas have been put forward, often with more complete physical justification and models, Archie's law and its variants have proven to be remarkably robust, and continue to be widely used, with the addition of the clay term. The formation electrical properties are thus directly related to both the clay content, through σ_c, and to the pore water quality, through σ_w . The two effects are sometimes difficult to separate, but Park and Dickey (1989) have suggested an empirical approach to do so, and Börner *et al.* (1993) have examined the effect of brine contamination on the complex electrical properties. The model is similar to the Cole-Cole model, but extended over a wider frequency range (Börner and Schön, 1995). Using the notation of Börner *et al.* (1993) in a slightly modified form, we can write the conductivity as a function of frequency:

$$\sigma(\omega) = \sigma'(\omega) - i\sigma''(\omega) \approx \sigma_{dc}(i\omega)^{(1-\alpha)} \tag{2}$$

where ω is the angular frequency $2\pi f$, for the frequency f in Hz. The simplified form on the right-hand side of (2) can be used since, over the frequency range studied, σ' and σ'' have essentially the same frequency dependence. The exponent α is of the order of 0.95 to 1.0, so that the imaginary part of σ is small. The real and imaginary parts, σ' and σ'', respectively, then take the forms:

$$\sigma' = A\omega^{(1-\alpha)}, \quad \text{and} \quad \sigma'' = B\omega^{(1-\alpha)} \tag{3}$$

Börner *et al.* found that the imaginary part, σ'', was particularly sensitive to the presence of contamination. Park and Dickey (1989) similarly report that the imaginary part is particularly sensitive to the clay content, and refer to Equation (1) as the Vinegar and Waxman (1984) model. While the approaches followed by Park and Dickey (1984) and by Börner *et al.* (1989) begin with the same starting model, they diverge in their goals and thus in their treatment of the separation of the individual responses. The former isolate the individual component response to estimate the clay contribution, σ_c, in Equation (1), whereas the latter measure the respective sensitivities of σ' and σ'' to the presence of brine contamination.

There have been a number of attempts to similarly define both theoretical and empirical relationships which relate the dielectric permittivity, ε, to the water content (e.g., Hoekstra and Delaney, 1974; Topp *et al.*, 1980; Feng and Sen, 1985; Knight and Endres, 1990; Zegelin *et al.*, 1992; Heimovaara *et al.*, 1994). To put the discussion of the effects of water on the dielectric properties into context, some necessary background theory will be outlined, using the notation of Topp *et al.* (1980) and of Davis and Annan (1989). The dielectric properties are usually expressed as the *relative* dielectric permittivity or dielectric coefficient, K^*, which is obtained by dividing ε by ε_0, the "free-space" value which is equal to 8.854×10^{-12} F m^{-1}. The dielectric coefficient may be expressed as the sum of real and imaginary parts as:

$$K^* = K' + iK''' \tag{4}$$

The real part, K', is the term most often used in studies of the effects of water content. The imaginary part, K''', is also called the *electric loss* part of the complex dielectric coefficient. It is sometimes convenient to separate K''' into two terms, one that is frequency-dependent and the other which is independent of frequency, in which case:

$$K^* = K' + i[K'' + \sigma_{dc}/(\omega\varepsilon_0)] \tag{5}$$

σ_{dc} is the "zero-frequency" conductivity, and ω is the angular frequency as before. K'' is then the frequency-dependent electric loss term. Apart from system and spreading losses, there are four types of losses in materials (Olhoeft, 1990): electrical conduction which generates heat; viscous dielectric relaxation of water; ionic transport on clay mineral surfaces; and scattering. Different material loss mechanisms dominate at different frequencies (Olhoeft, 1990), an issue which we will consider later when GPR and TDR techniques are discussed. In most laboratory studies, it has been found that the loss terms are small compared to K', and it is K' that has been generally examined as a function of water content (e.g., Topp *et al.*, 1980), but the loss terms are important in the field. More recent studies have also measured the loss terms, to obtain the electrical conductivity as well (e.g., Topp *et al.*, 1988; Zegelin *et al.*, 1990; Nadler *et al.*, 1991; Heimovaara, 1994; Heimovaara *et al.*, 1994). The propagation of radar is largely governed by K', since the GPR/TDR velocity is:

$$v = c/\{\tfrac{1}{2}K'[1 + (1 + \tan^2\delta)^{1/2}]\}^{1/2} \tag{6}$$

where c is the speed of light in vacuum, and $\tan\delta$ is $\{K'' + \sigma_{dc}/(\omega\varepsilon_0)\}/K'$. If $\tan\delta$ is much less than 1, which is normally the case at radar frequencies, then:

$$v \approx c/\sqrt{K'} \tag{7}$$

which is the usual expression encountered in most GPR papers.

The dielectric coefficient thus governs the propagation of radar waves in the ground. At frequencies between 1 MHz and 1 GHz, the water content dominates the dielectric properties (Hoekstra and Delaney, 1974; Topp *et al.*, 1980; Keller, 1987; Olhoeft 1990), since the dielectric permittivity of water is typically more than 20 times greater than the permittivity of the solid grains. For high water contents, a simple mixing law is the most reliable form to use for the dielectric coefficient (Theimer, 1990; Theimer *et al.*, 1994):

$$K' = \phi K'_w + (1 - \phi)K'_s \tag{8}$$

where K'_w is the dielectric coefficient for the fluid (water) component, of the order of 80, and K'_s is the dielectric coefficient for the solid fraction, of the order of 2 to 8 for most naturally occurring soils and rocks. At low to intermediate water contents, a variety of formulas exist, but as noted by Topp *et al.* (1980), they yield similar results, with a few exceptions. As for the electrical properties, the influence of contaminants on the dielectric properties are also being examined (e.g., Kutrubes, 1986), though not enough work is being done in this area, perhaps because of the inherent dangers.

In addition to the propagation of radar waves, we must still account for the electric and scattering losses, which are usually collected into a single exponential decay term (Davis and Annan, 1989; Theimer *et al.*, 1994). The amplitude of a radar wave, A, decreases with depth, z, as:

$$A(z) = S(z)\,\mathrm{e}^{-\alpha z} \tag{9}$$

where $S(z)$ includes effects of geometrical spreading, and α is an attenuation coefficient. In materials where the loss terms are small, which is correct for most natural situations, α is related to the ratio of the conductivity at radar frequencies, σ, to the dielectric coefficient, K', as:

$$\alpha = \tfrac{1}{2}\sigma\sqrt{(\mu/K')} \tag{10}$$

The attenuation depends linearly on the electrical conductivity at GPR frequencies, which is not the same as the low-frequency conductivity used in Equations (1) and (4); it is instead the conductivity at radar frequencies, and will, in general, be higher than the low-frequency conductivity.

Our discussion has come full circle, returning to the electrical conductivity, which is controlled by the water content, water quality, and clay content. The dielectric coefficient is almost entirely dependent on the water content. The electric and dielectric properties are thus sensitive to the parameters that are of interest to groundwater exploration, monitoring and protection. One last point needs to be considered here before the summary of recent advances in and adaptations of E & EM techniques. In the foregoing brief discussion, the conductivity and dielectric permittivity were usually quite separate; for example, at radar frequencies, the electric loss terms are normally much smaller than the real part of the dielectric permittivity. This is only true, however, at high frequencies. Similarly, the electrical conductivity was not presented as a complex quantity; at low frequencies, the dielectric effects are much smaller than the electrical conductivity, and are thus neglected. However, at intermediate frequencies, the electric and dielectric effects are almost equal, and the EM response will be a mixture of what would be normally called an EM response, i.e. due to the flow of induced current, and what would be considered a radar response, i.e. some sort of wave propagation. The frequencies at which this mixing occurs depends on the electric and dielectric material properties. If we look at Equations (5) and (6), we note that the imaginary radar loss term approaches the magnitude of the real part if K' and $\sigma_{dc}/(\omega\varepsilon_0)$ are approximately equal. Alternatively, we can consider the dielectric permittivity to be included in the imaginary part of a complex conductivity. K' will normally vary between 4, for dry soils and ice, to approximately 80 for water (e.g., Davis and Annan, 1989; Annan and Chua, 1992). The low-frequency conductivity in soils varies from less than 1 mS m^{-1} to more than 100 mS m^{-1}, that is the soil resistivity will range from more than 1000 ohm-m to less than 1 ohm-m. Then the frequency at which K' and $\sigma_{dc}/(\omega\varepsilon_0)$ are equal will be between 1 MHz for the resistive subsurface, and 3 GHz for the conductive subsurface. The range over which each makes a substantial contribution to the other, of the order of 10% say, will be that much wider again, and the lower limit will stretch into the 100's of kHz range. Many of the recent equipment developments have pushed deep into this grey area, with some success, though perhaps at the risk of getting a mixed message.

3. Review of Electrical and EM Techniques as Applied to Environmental Studies

Given the intended audience of this review paper, little review of the principles of E & EM methods is required. "Traditional" resistivity, IP and EM methods are more than adequately covered in such texts as Telford *et al.* (1990) or Parasnis (1986), and in monographs such as the ones edited by Nabighian (1987, 1991). GPR is sometimes mentioned, as in a few of the recent introductory level texts such as Kearey and Brooks (1991), but is barely covered, and TDR rarely rates even a mention; I will therefore provide a little more information than for the other techniques. I will briefly summarise some central points, and will emphasise a few associated issues that arise in the application of E & EM methods in environmental geophysics. One aspect where environmental applications are growing is in the use of geophysics for monitoring, including the use of tomographic reconstruction techniques. In addition, remote sensing, airborne methods, airborne adaptations of ground-based methods, and borehole methods are being used more widely in environmental applications.

By their nature, electrical and EM methods are sensitive in different ways to aquifers and aquitards, or to leachate and sea water plumes. As shown by Fitterman and Stewart (1986), electrical methods are better suited to resolving resistive layers, while EM methods are best used to detect conductive layers. There is the problem of *equivalence* in both E & EM methods (e.g., Flathe, 1955, 1963; van Dam, 1976; Dorn, 1985; Fitterman and Stewart, 1986; Fitterman *et al.*, 1988; Goldman *et al.*, 1994a; van Overmeeren, 1989; Simms and Morgan, 1991, 1992); the thickness and resistivity or conductivity may not be separately resolvable, but some combination of the two. Thus, while E & EM methods both respond to the subsurface electrical properties, the physics of the methods lead to differences in their responses.

3.1. RESISTIVITY METHODS

The basic procedures of resistivity, SP, and IP will not be outlined here. Instead, I will mention some modifications that have been made to the standard resistivity procedures over the years, and how those modifications may be useful in environmental applications. Unless otherwise stated, all comments could apply equally well to resistivity, SP, and IP surveys. In the hydrogeological literature, variations of the Wenner and dipole-dipole configurations are often used (e.g., Broadbent, 1992; Goyal *et al.*, 1991). The standard Wenner configuration, with equally-spaced electrodes, is called the α-resistivity array, the dipole-dipole configuration, again with equally spaced electrodes, is called the β-resistivity array, and the γ-resistivity array consists of alternating current and potential electrodes, again equally spaced. The responses are slightly different for each, with the potential for yielding more information. In practice, little additional information is obtained. A variation of the Wenner array can also be used that is similar in nature and intent to the focusing of the current in borehole focused resistivity tools; additional current electrodes are used so that the net current flow is more narrowly concentrated within a small lateral zone centred about the potential electrodes. The gradient array is not used as widely as perhaps it could be for mapping lateral variations in the subsurface electrical properties. The method is a variation of the Schlumberger geometry; the current electrodes are kept fixed at a large separation and the potential electrodes are moved across a site, both on a line between the electrodes (gradient profiling) and extending significant distances out to either side of the current electrode line (gradient array). See for example Ward (1990).

One aspect of resistivity surveys noted by some workers has been the lack of consideration of the directional dependence of the survey design and interpretation. Habberjam and Watkins (1967) proposed the use of a square array to aid in the identification of directional anomalies and of anisotropy in the electrical properties that may arise from thinly-bedded dipping layers (Maillet, 1947; Habberjam, 1972; Campbell, 1977; Matias and Habberjam, 1986). The square array has been subsequently used by Darboux-Afouda and Louis (1989) in surveys of fractured aquifers in Bénin and by Lane *et al.* (1995) in surveys of fractured crystalline bedrock in

New Hampshire. The apparent resistivity tensor and multiple-source bipole-dipole and -quadripole resistivity surveys have been suggested for areas with strong underlying structural controls (Bibby, 1977, 1986; Bibby and Hohmann, 1993). While the applications of the apparent resistivity tensor and associated survey techniques have been primarily in the geothermal areas of New Zealand, the methodology may be useful in areas where the hydrogeology is dominated by subsurface channels. An alternative approach is to rotate the resistivity array to determine the azimuthal dependence of the apparent resistivity (Ritzi and Andolsek, 1992). One problem with the method is that the rotation would need to be repeated for each electrode separation, since channel flow directions may vary with depth, even to the point of being perpendicular.

Resistivity surveys are often more time-consuming than shallow EM surveys; the electrode pairs must be moved and planted, a reading taken, then the process repeated. A greater number of people are needed for rapid field operations. Automated resistivity profiling systems have been proposed. For example, Christensen and Sørensen (Christensen, pers. comm., 1990; Sørensen, 1994) adapted a standard farm implement for resistivity surveying across farm fields. The current configuration uses a "tail" of electrodes towed behind a tractor, hence the technique is called the *pulled array continuous electrical profiling* (PA-CEP). A variable number of electrode arrays can be attached, e.g., three electrode separations are normally used now, but a ten-electrode tail is planned (Christensen, pers. comm., 1994). The voltage and current are digitally recorded at regular time intervals, and the times are converted to distance using the (constant) speed of the tractor. Large areas can be covered in a short period of time, 10 to 15 km per day. The technique has been used to delineate changes in soil type, which helped explain some soil drainage problems present in some farming districts in Denmark. The technique could also be used to determine the extent of soil salinity.

A variation of the towed-array technique has been developed for resistivity logging while drilling Sørensen (1989, 1994). A hollow-auger drill is modified so that portions of four adjacent parts of the drill are electrically isolated from each other and from the rest of the auger (Figure 3). As with standard resistivity logging, current is injected through the outer electrodes and the voltage is measured across the two inner potential electrodes. The Ellog technique, as it is called, is especially useful in sandy and gravelly soils where good core recovery is often difficult, and the resistivity logs then provide information that cannot be otherwise obtained. Resistivity logging is not at present carried out in steel-cased holes, since the steel serves to preferentially conduct the current flow. Kaufman (1990), Schenkel and Morrison (1990), and Kaufman and Wightman (1993) show, however, that at least in principle, resistivity logging should be possible even through steel casing. The resistivity tools would have to be more precise, finding small variations in low voltage readings, but with current technology, this should be possible. While the model studies were not carried out with environmental applications in mind, the

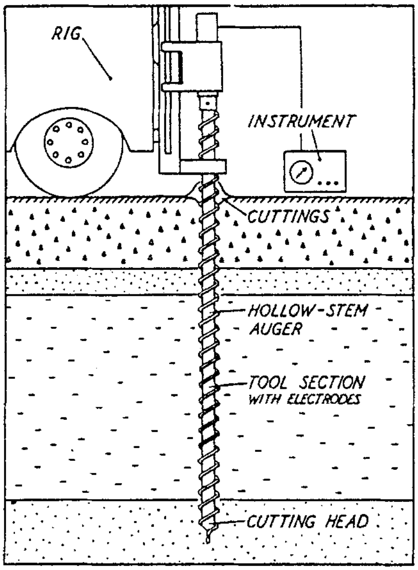


Figure 3. A sketch of the Ellog auger logging system. (From Sørensen, 1989.)

ability to use resistivity in steel-cased holes will add another geophysical tool to the environmental arsenal.

Finally, one last recent development is worthy of note: the development of electrical resistivity tomography (Dines and Lytle, 1981; Daily *et al.*, 1987, 1992, 1995; Daily and Owen, 1990, 1991; Daily and Ramirez, 1990, 1995; Spies and Ellis, 1995). A variant has been called computed impedance tomography, or CIT (Wexler *et al.*, 1985; Tamburi *et al.*, 1986). What started out as a laboratory technique (Wexler *et al.*, 1985; Daily *et al.*, 1987) has since expanded into a cross-borehole and surface-to-borehole field technique that is used for monitoring of fluid flow in the vadose zone (Daily *et al.*, 1992, 1995), and for monitoring the generation of a high-temperature melt and its subsequent cooling (Spies and Ellis, 1995). While the technique may not become part of the standard repertoire in environmental mapping and monitoring, given the complexity and associated cost, the development of resistivity tomography is a powerful tool for monitoring. In some applications, where direct borehole access may not be possible or desirable, such as at a hazardous waste disposal site, resistivity tomography may be the only realistic technique available for detailed monitoring of both the lateral and depth extent of any leakage. In resistivity tomography, tomographic reconstruction techniques are applied to a problem not in wave-propagation, and thus amenable to ray-tracing, but to current flow and diffusion. The governing equations are thus Poisson's equation (Tamburi *et al.*, 1986; Daily and Owen, 1990; Spies and Ellis, 1995), subject to the associated Neumann boundary conditions.

Daily *et al.* (1992) carried out finite-element modelling in along-strike wavenumber domain, to simplify the problem; the cross-hole resistivity data are then coupled to modelling and inversion routines, and an initial resistivity distribution is iterated until a stable solution is obtained. Spies and Ellis (1995) on the other hand use a Green's function approach, and follow the procedure of Ellis and Oldenburg (1994) for the inversion of three-dimensional resistivity data. While the approaches appear different, ultimately both methods require the minimisation of functions that are not markedly different; this is not surprising given the equivalence of the physical models. Other borehole-to-borehole and surface-to-borehole projects take similar paths (e.g., Wexler *et al.*, 1985; Asch and Morrison, 1989; Bevc and Morrison, 1991; Bryant *et al.*, 1991), and the process can be extended to IP tomography (LaBrecque, 1991).

3.2. ELECTROMAGNETIC METHODS

The usual EM techniques used in environmental applications are adaptations of the horizontal loop EM method. In normal practice, two small coplanar loops are used, one as the transmitter and the other as the receiver. A low-frequency signal is used so that the induction number is low, in which case the depth of penetration depends on the antenna separation (e.g., McNeill, 1980). While other geometries are possible, for example cross-coupled so that the transmitter does not generate any signal in the receiver because their orientations are perpendicular to each other, the standard ground-based geometries are horizontal coplanar and vertical coplanar. Vertical coaxial systems may be commonly used for airborne surveys, but the majority of environmental geophysical surveys are carried out on the ground because of the small scale of many of the problems that are faced. The EM systems are then used in profiling mode. In principle, the technique can be used to obtain depth information by taking measurements at different heights and with different coil orientations; in practice, however, environmental surveys are carried out using shallow EM systems, such as the Geonics EM31, EM34–3 and EM38, to delineate the location and lateral extent of a contaminant plume. The results then guide the placement of sampling and monitoring wells (e.g., Nobes, 1994).

There are a number of interesting variations on older themes in EM equipment. The frequency-domain EM systems have dominated in the past, such as the single-frequency EM31, EM34 and EM38 instruments. Recent progress in fast switching circuits has allowed time-domain/transient EM (TEM) systems to be used for hydrogeological and environmental studies. There are a number of such "fast rise time" systems now available. The standard TEM practices apply, but over a much smaller scale. Offset transmitter-receiver loop surveys are more common, since small localised sources, as small as 5 m by 5 m, can be used. The transmitters normally use low current, battery-operated sources, with currents of less than 10 A, and typically of the order of 1–2 A.

As with resistivity and IP methods, cross-hole and surface-to-borehole EM methods are being developed and tested (e.g., Lytle *et al.*, 1981; Daily and Ramirez, 1990; Zerilli and James, 1991), including a vertical electric dipole (VED) source (Bartel and Newman, 1991) similar to that used in sea floor studies (e.g., Edwards *et al.*, 1985; Nobes *et al.*, 1986). The surface-to-borehole and cross-hole techniques are primarily intended for monitoring of waste disposal sites, including fracture zones in hard rock.

Other advances have involved extensions of traditional methods, such as VLF and AMT. Turberg *et al.* (1994) have modified "classical VLF-resistivity equipment", and extended the frequencies to include a band of higher frequencies, overall 12–240 kHz, and thus to obtain shallow frequency soundings. They were able to relate the results to the hydrogeology and to the hydrogeological heterogeneity; this is a theme to which we will return. As Turberg *et al.* point out, given the higher frequencies and hence shallower depths of investigation associated with their system, then successive stations must not be too far apart; they suggest 250 m at most. However, the depth of penetration at 183 kHz appeared to range from 4 to 10 m, and thus a much smaller station spacing should be used. The apparent resistivities in the test area were all moderate in value, ranging from less than 20 ohm-m to greater than 80 ohm-m; the dielectric effects, which we can estimate as the product of K', ω, and ε_0, are of the order of 0.1 mS/m, whereas the apparent conductivity is of the order of 10 to 50 mS/m. Dielectric effects were not explicitly discussed, however.

Hollier-Larousse *et al.* (1994) have modified a high-frequency MT system, which they call Radio-MT, to operate towed behind a vessel in rivers and small fresh-water lakes. The frequency can range from 8 kHz to 1.6 MHz, and they, like Turberg *et al.* (1994), do not mention dielectric effects. Tests were carried out using frequencies of 16.8 and 162 kHz; the dielectric effects would have been minimal for the resistivities involved, of the order of 0.04 mS/m compared with a formation conductivity of the order of 10 mS/m (100 ohm-m resistivity), but the effects were not explicitly evaluated. At the higher frequencies, the dielectric effects would become important, and need to be evaluated before neglecting them.

One new methodology that does explicitly incoporate displacement currents, that is the dielectric effects, is the very-early TEM (VETEM) system (Stewart *et al.*, 1990, 1994; Pellerin *et al.*, 1994, 1995). The method is in a sense a hybrid method, but deserves mention here, since the topic of high frequency EM systems has been introduced. The intention is that the technique will bridge the gap between high-frequency EM (of the order of 300 kHz) and ground penetrating radar (GPR, up to 50 Mhz). GPR is discussed separately in the next section. At this stage, VETEM modelling studies have been carried out (Stewart *et al.*, 1990, 1994; Pellerin *et al.*, 1994, 1995), and some preliminary field studies have been completed (Pellerin *et al.*, 1994, 1995). However, the optimal design characteristics are still to be determined. The goal is to have a system that can provide the dense spatial coverage required for shallow mapping, with a depth of penetration of 10 m. The VETEM system operates over the nanosecond to microsecond time range, using loops with separations of 1 to 4 m. The system is initially designed to work in moderately conductive areas, of the order of 30 ohm-m (30 mS/m), but those of us interested in resistive environments, where even fast-rise time TEM systems do not work well (e.g., Bal, 1994), will be watching closely as well.

3.3. GPR AND TDR

Ground penetrating radar (GPR) and time-domain reflectometry (TDR) are not new techniques, but until recently these techniques have not been as actively taught and pursued within the geophysical community as the more traditional methods. The terms do not even appear in Sheriff's (1991) most recent edition of his *Encyclopedic Dictionary*. The theory and equipment for GPR and for TDR cannot be adequately covered here. Instead, the excellent reviews of Davis and Annan (1989) and Annan and Chua (1992), and the paper by Fisher *et al.* (1992) are recommended for GPR, and the papers by Topp *et al.* (1980), Zegelin *et al.* (1992), and Heimovaara (1994) are suggested for TDR. More complete sets of references can also be found in those papers. Only very brief summaries of GPR and TDR are presented here.

Whereas in what has traditionally been called EM the dielectric effects are neglected, in GPR and TDR, the electric loss terms cannot be neglected except in small-scale laboratory studies. The GPR loss terms, as discussed earlier, are incorporated into an all-encompassing attenuation coefficient (Section 2.2.2 above). Analyses of radar attenuation can yield estimates of the radar "conductivity", σ_{GPR} (e.g., Theimer, 1990), which can be double the low-frequency value obtained from standard shallow E & EM surveys. However, even using the low-frequency conductivity allows us to estimate the degree of attenuation we can expect at the site of a GPR survey. The depth of penetration can be determined, for a given electrical conductivity, using the radar range equation (Davis and Annan, 1989); such calculations have been shown to be in good agreement with field observations (Figure 4, from Theimer *et al.*, 1994). A survey protocol has, therefore, been suggested for radar surveys that includes standard electrical or EM surveys first (Theimer *et al.*, 1994), so that potential problem areas may be identified in advance. While the electrical conductivity determined from traditional electrical and EM surveys will be inherently different from that derived from measurements of radar attenuation, the low-frequency conductivity value still provides an estimate of the background attenuative losses that may be expected. The attenuation of radar signals by conductive pore fluids can sometimes be used to advantage; in the presence of leachate plumes, the GPR signal is often attenuated to such an extent that the contaminated zone appears as a large blank region in the radar profile, and the location of the leachate plume is readily identified. Unfortunately, for similar reasons, clays tend to significantly limit the depth of penetration of radar. The application of seismic acquisition and processing methods to GPR can, however, improve the utility of GPR (e.g., Fisher *et al.*, 1992), but the utility of GPR will

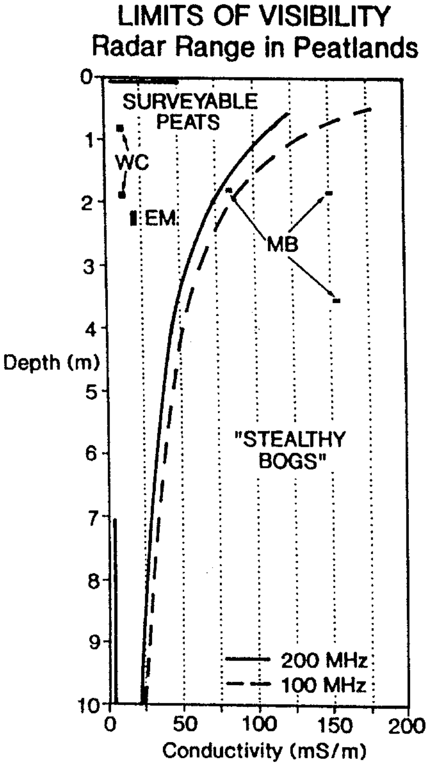


Figure 4. Depth of penetration computed for 100 MHz (dashed curve) and 200 MHz (solid curve) using the radar range equation (Davis and Annan, 1989; Annan and Chua, 1992), and measured in the field for 100 MHz GPR signal (Theimer *et al.*, 1994). The base of the peat was observable at two sites, Ellice Marsh ("EM") and Wally Creek ("WC"), whereas at Mer Bleue ("MB"), the base of the peat was detected at one location for a 100 MHz antenna, but otherwise was not detectable. Theimer (1990) coined the term "stealthy bogs" to describe peatlands that were essentially invisible to radar, that is for which the base of the peat could not be observed. (From Theimer *et al.*, 1994.)

continue to be limited in those areas where clays, clay-bound sands and gravels, and conductive pore fluids are present. TDR and GPR both use EM antennas, but the designs are markedly different. TDR antennas simply consist of two or more parallel line sources attached to a connector (Figure 5, from Zegelin *et al.*, 1992). In most arrangements, the lines are inserted into the ground, and the travel time is recorded for the passage of a high-frequency EM pulse. Most systems now record both the travel time and the amplitude, thus obtaining the attenuation and an estimate of the conductivity. The calculated dielectric permittivity is used to determine the water content, using one of a number of theoretical or empirical relationships (e.g., Topp *et al.*, 1980; Zegelin *et al.*, 1992; Heimovaara, 1994, and Heimovaara *et al.*, 1994). TDR is thus a useful adjunct to GPR. TDR antennas do not need to be as highly developed as GPR antennas. In a recent paper, however, Selker *et al.* (1993) suggested that reliable results could be obtained by placing the

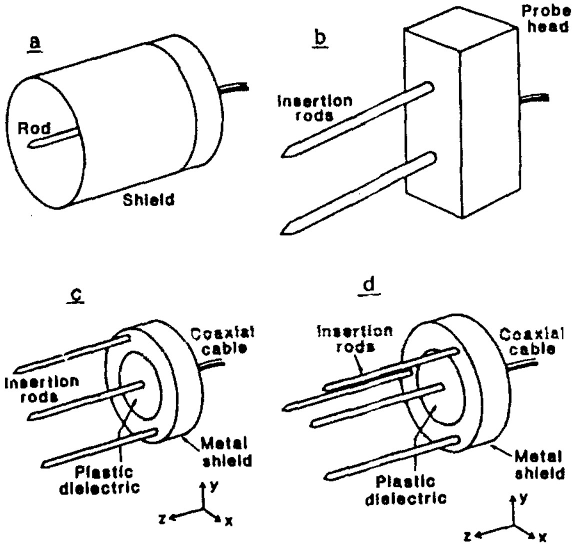


Figure 5. A sample of the different types of time-domain reflectometry probes that are used to measure the dielectric permittivity and, in some cases, the electrical conductivity at radar frequencies. (Redrawn from a preprint of Zegelin *et al.*, 1992.)

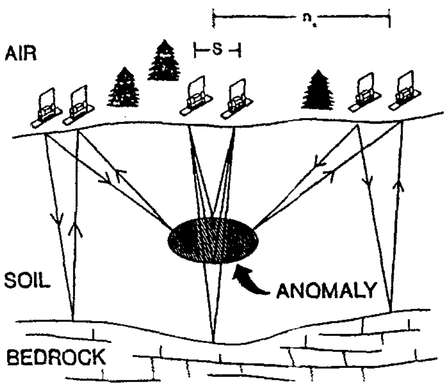


Figure 6. The configuration of the "common offset" mode for ground penetrating radar surveying. The antenna separation is kept constant ("s") while the antennas are stepped along at a constant interval between sampling recording stations ("n_x"). The soil-bedrock interface, and any intervening boundaries, reflect the transmitted energy back to the receiving antenna. (From Annan and Cosway, 1992.)

TDR probes on the ground, which is essentially the same as GPR but without the benefit of antenna design.

In GPR, a pair of inter-changeable radar antennas are used as transmitter and receiver (Figure 6, from Annan and Cosway, 1992). A pulse of high-frequency EM energy is directed into the ground, and the EM "echoes" are recorded at the receiving antenna. Much work has gone into the development of GPR antennas so

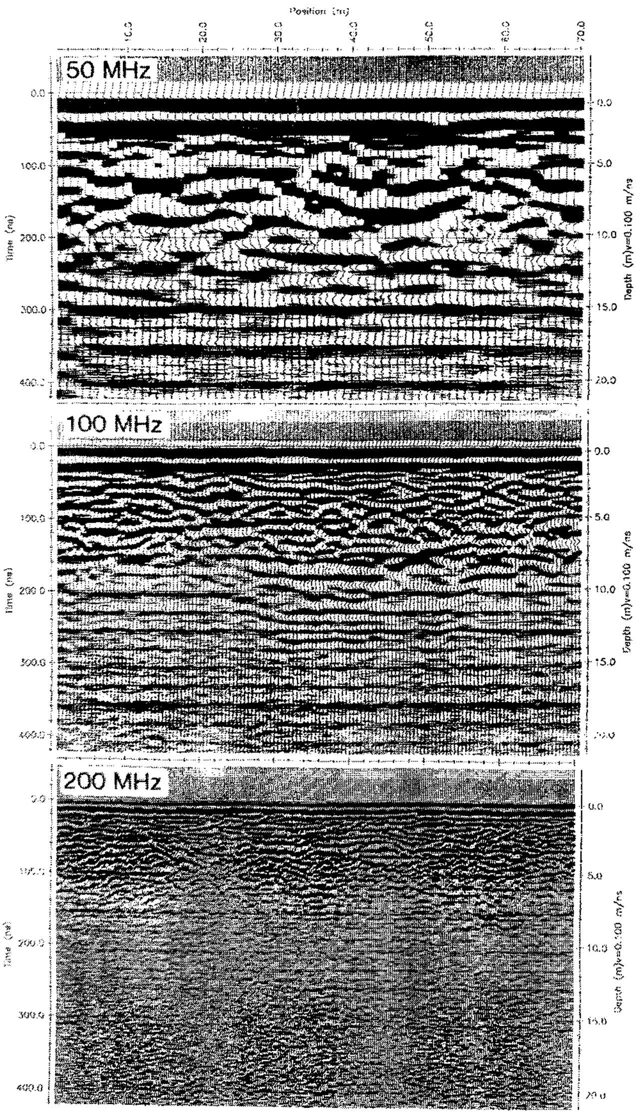


Figure 7. GPR profiles from an area with complex near-surface geology, a result of deposition in a braided river environment where the channel and bars criss-cross and are continually changing. The profiles illustrate the competition between depth of penetration and resolution. At low frequencies (top, 50 MHz) the penetration is of the order of 15 m, but the resolution is poor. At high frequencies (bottom, 200 MHz), the resolution is excellent, but the depth of penetration is only about 8 m. A mid-range frequency (e.g., 100 MHz, middle) is often selected, depending on the application, as a compromise between depth of penetration and resolution. The depth of penetration has also been affected by the presence of two clay-bound gravel layers, one at about 7 m depth and the other at 10 to 12 m depth, and by the depth of the water table, at about 13 m depth. The strong horizontal reflections at late times are multiple reflections generated between the base of the deeper clay-bound gravel and the water table. Filtering can remove the multiples, but the reflections from the sediment layering are usually removed as well.

that the signal is directed as much as possible into the ground (Annan and Cosway, 1992). The propagation of GPR waves can be compared to that of seismic waves, and in fact the same acquisition and processing techniques used in seismic reflection can be used in GPR (Fisher *et al.*, 1992). GPR refraction, however, cannot be used as seismic refraction is. At the water table, the acoustic velocity increases, and the seismic wave is refracted towards the horizontal. At some angle of incidence, critical refraction will occur, and the energy will travel along the boundary, generating "head waves" which return to the surface. For GPR, conversely, the radar velocity *decreases* at the water table, and the wave is refracted towards the vertical and away from the (horizontal) boundary. The water content generally decreases with depth, as the degree of compaction increases, so that at some point the energy may be refracted back towards the surface. Unfortunately, the distance required to obtain a first-arrival as in seismic refraction is normally prohibitive. Thus, GPR is only practical in the reflection mode. The resultant GPR profile looks to some extent like a geological cross-section (Figure 7), hence its appeal amongst geologists, engineering geologists, and so on (e.g., Huggenberger, 1993; Huggenberger *et al.*, 1994; Jol and Smith, 1991; Jol, 1995).

The resolution of GPR depends on the band-width of the pulse used. A simple approximation to the resolution is the size of the Fresnel scattering zone, which at the surface is equal to one-quarter of the wavelength, which in turn is equal to the velocity divided by the frequency:

$$\text{Resolution} = \lambda/4 = v/4f \tag{11}$$

where λ is the wavelength, v is the radar velocity as defined in Equation (7), and f is the frequency. The velocity is normally expressed in m ns^{-1}, and f in MHz or GHz. As for other geophysical techniques, there is a fundamental trade-off between the depth of penetration and the resolution (Figure 7). High frequency signals yield better resolution, but have poorer depth of penetration because of increased electric losses (Figure 4), as discussed previously. Low frequency signals conversely have good penetration but poor resolution. The choice of frequency depends on the application, on the depth of penetration needed, and on the geological setting.

3.4. HYBRID METHODS, MULTI-PARAMETER TECHNIQUES AND OTHER ASPECTS

A number of new techniques have evolved that are not strictly electrical or electromagnetic methods, as they have traditionally been used. E & EM methods are being combined with other techniques, or the new methods are pushing into areas that are in a sense "in between", not quite one thing or another. For example, Tabbagh *et al.* (1993) and Benderitter *et al.* (1994) have devised a different approach to the rapid determination of the electrical properties of the ground over a substantial area. Instead of the traditional galvanic system, they have built an electrostatic quadrupole system that does not need to be in contact with the ground. Two horizontal dipoles are used, placed as close to the ground as possible; in the field tests, the elevation was 0.2 m, and the dipoles were laid out in a 1 m square array. The electric potential difference is then measured at a range of frequencies, from 100 kHz to 10 MHz. Both the resistivity and dielectric permittivity are obtained as a result. While the field trials were carried out at archaeological sites, the applications for mapping soil types, soil salinity, and shallow contamination are obvious. The towed electrode array of Christensen and Sørensen (1994), and the electric quadripole technique of Tabbagh *et al.* (1993) illustrate what may be a growing trend; resistivity methods are easily understood by the hydrogeological and archaeological community, and variations of these techniques that improve the speed of the technique and circumvent some of the weaknesses will become more common.

A variation on this theme is the AC/geoelectrical sounding method (Christensen, 1987). The survey is carried out in the same way as for a standard galvanic resistivity survey, and the apparent resistivity is plotted, as usual, as a function of the electrode spacing. The voltage and current are measured for a number of frequencies, however, so that instead of one curve of apparent resistivity vs separation, there is a family of such curves. The resistivities and thicknesses of individual subsurface layers are then better resolved, since together the galvanic and inductive responses are used to reduce the problem of equivalence.

While no new equipment or system is involved, Sandberg (1993) has shown that by combining resistivity and IP with TEM, then the resolution of individual layers is greatly improved. IP, in particular, has a significant impact, possibly because a completely different physical property, the chargeability, is measured, which complements the resistivity. Goldman *et al.* (1994b) suggest that problems of equivalence in shallow TEM can, at least in part be rectified by accurate measurement and modelling of early delay time measurements. Goldman *et al.* (1994a) have combined nuclear magnetic resonance (NMR) with TEM. A "Hydroscope" (Schirov *et al.*, 1991) was used to generate the NMR signal, which is sensitive to the number of protons, i.e. hydrogen nuclei, present in the ground. The NMR results are interpreted to provide a measure of the water content versus depth (Trushkin *et al.*, 1994, 1995). The TEM results are then used to determine the water quality, since EM methods generally are well-suited to the delineation of conductive zones (e.g., Fitterman and Stewart, 1986). The NMR results are limited to some 10's of metres in depth, but the NMR and TEM results were generally in good agreement. In one case, the two data sets were in direct conflict with lithologic logs, which Goldman *et al.* (1994a) interpreted as local variation in the lithology. It must be noted, however, that the lithology logs which are acquired during the process of drilling, often do not accurately reflect the thicknesses and depths of the formations present.

Erchul (1990) describes a combined electrical conductivity-cone penetrometer tool. The cone penetrometer provides geotechnical information, and the electrical conductivity can be correlated with the geotechnical data, either to obtain estimates of liquefaction potential (e.g., Erchul and Gularte, 1982; Arumoli *et al.*, 1985), which is beyond the scope of this review as outlined in the Introduction, or to

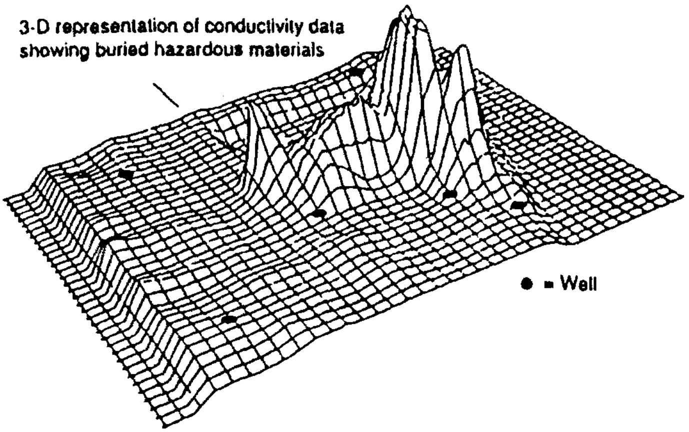


Figure 8. The leachate plume at Love Canal, New York, which originated at the Hooker Chemical Plant, was not found using the "standard" practice of drilling a suite of regularly spaced holes; the holes bracketed the plume. An EM survey, however, did map the position and extent of the plume. (From Barinaga, 1990.)

determine the water content and/or water quality within the context of a broader site investigation (Erchul, 1990; Drakovits and Fejes, 1994). Unfortunately, "standard practice" in engineering studies is often to drill a series of regularly spaced holes or to take a similar set of shallow probes, and to accept the properties measured in the holes to be representative of the entire site. In spite of evidence to the contrary (e.g., Figure 8, from Barinaga, 1990), this practice continues. Thus, while the conductivity cone penetrometer is a useful addition to the range of tools available, many environmental and engineering consultants may be tempted to use it, however incomplete its coverage may be, as an alternative to more complete geophysical surveys.

Over the years, researchers have proposed that seismoelectric coupling could be a useful exploration tool (e.g., Thompson, 1936, and Martner and Sparks, 1959, cited in Thompson and Gist, 1991, 1993). The basic idea is that acoustic waves can generate an "electrokinetic" response, particularly at a boundary such as at the water table or at the boundary between oil and water. The acoustic signal is converted at a boundary into a Biot slow wave (Thompson and Gist, 1993), which in turn causes a relative displacement between the pore fluid and the grains, thus generating a "streaming potential". The response depends on the rock permeability and the properties of the pore fluid. While electroseismic prospecting (ESP) has been proposed for hydrocarbon exploration, it has obvious potential applications to subsurface mapping of the water table and of groundwater contamination. More recently, Haartsen (1995) has explored the subject of electroseismic wave propagation in more depth. Thompson and Gist (1993) also introduced the concept of electro-osmotic surveying (EOS), in a sense the opposite of ESP. A source antenna at the surface generates a time-varying electric field, which at depth generates a fluid pressure gradient which in turn generates a seismic response.

Finally, a few new computational schemes have appeared or been used to a greater extent in the last few years. EM modelling and inversion will not be discussed to any extent, since they are covered by the review of Raiche (1994), although some new initiatives have appeared recently which pay particular attention to shallow geophysical applications (Ellis and Oldenburg, 1994; Farquharson and Oldenburg, 1993; Oldenburg *et al.*, 1993), and others may be applied to environmental problems (Li and Oldenburg, 1994). Modelling has also been applied specifically to groundwater studies (Flathe, 1963; Patra, 1970; Fitterman and Stewart, 1986). In a simpler mode, Sheriff (1992) showed how to carry out resistivity modelling using a spreadsheet program. For specific applications in environmental studies, quantitative interpretation schemes have been developed which use multiparameter data sets, including E & EM methods. Pesti *et al.* (1993) show that cokriging of electrical resistivity data with well data yield much improved estimates of the thickness and continuity of a clay aquitard. Kassenaar (1991) has used principal component analysis (PCA) for the quantitative interpretation of borehole logging data to yield lithology and aquifer "logs"; E & EM logs play a central role in the analysis, since the electrical properties are sensitive to the clay content. Such statistical techniques are not inversion methods, but instead circumvent some of the interpretation to illustrate certain features that dominate the collective, multi-parameter data set.

4. Some Special Considerations

4.1. VARIATIONS IN WATER SATURATION AND PHYSICAL PROPERTY HYSTERESIS

While the basic principles and methodology of resistivity and EM techniques can be to a large extent easily and directly carried over into environmental studies, there are certain "special problems" that must be considered. First of all, in most cases, environmental geophysical studies are used to delineate the extent of an anomaly, whether it be a buried barrel, a fracture zone in bedrock, or a leachate plume. We generally look at the relative response rather than the absolute response. The reasons for this are many, but one of the most important has not had, in my opinion, enough discussion. In simple terms, the response depends on the degree of water saturation, and that will vary markedly from season to season, and even from day to day. There is a certain delay, as well, for fresh rain water to penetrate the ground and percolate down to the water table. In areas with clay soils, water can remain "perched" at or near the surface (Figure 1), isolated from the actual regional water table, which may lie many metres below the surface. Such perched water tables are common.

In addition, the response does not depend simply on the degree of saturation, but instead depends on whether the soil is being saturated or dried. Laboratory studies by Knight and her co-workers have indicated that the physical properties of soil and rock display consistent and repeatable hysteresis as a function of the degree of water saturation (Endres and Knight, 1991; Knight and Endres, 1990; Knight, 1991a,b). A similar hysteresis in the hydraulic properties has been recognized by hydrogeologists for some time (Narasimhan, 1982). The physical process is readily explained: Initially, a relatively dry material will have only a thin layer of water coating the grains and pore spaces (Figure 9a, from Knight, 1991a, which corresponds to label "a" in Figure 10); the electric and dielectric properties are dominated by any water that may be present, and so the conductivity and permittivity increase markedly with a small initial increase in water content. The acoustic velocity, on the other hand, depends on the connection of water across the pores before water influences the velocity in any substantial way. As the water content increases, that is as the water table rises during a prolonged wet season, the pore water will become connected across the pores, and air bubbles can become trapped in the water (Figure 9b, and label "b" in Figure 10). The bulk water connection across the pores allows for acoustic wave propagation across the pores, and the surfaces of the air bubbles contribute to the conductivity and permittivity in much the same way as the surface effects at the water-grain boundaries do. That is, there is an enhancement of the conductivity and permittivity because of the surface effects at the air bubble-water boundaries. At a certain level of water saturation (approximately 70 to 80%, depending on the property involved) the air bubbles collapse and the properties approach the values for complete water saturation (Figure 9c, and label "c" in Figure 10). As the water drains away due to a fall in the water table during a prolonged dry period, water is left coating the pores and grains and the physical properties change in a simpler fashion (Figure 9d, and dashed curve and label "d" in Figure 10). The laboratory results have yet to be clearly isolated in field experiments; most locations rarely have dry intervals followed by extended periods of rainfall followed by another extended dry period. Roberts *et al.* (1991) examined the seasonal GPR response, but merely noted that reflections were repeatable.

Thus, in any interpretation, we must take into account the effects of partial saturation in the vadose zone. The easiest way to do this is to simply conduct a survey as much as possible within one extended period of time, so that the ground conditions are consistent for the entire survey. We would then look for readings that deviate from some background value without regard for the absolute readings. Alternatively, the survey would be laid out and repeated at regular intervals throughout a lengthy period of one or more years, so that the expected response can be determined for a given location at a particular time of year and in specified ground conditions (e.g., Cosentino *et al.*, 1978; Ernstson and Scherer, 1986). This latter strategy is recommended if monitoring of ground water conditions is being carried out. The work of Cosentino *et al.* (1978) and of Ernstson and Scherer (1986) was not carried out within the context of physical property hysteresis, but some of

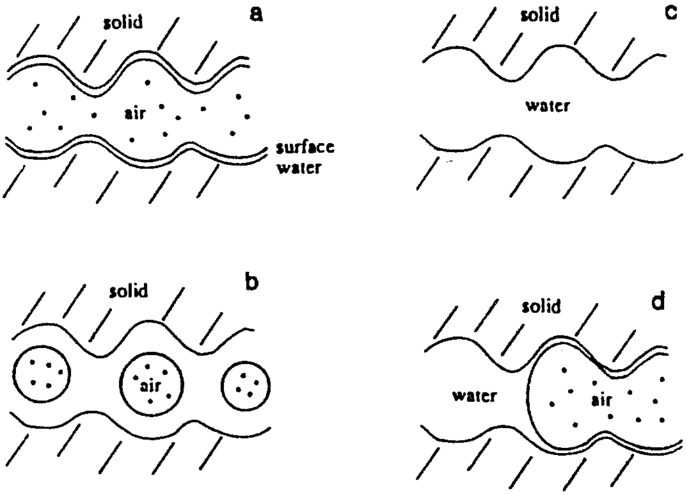


Figure 9. The geometry of pore water during a wetting (imbibition) and drying (drainage) cycle. The component figures, (a) through (d), correspond to the labels in the companion Figure 10. The initially dry pore (a) has only a thin layer of water on the grain and pore boundaries. As the water level starts to rise, the water layer builds up, until the water is connected across the pore (b); air bubbles are trapped, and the air bubbles contribute to the surface electric conduction mechanisms. At full saturation, the air bubbles collapse, and the contribution of the air bubble surfaces to the electric and dielectric properties disappears. Finally, as the water drains away, the thin film of water is left coating the grains and pores, but the drainage part of the cycle has no trapped air bubbles as the imbibition portion of the cycle did. (Adapted from Knight, 1991a.)

the procedures and results appear to foreshadow some of the concepts developed and extended by Knight and her co-workers.

4.2. EFFECTS OF TOPOGRAPHY

The effects of topography arise primarily from the change in distance from a particular layer, such as a clay layer, that may have a significant influence on the E & EM response. This reference layer provides a datum level for the survey. A case in point is one encountered in many coastal areas: The underlying sediments may be relatively flat-lying clay, silt and sand layers, such as are deposited in the low-energy environments of lagoons or lakes. The overlying sediments are often dune sands, or some similar aeolian deposit, which may have also been subsequently eroded by the action of wind and rivers. Thus, the measurements at stations located at higher elevations, farther from the datum reference level, will be lower that the measurements taken at stations that lie at lower elevations, closer to the datum reference level.

The data may be corrected for topographic effects in a number of ways, but the simplest and most-effective is likely the one proposed by Monier-Williams (1989), and summarised in Monier-Williams *et al.* (1990). The approach is strictly empirical; the exact nature of the correction will depend both on the site and on the

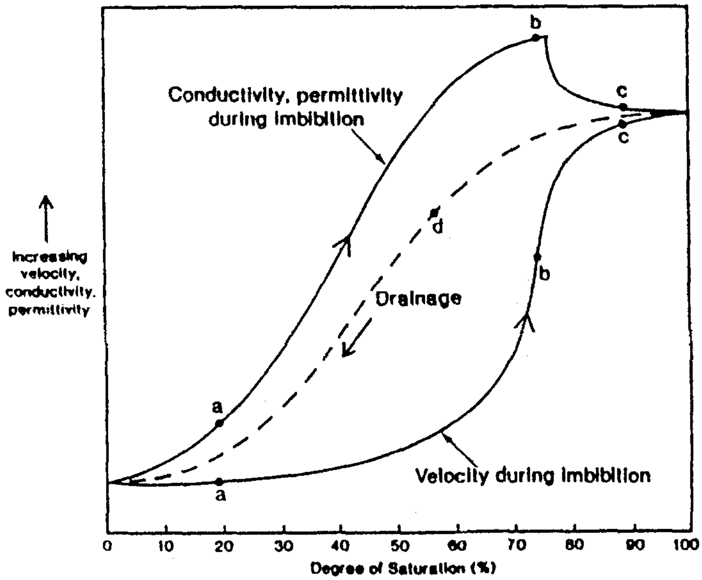


Figure 10. A schematic figure showing the basic features observed in the physical properties, specifically the acoustic velocity, electrical conductivity and dielectric permittivity, during an imbibition-drainage cycle. The labels "a" through "d" correspond to parts (a) through (d), respectively, of Figure 9. The conductivity and permittivity reach maximum values ("c") during imbibition, when surface effects at the boundaries between the water and trapped air bubbles make a small but significant contribution. (Based on results and concepts in Knight, 1991a, b; Knight and Endres, 1990; and Endres and Knight, 1991.)

particular geophysicist carrying out the survey. Experience has shown, however, that the results are, overall, robust; the exact details of the corrections may vary slightly, but the primary features are rarely, if ever, different.

Many of the features observed in surveys are contained in the basic model (Figure 11), developed to represent a specific situation encountered in a Brazilian survey (Monier-Williams *et al.*, 1990), but which may be used more generally. The subsurface stratigraphy consists of relatively horizontal strata, with a conductive clay layer near the surface. This clay layer is, using the terminology presented earlier, our reference datum level, which may alternatively be the water table, a relatively impermeable cemented sand layer, or similar feature. The horizontally bedded layers are capped by an undulating sand layer. The topographic variations are due to erosion, either by wind or water. The water table varies in depth below the surface. The electrical conductivity has a background variation with elevation, which is due to the varying depth from the surface to the reference layer. If we plot the conductivity against elevation, then there is a minimum base level, and all or almost all of the measurements are above this level (Figure 12). The exact form of this level will vary slightly from one interpreter to another, but the basic form will remain the same, and the resultant analysis will be similar. An equation is

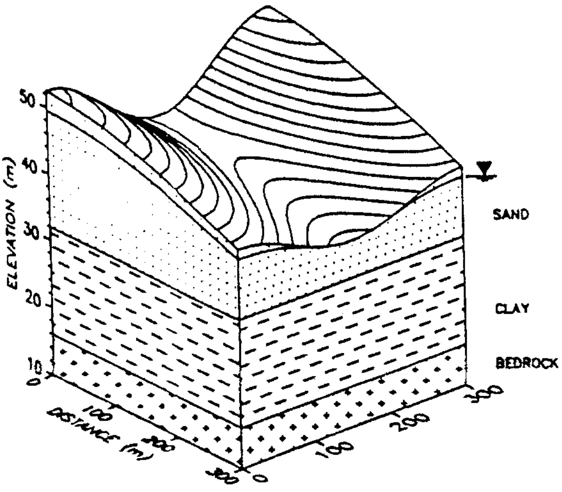


Figure 11. The model used to derive the method for empirically correcting shallow EM data for topographic variations. (From Monier-Williams, 1989, and Monier-Williams *et al.*, 1990.)

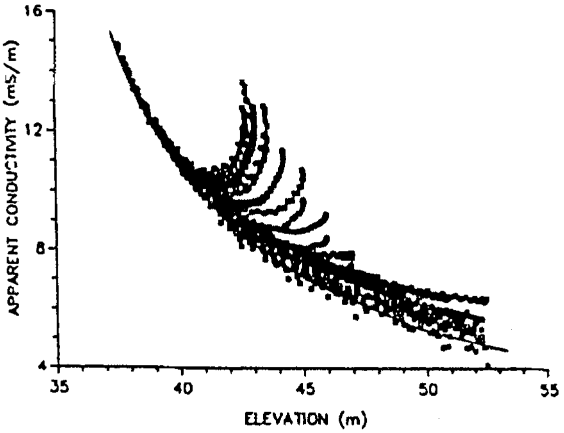
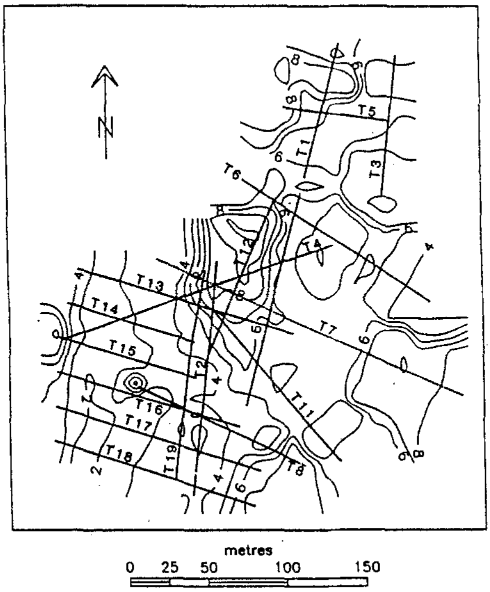


Figure 12. The variation of the apparent conductivity (in mS m^{-1}) vs the elevation (in m), showing the basal background trend (indicated by the solid line). This background trend is then used to define a corrected conductivity, in dB, as outlined in the text. (From Monier-Williams, 1989, and Monier-Williams *et al.*, 1990.)

found which best fits the background trend, either a low order power series relating conductivity to elevation or a logarithmic equation. The background conductivity, σ_B, is defined as a function of elevation, e, and the measured conductivity, σ, at location (x, y) and elevation e is normalised with respect to the background conductivity as (Monier-Williams *et al.*, 1990):

$$\sigma_C = 20\log_{10}(\sigma(x, y, e)/\sigma_B(e)) \tag{12}$$



Kaiapoi Landfill Study Site, Raw EM31

Figure 13. The raw EM31 apparent conductivity measured adjacent to the Kaiapoi landfill site. Contour intervals are 1 mS m^{-1}; the measurement points are indicated by the dots, which were arranged along lines as shown. The former landfill site is to the northwest; the current site is to the northeast. GPR profiles were also taken along lines T1, T4, T5, T6, and T7. Note the conductivity high (maximum 11 mS m^{-1}) along T12, between T4 and T6, which is due to the leachate plume emanating from the former landfill site. The flow is to the south-southeast, which is perpendicular to the regional trend, which is toward the coast to the east (to the right). There are other highs and lows as well, but the sand dune topography is interfering with the readings, and obscuring the main anomaly. (From Armstrong, 1993, and Nobes *et al.*, 1994.)

The corrected conductivity, σ_C, is expressed in decibels (dB). An anomalous value of 2 dB is 26% above the background trend, 4 dB is 58% above background, and 6 dB is 100% above the background trend in the conductivity vs elevation.

The technique has been successfully applied elsewhere (e.g., Armstrong, 1993; Nobes, 1994; Nobes *et al.*, 1994). For example, at a landfill site near the town of Kaiapoi, in New Zealand, a shallow EM31 survey was carried out to better delineate a possible leachate plume that had been previously detected by resistivity soundings and profiling (Broadbent, 1992). The dune sand topography ranged up to 3.5 m in elevation. The raw EM31 apparent conductivities show the presence of the plume (Figure 13), but there are numerous additional conductivity anomalies that, from field notes, are known to be correlated with topographic lows, that is the readings were simply that much closer to the water table. The conductivity vs elevation shows a clear trend (Figure 14). The corrected EM31 conductivities (Figure 15) show the presence of the main leachate plume flowing from a previous landfill site,

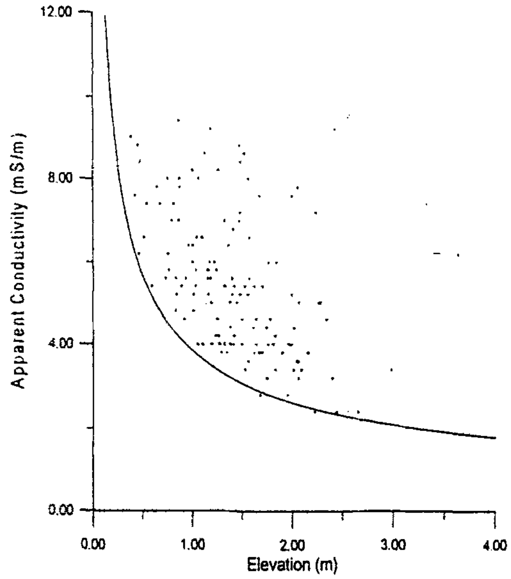


Figure 14. Apparent conductivity vs elevation, showing the clear background trend (solid line) in the data. (From Armstrong, 1993, and Nobes *et al.*, 1994.)

and there is a second anomaly that may be a secondary plume emanating from the current landfill operation.

4.3. ANISOTROPY AND HETEROGENEITY

There have been a number of papers over the years discussing the problems associated with geological complexity, or geological "noise", the associated effects of heterogeneity in E & EM methods, and how to try to deal with such complexity (e.g., Groom and Bailey, 1991; Zhao *et al.*, 1986; Jones, 1983). Hydrogeologists have used various statistical and stochastic averaging schemes to obtain regional measures of the hydraulic properties (e.g., Neuman, 1982; Durlofsky, 1991, 1992; Dykaar and Kitanidis, 1992a, b). Amongst both geophysicists and hydrogeologists, there has been a growing realisation that the "noise" contains information, but the geologic "noise" has been to a greater or lesser extent discarded to allow further interpretation to proceed. As noted by Flathe (1976), a careful consideration must be made of the geological model to be used for the interpretation of geophysical survey results, in his case resistivity, for hydrogeological applications. If the geophysical results depart significantly from the proposed geological model, then the model must be reconsidered.

Hydrogeologists have been moving from a regional picture of groundwater flow, to a realisation that the subsurface is complex, and that "hidden" channels can provide flow paths for both groundwater resources and for contaminants (Figure 16, from Davis and Thornhill, 1985). Larger scale channelling should be apparent

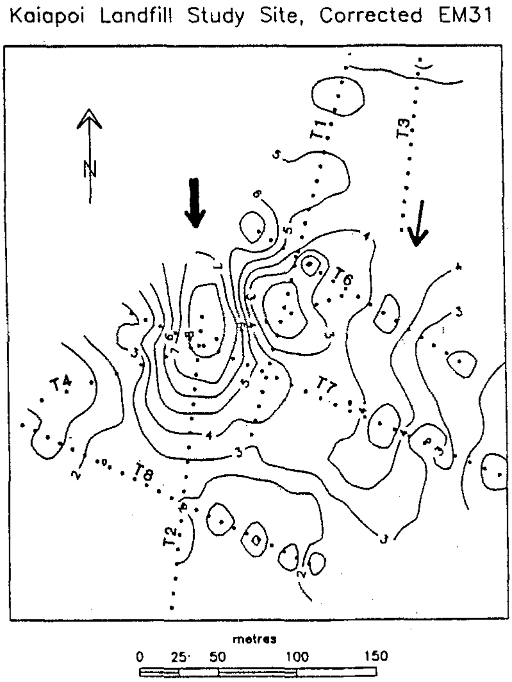


Figure 15. The corrected conductivity, in 1 dB contour intervals, shows a distinct primary leachate plume (large arrow, upper left), and a potential secondary plume (smaller arrow, upper right) which may be flowing along a buried channel from the current landfill operation. The primary anomaly is shifted to the west slightly, and the numerous highs and lows are gone. The secondary anomaly was hidden because of effects of the dune topography. (From Nobes *et al.*, 1994, adapted from Armstrong, 1993.)

as anisotropy in the geophysical responses, but may be obscured by the details arising from the heterogeneities. Such channels can be easily missed by borehole studies, yet, as mentioned earlier, this is still very much "standard practice". There may be a whole series of such channels, scoured and filled over time as a river winds back and forth across a landscape. The problem must be to provide a quantitative characterization of the subsurface hydraulic heterogeneity and anisotropy.

A number of researchers are starting to tackle this problem. Desbarats and Bachu (1994) examine the implications of the range of scales of heterogeneity in hydrogeology using a statistical framework. Some of the geophysical methods described earlier (Section 3) are being used to examine the heterogeneity and anisotropy of the subsurface hydrogeology, such as the relationship between the resistivity and transmissivity (Ritzi and Andolsek, 1992), and surveys using tensor resistivity (Bibby 1977, 1986) or using square resistivity arrays (Habberjam 1972; Habberjam and Watkins, 1967; Lane *et al.*, 1995) are potentially useful tools.

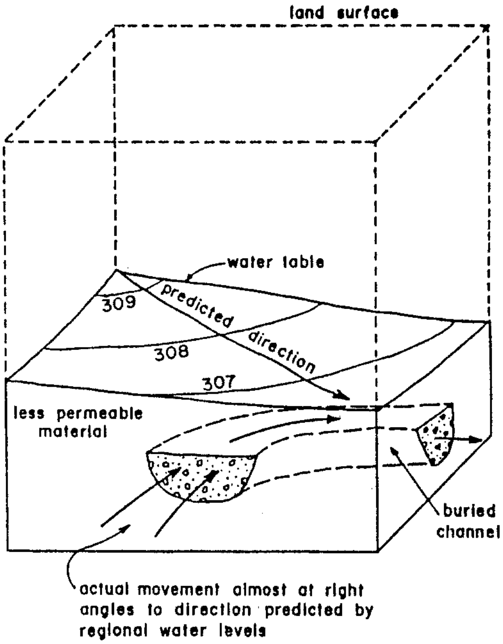


Figure 16. Regional water table levels will indicate an average predicted flow trend, perpendicular to the water level elevation contours, but subsurface channels, other heterogeneities, and anisotropy can cause the flow path to radically diverge from the regional trend. (From Davis *et al.,* 1985.)

The relationships between the hydraulic properties, and the transverse resistance, T, and longitudinal conductance, S, in particular, have been examined in a number of studies (Henriet, 1976; Ponzini *et al.*, 1984; Kalinski *et al.*, 1993).

$$\mathsf{T} = \mathsf{h}\rho = \mathsf{h}/\sigma \tag{13a}$$

and

$$\mathsf{S} = \mathsf{h}/\rho = \sigma\mathsf{h} \tag{13b}$$

where h is the layer thickness and ρ is the layer resistivity. The parameters T and S are sometimes, though less frequently now, called the Dar-Zarrouk parameters (Maillet, 1947). The hydraulic conductivity, K, is then examined as a function of T or S. The process may be refined by substituting the transverse resistivity, ρ_T perpendicular to bedding, for ρ in (13a) and the longitudinal resistivity, ρ_L parallel to bedding, for ρ in (13b), as suggested by Ponzini *et al.* (1984) and Kalinski *et al.* (1993). If there are a number of thin beds, which cannot be separately resolved, then ρ_T and ρ_L are defined as (Maillet, 1947; Campbell, 1977):

$$\rho_\mathrm{T} = \Sigma_i \mathsf{H}/(\mathsf{h}_i/\rho_i) \quad \text{so that} \quad \mathsf{T} = \mathsf{H}\rho_\mathrm{T} \tag{14a}$$

$$\rho_{\mathrm{L}} = \Sigma_i \rho_i \mathrm{h}_i/\mathrm{H} \quad \text{so that} \quad \mathrm{S} = \mathrm{H}\rho_{\mathrm{L}} \tag{14b}$$

where ρ_i is the resistivity of layer i, and h_i is the thickness. H is the total thickness of all of the thin beds. Henriet (1976) and Ponzini *et al.* (1984) concentrated their attentions on T, and the information it may convey about the extent of the protection provided by any aquitards that may be present. Kalinski *et al.* (1993) correctly point out that which of T or S we use depends on the nature of the aquifers and aquitards. If the protective layers are more conductive than the aquifers, as will be the case when the aquifers are filled with very fresh water and the aquitards have high clay contents, then S may be the more appropriate parameter to use. In arid environments, on the other hand, the very presence of water makes the aquifers appear conductive, and the aquitards may instead be cemented layers, in which case T may be the parameter of choice. Schimschal (1981) went the next logical step and considered the anisotropy of the hydraulic conductivity, defining K_{T} and K_{L} in a fashion similar to that used in Equation (14):

$$K_{\mathrm{T}} = \Sigma_i \mathrm{H}\,(\mathrm{h}_i/\mathrm{k}_i) \quad \text{and} \quad K_{\mathrm{L}} = \Sigma_i \mathrm{k}_i \mathrm{h}_i/\mathrm{H} \tag{15}$$

where as before h_i is the thickness of the ith thin bed, and k_i is the hydraulic conductivity in layer i. Schimschal combined the results of resistivity surveys with neutron logs, core samples, and the measured hydraulic conductivities to derive empirical relationships for a specific site, so that the surface geophysical surveys could be interpreted in greater detail and with greater utility across a dam site in New Mexico.

The foregoing discussion still contains an implicit assumption of an anisotropy that arises from a large-scale average of some simple small scale structure, in that case the superposition of numerous thin beds. However, there still remains the problem of the greater complexity arising from wide-spread heterogeneity, which may or may not have an average directional trend. The GPR data shown in Figure 7 and the EM data in Figure 15 illustrate the point; while the regional hydraulic trends are readily identified, with flows directed eastwards toward the coast, there will be local variations due to underlying ancient channels, bars, and meanders, and the local flow may be perpendicular to the regional trend. We are faced with attempting to characterise the hydraulic properties using geophysical surveys in the presence of geological complexity.

The change in radar resolution for antennas of different primary frequencies may be used, for example, by combining data gathered along a common line at different frequencies to better characterise the heterogeneity of the subsurface. We may also analyse the continuity of reflectors along single profiles, to obtain either qualitative or quantitative estimates of heterogeneity. One approach is to look for the kinds of reflectors that may be diagnostic of certain depositional settings that give rise to heterogeneous flow (Huggenberger, 1993; Huggenberger *et al.*, 1994). In some sense, the techniques are negative ones, since we are using statistical measures of continuity to look for the lack of continuity. Another approach may be to intensively study one site, as a few groups are starting to do, and try to understand what measures yield the "best" measure of heterogeneity of the hydraulic properties. We can use shallow E & EM to delineate individual shallow channels, but the environments within which we are liable to have shallow buried channels are those settings where we often get a multitude of such channels, thus adding to the complexity. This is where a great deal of effort will be needed and expended in the future.

5. Specific Environmental Applications

While some illustrative items have been presented in the foregoing sections, the examples presented in this section serve to show the variety of applications and approaches that fall under the general heading of "environmental geophysics". The reader is referred to the journals listed in the Introduction, above, for additional case histories which may appear on an irregular basis. The range of applications can be grouped into a few broad ranges of categories: (1) mapping of groundwater resources (Figure 1, labels "4" and "5"); (2) characterization of aquifer structure and properties, including the presence or absence of protective aquitards (Figure 1, labels "1", "2" and "3"); (2) mapping and monitoring of contamination, including salt-water incursion into aquifers (Figure 1, labels "6" and "7"); (4) soil moisture and salinity; and (5) monitoring the integrity of hazardous waste disposal sites, including the characterization of fracture zones, which can also be gathered under (2).

5.1. GROUNDWATER RESOURCES

Some of the earliest work used resistivity methods to search for groundwater resources (e.g., Swartz, 1939; Johnston and Huberty, 1940), and descriptions of the search for new groundwater resources continue to make up a major portion of the literature. Electrical methods, including resistivity, SP and IP, have dominated the use of E & EM methods in groundwater surveys, much of it concentrated in the search for fractured bedrock aquifers in arid and semi-arid areas (Aubert *et al.*, 1984; Bose *et al.*, 1973; Briz-Kishore *et al.*, 1992; Fournier, 1989; Homilius, 1969; Minasian, 1979; Satpathy and Kanungo, 1976; Vacquier *et al.*, 1957; van Overmeeren, 1981; Vincenz, 1968; Worthington; 1977; Zohdy, 1969; Zohdy and Jackson, 1969). Many of these studies have also been concerned with the delineation of the boundary between salt-water and fresh-water, and often used combinations of other techniques and data. Similar work has been carried out to look for faults or valleys buried in unconsolidated sediments (Breusse and Huot, 1954; Merriam, 1954; Lennox and Carlson, 1967; Mladenovic and Krulc, 1969; Rijo *et al.*, 1977; Vandenberghe, 1982). More recent studies have used sophisticated microprocessor systems (Olayinka and Barker, 1990), or combinations of resistivity with EM (Beeson and Jones, 1988; Hazell *et al.*, 1988), and with remote sensing (Carruthers *et al.*, 1991). IP methods have also been used (Bodmer *et al.*, 1968; Ogilvy and Kuzmina, 1972).

EM methods have become much more common in the search for groundwater resources; Palacky (1987) discusses the nature of groundwater and aquifer targets and provides some references. Palacky himself was involved in one of the early applications of EM in the search for groundwater (Palacky *et al.*, 1981) again in fractured bedrock in an arid region. More recent EM studies have been mainly airborne surveys carried out in arid and semi-arid regions (Bromley *et al.*, 1994; Paterson and Reford, 1986). AMT (Bernard *et al.*, 1990) and TEM (Goldman *et al.*, 1991; Taylor *et al.*, 1992) have also been used. With the advent of the fast-rise time TEM systems, shallower surveys for groundwater work are now realistic, and will become more commonplace. EM methods have also been combined in multiparameter surveys (Goldman *et al.*, 1994; Trushkin *et al.*, 1995), just as for the resistivity methods.

In all of these cases, care had to be taken in interpreting the survey results. In some geologic settings, arid and semi-arid environments for example, the aquifers will be relatively conductive, since any amount of water will make the underlying strata more conductive. In areas where the fresh-water aquifers are interbedded with clay aquitards, or where fresh-water lenses are interspersed with salt water, then the desired targets are more resistive. As in all geophysical surveys, if more information, both geological and hydrogeological, is available, then better and more detailed analyses and interpretations are possible; this point is not new, see for example Flathe (1976), but does bear repeating.

5.2. AQUIFER AND AQUITARD PROPERTIES

Once the resource has been identified, the continuity and connectivity of the aquifer need to be clarified, particularly for fractured aquifers and karst terrains; and E & EM surveys have played a role here as well (Dutta *et al.*, 1970; Kaspar and Pecen, 1975; Lazuo and Stylianou, 1989; Vogelsang, 1987). A number of surveys have been carried out specifically to determine the continuity of an aquifer or of a protective aquitard (Bauman, 1989; Bauman *et al.*, 1990; Bourgeois *et al.*, 1994; Chouteau *et al.*, 1994; de Lima, 1990; Draskovits and Fejes, 1994; Flathe, 1976; Mbonu *et al.*, 1991; Ogilvy *et al.*, 1991; Owen *et al.*, 1992; Park *et al.*, 1990; Serres, 1969; Sreedhar Murthy *et al.*, 1984), and GPR surveys, because of the nature of the data, are being used more (Bauman, 1989; Bauman *et al.*, 1990; Benson and Yuhr, 1990). There is a growing literature describing what might best be called "radar stratigraphy", analogous to seismic stratigraphy (Huggenberger, 1993; Huggenberger *et al.*, 1994; Jol and Smith, 1991); many aspects of radar stratigraphy have been specifically used for mapping aquifers (Beres and Haeni, 1991).

Characterization of the aquifer continuity and hydraulic properties are often determined by tracer tests; a certain measured amount of an innocuous tracer, such as a concentrated solution of ordinary salt and water, is pumped into the aquifer within a short period of time. The injected tracer, known as a *slug*, can be followed by sampling from adjacent wells drilled for the purpose. Common practice, however, is to use resistivity or, more rarely, EM methods to monitor the flow of the tracer at depth. While the use of E & EM methods for tracer tests has occurred for many years (Schiavone and Quarto, 1984; White 1988; Yager and Kappel, 1987; Lantier, 1994), only recently has a systematic study been carried out to determine what electrode configurations are optimum in tracer tests (White, 1994). Many of these same studies are directly applicable to contaminant studies, and some are, in fact, carried out to determine what flow paths contaminants might follow, so that monitoring arrays, both for geophysical surveys and for sampling wells, can be installed for greatest efficiency and economy.

The more direct utility of E & EM methods in the determination of quantitative hydraulic properties was discussed in Section 4.3. There is a large range in the degree to which the aquifer properties are defined. Some studies are simply carried out to determine the extent of anisotropy (Christensen *et al.*, 1990; Darboux-Arfouda and Louis, 1989) or the degree of heterogeneity (Turberg *et al.*, 1994; Verma and Bischoff, 1989). Turberg *et al.* made a point of comparing the geophysical heterogeneity with the geological heterogeneity, and found that the geophysical results reflected the reality of the underlying geological complexity (Figure 17). Shettigara and Adams (1989) used the gradient array to examine the lateral variability of the resistivity and thus mapped localised water resources. Downhole E & EM methods are commonly used to examine both the hydraulic properties and the water quality (Duran and Magnusson, 1984; Löw *et al.*, 1994; Pedler *et al.*, 1990), and electrical resistance tomography has been used to study the hydrological properties of core samples (Daily *et al.*, 1987). A growing list of workers are attempting to characterise the hydraulic properties from surface and borehole E & EM surveys (Kalinski *et al.*, 1993; Ponzini *et al.*, 1984; Ritzi and Andolsek, 1992; Schimschal 1981; Sill and Sjostrom, 1990), a subject discussed in more detail previously (Section 4.3). A number of studies have been designed recently to carry out hydrogeological studies that are more broadly based (Auken *et al.*, 1994; Christensen and Sørensen, 1994). Dassargues (1992) has used a large number of resistivity soundings and borehole logs combined with hydrogeological and geological information to construct a detailed finite-element model of the heterogeneous flow in an alluvial plain between the Albert Canal and the Meuse River in Belgium. Such a synthesis of geophysical, geological and hydrogeological data sets enables a complex and sophisticated analysis of the flow to be carried out, and options for future uses of the area can be better evaluated.

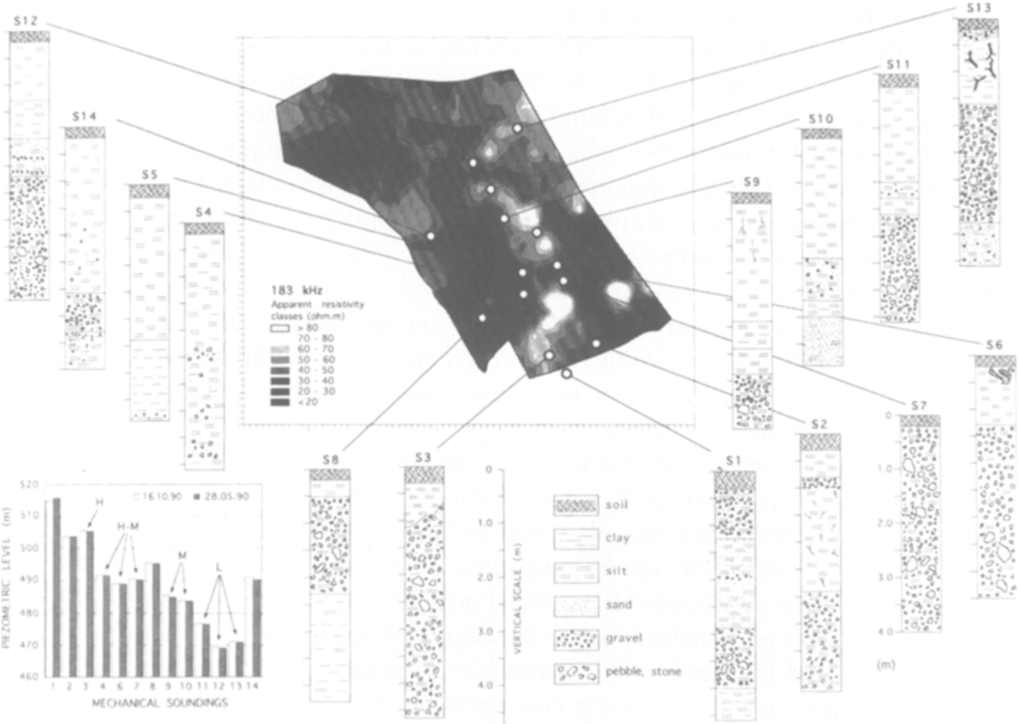


Figure 17. Radio-MT apparent resistivity for 183 kHz compared with 14 lithologic logs (all at the same depth scale) and the corresponding water elevations ("Piezometric level", lower left) (from Turberg *et al.,* 1994). The water levels are classified according to the positions of the measurement points in the channel, "H" for the upper part, "M" for the middle part, and "L" for the lower part of the channel.

5.3. WATER QUALITY AND MAPPING OF CONTAMINANTS

The techniques used to examine the aquifer and aquitard properties can also be used to estimate the water quality. There is, however, a substantial proportion of the literature that focuses on the mapping and delineation of contaminants and/or the flow paths for contaminants. While the work is often directly and obviously motivated by a specific goal or programme, such as the mapping of salt-water intrusion or the delineation of faults in a hard rock repository for radioactive waste, it should be emphasised that the techniques are more widely applicable. However, to ease the discussion, I will divide the subject of water quality into four classes: (1) the mapping and monitoring of salt-water intrusion, including the delineation of salt-water/fresh-water boundaries; (2) the characterization of fractures in rock near a radioactive waste storage facility, whether proposed or in operation; (3) the mapping and monitoring of contaminants, whatever the source; and (4) the examination and monitoring of containment structures, such as landfill liners or containment walls.

5.3.1. *Salt-water boundaries and salt-water intrusion*

Many of the surveys carried out for groundwater resources, including the earliest references (Swartz, 1937, 1939) have also incorporated, either explicitly or implicitly, the search for boundaries between salt water and fresh water. This section, however, will consider those studies that have explicitly focussed on the delineation of salt-water incursion into fresh-water aquifers, or the mapping of lenses of fresh water within a salt-water aquifer. As noted earlier, most of the techniques used in the search for salt water can be used for mapping and monitoring contaminants and for tracer tests.

The mapping of the boundary between salt water and fresh water at depth has made use of both resistivity (Hallenbach, 1953; Leite and Barker, 1978; Mbonu *et al.*, 1991; Mladenovic and Krulc, 1969; Oteri, 1981; Patra and Battacharya, 1966; Schrøder, 1970; Urish and Frohlich, 1990; van Dam and Muelenkamp, 1967; van Overmeeren, 1989; Volker and Dijkstra, 1955; Worthington, 1977; Zohdy, 1969; Zohdy and Jackson, 1969) and of EM. Frequency domain EM systems have been widely used (Bartel, 1983; Bartel and Newman, 1991; Bernard *et al.*, 1990; Hanson *et al.*, 1991; Sengpiel, 1986; Stewart, 1982; Verma and Bischoff, 1989) and TEM systems have become more popular recently (Goldman *et al.*, 1991; Koefoed and Biewinga, 1976; Mills *et al.*, 1988; Sandberg, 1987). When we look at the ages of the work, the shift with time from resistivity to FEM to TEM is apparent. Increasingly, however, resistivity and EM methods are being combined (Yang and Tong, 1990; Sandberg, 1993), or combined with downhole logging (Frohlich, 1974), or in a tomographic survey mode (Bevc and Morrison, 1991; Bryant *et al.*, 1991). Resistivity and EM have also been combined with GPR, in particular to examine the hydrogeology of deltaic aquifers in fjords to locate saline waters to be used for fish farming (Soldal *et al.*, 1994). In a few cases, downhole logging has been used alone (Brassington *et al.*, 1992; Pelder *et al.*, 1990), but this is not recommended except as a last stage of investigation to complement other geophysical surveys.

Given the nature of the salt-water boundary and its chemistry, IP and SP methods have been used to a greater extent in mapping the extent of salt water and leachates in aquifers than in the more direct detection of groundwater resources. IP has been particularly useful in combination with resistivity (Roy and Elliott, 1980; Seara and Granda, 1986) or TEM (Sandberg, 1989). Combinations of techniques help to alleviate some of the weaknesses inherent in the use of resistivity, IP or EM alone, and multiparameter surveys should be encouraged. For example, Goldman *et al.* (1994) found that NMR helped define the water content at depths of 10's of metres, and TEM could then be used to evaluate the water quality.

5.3.2. *Fracture Mapping and Characterization*

Much of the work on the mapping of bedrock fractures and their continuity and hydraulic properties has been generated because of the concern over the safety of radioactive waste disposal sites. Airborne EM, including VLF, have been used extensively (Bazinet and Legault, 1985; Craig, 1989; Hasbrouck, 1990; Pedersen *et al.*, 1994; Sinha and Hayles, 1988; Soonawala and Hayles, 1986) for surface mapping, although earlier studies used resistivity (Arandjelovic, 1966), consistent with the pattern observed previously for salt-water mapping (Section 5.3.1). The fractures are then examined in detail, both for extent and geometry, and for the hydraulic properties, using borehole, cross-hole tomographic and borehole-to-surface tomographic resistivity (Craig, 1989; Jämtlid *et al.*, 1984; Shima and Saito, 1988) and radar (Andersson *et al.*, 1990; Holloway and Stevens 1990; Niva *et al.*, 1990; Olsson *et al.*, 1984, 1992). Some more general work on the monitoring of fluid flow using resistivity and EM tomography can be applied to the detailed mapping of fracture zones and their properties (Lytle *et al.*, 1981; Nelson et al, 1982; Zerilli and James; 1991). Rouhiainen (1987) combined a mise à la masse survey with cross-hole seismic data to better characterise the fractures at a radioactive waste disposal site.

While fracture mapping has been dominated by radioactive waste research, the mapping of fracture continuity and hydraulic properties is needed when evaluating fractured bedrock aquifers (Dutta *et al.*, 1970; Kaspar and Pecen, 1975; Lazuo and Stylianou, 1989; Vogelsang, 1987; Lane *et al.*, 1995), as noted in a prior section (5.2). Detailed mapping of fractures has also been carried out where there is a concern with the migration of chemical contaminants (Yager and Kappel, 1987), and for simple mapping of karstic features (Guerin and Benderitter, 1995).

5.3.3. *Mapping and Monitoring of Contaminants*

In Section 2.2, the basis was presented for the utility of E & EM methods in mapping and monitoring contaminants. While the discussion there centred on saline fluids, the results are more generally applicable. Saksa and Korkealaakso (1987) have shown that the electrical conductivity increases as a function of the concentration of chloride, permanganate ($KMnO_4$), phenol (C_6H_5OH), and a chlorinated hydrocarbon (1,2-dichloroethane). Towle *et al.* (1985), Vanhala *et al.* (1992) and Vanhala and Soininen (1995) have similarly examined the IP response of hydrocarbons and organic chemicals, respectively, and Kutrubes (1986) has shown that hazardous chemicals, such as dry cleaning fluids, affect the dielectric permittivity. Thus, much of the applicability of E & EM methods can be considerably broadened.

In addition to the laboratory studies mentioned above and in Section 2.2, a number of field studies have demonstrated the utility of surface E & EM methods for mapping and monitoring the flow of contaminants, both landfill leachates (Armstrong, 1993; Broadbent, 1992; Draskovits and Fejes, 1994; Erchul, 1990; Fried, 1975; Glaccum *et al.*, 1982; Greenhouse and Slaine, 1983; Hanson *et al.*, 1991; Kelly, 1976; Monier-Williams, 1989; Monier-Williams *et al.*, 1990; Ogilvy and Bogoslovsky, 1979; Senos Matias *et al.*, 1994; Stierman, 1984; Stollar and Roux, 1975; Smith, 1992; Warner, 1969; Weber and Flatman, 1986; Zonge *et al.*, 1985) and acid mine drainage (Brooks *et al.*, 1991; Ebraheem *et al.*, 1990; Merkel, 1972). McNeill and Bosnar (1986) and Nobes (1994) (quoting results from Armstrong, 1993) show that the apparent conductivity does correlate with TDS. Many surveys are carried out to guide the location of sampling wells (Donohue *et al.*, 1990; Kobr and Linhart, 1994; Nobes, 1994).

In principle, electrical methods should be well suited to delineate conductive zones, but Frohlich et al. (1994) point out that at larger electrode spacings, the voltage signal becomes small, and perhaps difficult to measure, in conductive layers. This is particularly a problem in coastal environments, the focus of Frohlich *et al.* They suggest that instead of using a much larger current, a number of readings should be taken. The errors should be analysed for each measurement, and then the measurements should be stacked together to improve the overall signal-to-noise.

While the depth of penetration of TEM has, in the past, been too deep to adequately map the extent of leachates, the fast-rise time systems make shallower depths accessible. Buselli *et al.* (1990) have done some early work on the detection of leachate, and Melis and Nobes (work in progress) are currently investigating the utility of TEM for mapping the presence and extent of leachate beneath and adjacent to landfill sites. The potential use of TEM is still being evaluated.

Borehole methods also have serve to confirm and to calibrate the surface E & EM methods. Irons (1989) and Nelson *et al.* (1982), in particular, discuss the use of logging at a hazardous waste disposal site, and McNeill and Bosnar (1991) discuss EM logging for the delineation of leachates, which can split into lobes that follow subtle preferential flow paths. Borehole methods are also being adapted for cross-hole and surface-to-borehole tomographic surveys (Asch and Morrison, 1989; Bartel and Newman, 1991; Bevc and Morrison, 1991; Bryant *et al.*, 1991; Daily and Owen, 1990, 1991; Spies and Ellis, 1995; Zerilli and James, 1991). Daily *et al.* (1992, 1995) and Daily and Ramirez (1995), in particular, illustrate how far the technique has come for monitoring the flow of fluid, both water (Daily *et al.*, 1992) and trichloroethylene (Daily and Ramirez, 1995), through the vadose zone. While the interpretation by Daily *et al.* (1992) of the response in terms of the degree of saturation does not take into account the possible effects of physical property hysteresis (Figures 9 and 10), as described in Section 4.1, the results are nevertheless excellent. I will not attempt to present their colour figures here, but refer the reader to the Daily *et al.* (1992) article.

Multiparameter surveys are, as before, useful for corroboration of results and thus for better interpretation of the results. For example, GPR profiles taken across the leachate plumes shown in Figure 15 show areas with little or no return of reflected energy, line T1 for example (Figure 18, from Armstrong, 1993, and Nobes *et al.*, 1994). Goupil *et al.* (1990) used EM and GPR to map the flow of biogas through fractured limestone. Soldal *et al.* (1994) used GPR to follow up on resistivity surveys; the loss of GPR reflections was indicative of saline pore waters. Multiparameter surveys have been used to look for buried containers that may enclose hazardous materials (Annan *et al.*, 1990; Carr *et al.*, 1990; McConachie, 1994); EM and GPR combined with magnetometer surveys appear to be most productive. GPR has also been used alone to map the extent of leachates and other

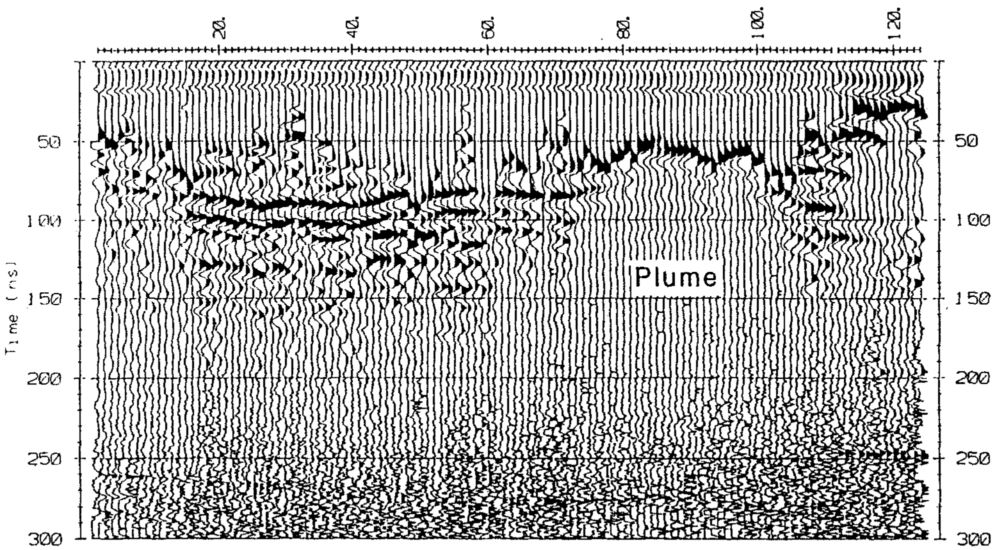


Figure 18. GPR profile along the southern half of line T1, south of the Kaiapoi landfill (Figures 13 and 15). The northern end (to the left) starts in an area affected by leachate. The profile crosses an unaffected area where the reflectors are clear and strong, and then passes over a lobe of the primary leachate plume noted in the corrected EM conductivity (Figure 15). The stratigraphy apparent on either side of the plume continues through it, but the energy is attenuated by the conductive leachate. (From Armstrong, 1993 and Nobes *et al.*, 1994).

contaminants (Daniels and Vendt, 1990). In order to test the efficacy of both single and multiparameter surveys, Schönivsky (1991) has proposed the construction in Europe of an environmental geophysics "test park", where different object would be buried and different survey instruments and techniques can be tested. Such a test park already exists in southern Ontario, on the campus of the University of Waterloo. There are buried metal barrels, pipes, sheets and blocks, and buried plastic objects as well. A number of techniques have been tested (e.g., Annan *et al.*, 1990).

One of the most complete multiparameter surveys yet to appear in the literature describes, briefly, the Borden experiment (Greenhouse *et al.*, 1993). More detailed reports of the individual aspects of the experiment will undoubtedly appear in the literature over the next few years (e.g., Brewster and Annan, 1994), but the reader is encouraged to read the summary paper. A dry cleaning solvent, perchlorethylene (PCE, C_2Cl_4), was injected into a contained location, and its progress through the surficial sands was monitored by surface resistivity, EM and GPR surveys, cross-hole radar tomography, TDR probes, and borehole neutron, natural gamma, gamma-gamma density, resistivity and EM logging. PCE is a DNAPL (dense non-aqueous phase liquid) that is more dense than water, and thus sinks through the vadose zone and down into and often through the water table. DNAPL's are often dangerous chemicals that are difficult to remove from the water supply once a spill

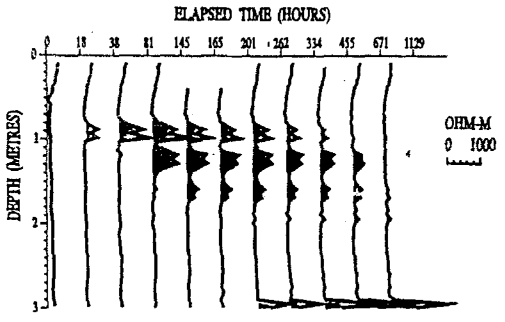


Figure 19. Borehole resistivity as a function of time from just before injection of PCE at 0 hours (far left) to 1129 hours after injection (far right). The results show the progressive downward flow of the PCE through the surface unconfined sand layer. Subtle layers are apparent, where the PCE briefly pools before continuing to flow downward. Cores of the sand appear to be homogeneous and are apparently lacking in bedding. (From Greenhouse *et al.*, 1993.)

has occurred. Thus the utility of geophysical methods to detect and delineate the extent of DNAPL's is important and of great interest to environmental scientists and regulators. The results could probably be described as spectacular. While the surface resistivity and EM methods did not have the sensitivity or resolution to detect the thin PCE beds that formed as the DNAPL pooled at subtle stratigraphic beds, clear responses were obtained by the downhole methods and surface GPR. The downhole resistivity (Figure 19) and surface GPR (Figure 20), for example, both from Greenhouse *et al.* (1993), illustrate the evolution of the PCE flow with time.

5.3.4. *Inspection of Containment Facilities*

One reason for the extensive development of E & EM methods for mapping contaminants is that the landfill sites and hazardous waste disposal sites sometimes leak. Buried petrol tanks, reservoir dams, containment dikes, and underground conduits also leak, and such leaks must be detected easily and promptly. As an extension of the delineation of contaminants, then, the use of geophysical methods to determine the integrity of containment structures has grown. The same pattern of evolution of technique usage with time, from resistivity to EM to GPR, is apparent here. One of the earliest articles that directly refers to the use of E & EM techniques for detecting leaks is that of Unz (1959), who used resistivity. SP has been especially used in leak detection (Bogoslovsky and Ogilvy, 1970; Ogilvy *et al.*, 1969; Wurmstich *et al.*, 1991), as has IP (Bogoslovsky and Ogilvy, 1973a, 1973b; Ogilvy and Kuzmina, 1972), although the literature for the subject appears to be dominated by a very few workers. SP and IP techniques have, nonetheless, proven useful in the detection and delineation of leaks in dams and in containment walls.

Resistivity has similarly been used for locating leaks, on its own (Parra, 1989; Parra and Owen, 1989), in combination with seismic (Carpenter *et al.*, 1991),

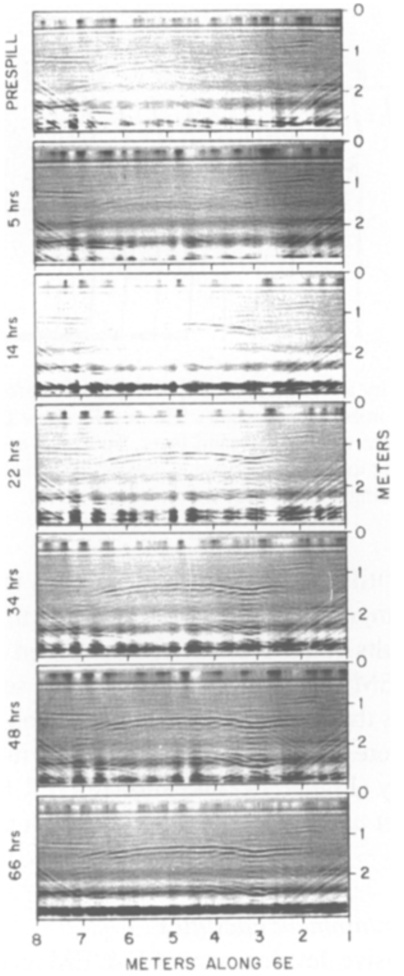


Figure 20. A succession of 500 MHz GPR profiles taken along one of the central lines across the controlled PCE spill site, adjacent to the location of the resistivity log shown in Figure 19. The prespill profile is at the top, and the time since the spill increases towards the bottom. The diagonal reflective events at the lower left and right of each frame are reflections from the metal containment walls. The PCE solvent enhances the subtle stratigraphy as it flows down through the surficial unconfined sand layer. (From Greenhouse *et al.*, 1993.)

combined with borehole logging (Abu-Zeid, 1994), and in combination with GPR (Holub and Dumitrescu, 1994). Multi-parameter surveys help to reduce the problems of equivalence. The pore fluid resistivity has also been used to trace the origins of surface waters (Ogilvy *et al.*, 1979), that is to determine whether a pool of surface water originated from a containment pond or reservoir. Barton (1985) used EM to examine the integrity of a containment wall, and de Feijter *et al.* (1990) used GPR to detect erosion under a dike along a shore. Tomography has had a part to play here as well; Daily and Ramirez (1990) have used EM tomography to monitor the penetration of grout, a material that hardens into a relatively impermeable containment wall, into fractures.

5.4. SOIL MOISTURE AND SALINITY

Soil and agricultural scientists are concerned with the water content, storage capacity, and salinity of soils. While SP and resistivity have been used for locating the water table (Johnston and Huberty, 1940; Fournier, 1989; Birch, 1993), EM, GPR and TDR dominate the determination of soil moisture content, salinity and the position of the water table. Birch (1993) points out that while SP can be used to locate the water table using Fournier's (1989) method in most of the test cases, the technique is non-unique; the response does not appear to be related to the thickness of the vadose zone, as suggested by Fournier, but rather is highly correlated with the topography (Birch, 1993). GPR, on the other hand, is highly sensitive to the position of the water table, because of the dominant influence of the water content over the dielectric permittivity (Section 2.2.2). Recent GPR work has investigated the utility of GPR for locating the water table (Annan *et al.*, 1991; Daniels and Vendt, 1990), for mapping water movement in the vadose zone (van Dalfsen, 1990; Vellidis *et al.*, 1990), and, along the same line, the seasonal variation in the water table (Roberts *et al.*, 1991). Changes in the soil moisture content are, of course, related to the position of the water table, so that the studies noted above deal with the broader topic of soil moisture as well. TDR, on the other hand, is more directly related to the soil moisture content, and that is where its major application lies (Nadler *et al.*, 1991; Selker *et al.*, 1993; Topp *et al.*, 1980, 1988; Zegelin *et al.*, 1990, 1992), as was outlined earlier (Sections 2.2.2 and 3.3). Knight (1992) has recently investigated the effects of lateral variations in the soil water content on the TDR response.

Finally, EM has been used both for determining soil moisture and salinity (McKenzie *et al.*, 1989; van der Lelij, 1983; Williams, 1983). The fixed frequency, loop-loop shallow EM systems and VLF have been the most widely used tools for soil salinity and moisture mapping, although some of the modified resistivity and EM techniques described in Section 3, such as the pulled array continuous electric profiling (PA-CEP) and electric quadripole methods, may have application for such mapping.

6. Summary – The Way Ahead

In a review of this nature, one cannot come to any "conclusions"; the field is too broad and is still evolving. Nonetheless, there are trends and patterns of success that can still be identified and stressed. At the risk of belabouring a point that has already been made, but is of central importance, it must be noted that multiparameter surveys and data sets provide much more information and can be used to constrain the survey analysis and interpretation. Combinations of resistivity, IP and TEM (Sandberg, 1993) are more complete than each technique by itself. TEM combined with NMR provides not only water content but also water quality information (Goldman *et al.*, 1994). The time variation of the geophysical response (Cosentino *et al.*, 1978) can be used to constrain the seasonal hysteresis (e.g., Knight, 1991a). The problems of equivalence can be largely solved by incorporating as much information as possible, whether from multiparameter surveys or by using the available geological data. Dorn (1985), for example, used a two-stage interpretation scheme, first to get the broad structure from the resistivity data, and then a more detailed structure constrained by the available geological information.

Secondly, recent modifications to survey methods and protocol have allowed all of the E & EM methods, including resistivity, to be used as part of an arsenal of techniques that can be carried out rapidly and efficiently to yield shallow information. The growth in the environmental application of E & EM methods, including GPR and TDR, will continue. Fewer articles may appear in the literature as E & EM techniques enter the realm of everyday application by geologists, hydrogeologists and engineers, but the problems of heterogeneity and anisotropy of the electric and dielectric properties and their relationships to the hydraulic properties will occupy the attention of researchers for some time yet as we attempt to wrest ever more information and detail from our survey results. Just as the use of 3D seismic data acquisition and interpretation has grown enormously in the oil and gas industry in recent years, so too will the demand grow for more detail, both qualitative and quantitative, from our surveys.

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This reference list is not intended to be complete, but instead is meant to provide a broad sample from the range of publications available to the author at various times, and to indicate the period of time over which E & EM methods have been employed in environmental and groundwater applications. While many older references have been included, the majority of the citations are from the last five years, and while the majority are cited in the text, a few are not. Some additional references have been added since the presentation of this paper at the EM Induction Workshop in Brest, but as noted earlier, it is impossible to read all of the literature, and so only a sample can be included.

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