Applied Geophysics for Groundwater Studies

Abstract

Introduction

In many developed and developing countries there is not only a heavy reliance on ground water as a primary drinking supply but also as a supply of water for both agriculture and industrial use. The reliance on groundwater is such that it is necessary to ensure that there are significant quantities of water and that the water is of a high quality. The use of geophysics for both groundwater resource mapping and for water quality evaluations has increased dramatically over the last 10 years in large part due to the rapid advances in microprocessors and associated numerical modelling solutions. However despite its sometimes spectacular success, for the majority of groundwater studies, the use of geophysics is still often not considered. Why is this? In part it is poor publicity of the potential use of geophysics and poor dissemination of some of the more complex technical issues. It is also due in part to practical implementation difficulties and cost limitations. Unfortunately it is sometimes because geologists and engineers may have experienced an in-appropriate use of geophysics in the past or more unfortunately had some geophysics over-sold to them under false pretences of its possibilities thus leading to not just the poor use of the geophysics but to the delivery of misleading or wrong results.

This paper attempts to guide the reader to some of the important sources of information on the use of geophysics for groundwater exploration that have been published recently. The use of geophysics for groundwater contamination studies is mentioned however this application is not extensively reviewed. The papers that are cited by no means represent an exhaustive list of contributions however they are intended to indicate the variety of geophysical methods used for groundwater exploration and the range of situations where geophysics has been used.

Geophysics Background

The main use of geophysics in the geosciences is for hydrocarbon exploration typically at depths greater than 1000m. Significant technological advances have been made in this industry over the last thirty years especially with seismic reflection techniques. In contrast, near-surface geophysics for groundwater investigations is usually restricted to depths less than 250m below the surface and developments have not concentrated on one specific geophysical technique. Groundwater applications of near-surface geophysics include mapping the depth and thickness of aquifers, mapping aquitards or confining units, locating preferential fluid migration paths such as fractures and fault zones and mapping contamination to the groundwater such as that from saltwater intrusion.

The theoretical and practical background to geophysics has been extensively reviewed and can be studied in standard text on the subject, for example: Kearey & Brooks, 1991, Telford et al. (1976), Parasnis (1996), Dobrin, (1976), Grant and West (1965). Basic outlines of geophysical methods are also given in standard hydrogeology text such as that by Fetter (1980). Groundwater and near surface investigations in particular have been specifically covered in some detailed in recent text by Reynolds (1997), Milsom (1996). Further examples on near surface geophysics can be found with the special series of papers “Geotechnical and Environmental Geophysics” published by the Society of Exploration Geophysicists and edited by Ward (1990). A number of journals publish papers on groundwater geophysics including

Geophysics, Geophysical Prospecting, Applied Geophysics, Journal of Environmental and Engineering Geophysics, Ground Water. Important publications on geophysical studies for groundwater in developing countries that sought to produce simple rules of thumb for the application of the geophysics include "The Hydrogeology of Crystalline Basement Aquifers in Africa" (Wright and Burgess ed., 1992) and a general guide to techniques for finding groundwater has been produced by the Worldbank (Van Dongen and Woodhouse, 1994). Practical manuals of geophysics are also increasingly being provided on the world-wide-web through university and society collaborations (Colorado School of Mines) and also through manufacturer and equipment suppliers. A number of these sites are listed in appendix A.

The near surface geophysics community is now also served by specialist societies and sections of societies dedicated to near surface geophysics. Within these there are sub-groups with interests in hydrogeology and the study of groundwater. These groups include The Environmental and Engineering Geophysical Society in the US with a European Chapter, the American Association of Petroleum Geologists Environmental Division, AGU. Finally, useful information on ground water can also be found through the publications and online details of work by the United States Geological Survey.

Many geophysical techniques have been applied to groundwater investigations with some showing more success than others. In the past, geophysics has either been used as a tool for groundwater resource mapping or as tool for groundwater character discrimination. For groundwater resource mapping it is not the groundwater its self that is the target of the geophysics rather it is the geological situation in which the water exists. Potential field methods, gravity and magnetics, have been used to map regional aquifers and large scale basin features. Seismic methods have been used to delineate bedrock aquifers and fractured rock systems. Electrical and electromagnetic methods have proved particularly applicable to groundwater studies as many of the geological formation properties that are critical to hydrogeology such as the porosity and permeability of rocks can be correlated with electrical conductivity signatures. General methods of practice have been produced for geophysical techniques in groundwater exploration (Van Dongen and Woodhouse, 1994) but as MacDonald et al. (2001) point out, situations with complex geology and hydrogeology do not lend themselves to the generic approach and require specific targeting of methods for particular problems. Most geophysical techniques have been used for groundwater characterisation but once again it is with the electrical and electromagnetic methods that the greatest success has been shown in directly mapping and monitoring contaminated and clean groundwater.

The use of geophysics for groundwater studies has been stimulated in part by a desire to reduce the risk of drilling dry holes and also a desire to offset the costs associate with poor groundwater production. Today the geophysicist also provides useful parameters for hydrogeological modelling of both new groundwater supplies and for the evaluation of existing groundwater contamination.

Before a review is made of individual geophysical methods, a brief discussion is given on the design of geophysical surveys for groundwater application. For further information on the design of surveys see Reynolds (1997) and Dobecki and Romig (1985).

Designing a Successful Survey

Achieving a successful geophysical survey is reliant on three features: implementing the geophysical survey early in the project planning stages, designing the correct geophysical survey and choosing the appropriate geophysical contractor.

Planning the Survey

Ideally the use of geophysics should be discussed early in the planning stages of a survey in order to gain most benefit from the geophysics. Unfortunately this is not always the case and geophysics is only used when all other investigation techniques have failed. This has led to unjustified bad publicity for geophysics; if all else has failed then it is unlikely that the geophysics will be successful usually because the original survey objectives have not been clearly defined at the start of the project. Using geophysics to solve a problem in this manner is often expecting too much from the geophysics and will result in failure. Geophysics is only one tool that can be applied to a groundwater investigation and its success must rely on the careful interpretation and integration of the results with the other geologic and hydrogeologic data for the site. Only then will the geophysics be a success.

Geophysics is typically used in one of two ways. Either it is used to project an interpretation of the geology and hydrogeology from boreholes and surface exposure into a formation or the geophysics is used in an area of unknown geology and hydrogeology in order to better focus the direct sampling programme. For both of these types of use, if the geophysics is discussed early in the proceedings then the most appropriate techniques can be found and used in the most cost effective manner. A parallel for groundwater development can be found in the hydrocarbon world where the successful use of an integrated geophysical programme is seen at all stages of developing a hydrocarbon reservoir. First a geophysical regional recognisance study is conducted with potential field methods (gravity and magnetics). This is followed by regional seismic programmes and exploration wells. Based on these results, more detailed local 3D geophysical surveys are made and the surface geophysics is tied to the subsurface geology by borehole geophysics. Ultimately high frequency borehole geophysics is conducted for reservoir modelling purposes. This integrated use of geophysics is recommended in developing a groundwater resource however, due to cost limitations it is not always possible. It is therefore vital that the geophysics is used in the most appropriate manner at the most appropriate time in a project if it is to be successful in helping to develop a groundwater resource.

Designing the Geophysical Survey

Paramount to designing a successful geophysical survey is the definition of a clear set of objectives and the choice of appropriate methods. The objectives must be based on reasonable, geophysically achievable criteria. For this it is important that the geophysical target has physical properties that can be distinguished from background signatures (geological and hydrogeological features) and background noise (ambient cultural noise together with system induced noise). The next stage in defining a project is to be able to provide an adequate site description along with any previous data that has been collected, site maps or other data that would pertain to the project. This includes logistical features such as access to the site, noise sources and working restrictions. The client must specify early in the project what the ultimate results will be used for and what format they should be provided in. This will ensure that the geophysical results are fully integrated into the project as a whole. If the results are not presented in a manner that the client can fully understand and utilise then they are as good as useless results!

Choosing the appropriate geophysical methods and applying the methods in an appropriate manner is also critical to a successful survey. Only once the objectives have been clearly defined and agreed on by both the client and the contractor can the appropriate geophysical methods be chosen. The incorrect choice of technique and insufficiently experienced personnel conducting the investigation have been cited as primary reasons for the failure of many geophysical surveys (Darracott and McCann, 1986; MacDonald et al., 2001). In choosing the methods, the contractor should first conduct forward models based on the objectives and known site conditions to determine the likely success of each method.

Quality control throughout all stages of the work is paramount to a successful outcome. Field quality control should include basic equipment calibration procedures, accurate field reporting including field printouts of digital data, checks for digital data recording and up-loading to computers, and repeat measurements at base or calibration sites. During processing this quality control will include manual calculations of computer-processed data, documentation of processing steps and separate data reviews by an independent person not directly involved in the project. Finally, the ownership of the data should be discussed prior to the commencement of the work if the data is destined for publication.

Choosing a Contractor

A successful survey requires the choice of an appropriate contractor. This will be one who has the general knowledge to be able to suggest the most appropriate geophysical survey tools to meet the objectives. A good contractor should also possess the knowledge and professional integrity to admit the inadequacies of the geophysics if it is not likely to meet the survey objectives. The contractor should have sufficient specialist knowledge to be able to carry out the geophysics or to suggest an expert who has the necessary specialised knowledge. It may be that more than one contractor is needed with experts for field acquisition, for data processing and for data integration. It may often be beneficial to use more than one contractor on large investigations and have them conduct trial surveys to test various methods before a commitment is made to a full survey programme. This allows more precise models of the geology and geophysics to be constructed in order to maximise the results of the geophysics.

It is important throughout the process of choosing a contractor to be aware of who shall have responsibility for the different parts of work. Some guidelines to geophysical survey work have been provided in recent documents and recommendations by working parties for ASTM, for Brithish Standards Institute (BS 5930, 1981; referred to by Hawkins, 1986) and the Geological Society Engineering Group Working Party Report on Engineering Geophysics (1988), however, there is no worldwide organisation yet established for either setting out work practice documents of for regulating the geophysical industry. Furthermore, it is unlikely that there will be such arrangements for taking these responsibilities in the near future. In different countries, commissioning bodies and other organisations such as the Geological Society of London and the American Association of Petroleum Geology now offer some regulation of practising geophysicist by means of charter status but many still practice to high standards outside of the organisations. Careful scrutiny of the qualifications of individuals who will be working on the project is thus recommended.

Survey techniques

The range of geophysical techniques used in groundwater investigations is only briefly described here in order to provide an introduction to the methods and some useful literature references. The techniques, together with the physical parameters that they measure, are summarised in Table 1.

All geophysical techniques measure variations in a material's physical properties. For soils and rocks the properties can be divided into a framework or matrix component and the pore content component. Different materials exhibit different parameter signatures such as their resistivity or its inverse, conductivity, acoustic velocity, magnetic permeability and density. Typical ranges for these properties are given in Table 2. These parameters are influenced by the mineral type, grain packing arrangement, porosity, permeability, and pore content (i.e. gas or fluid type). In general, no one property is unique to any material, rather a material is described by ranges of each property. In most geophysical surveys therefore it is important that the changes or contrasts in geophysical parameters are measured and that the target shows large property differences with surrounding material.

For groundwater investigations, the most significant parameters that have been used for describing an aquifer system are ones that relate to the porosity and permeability of the aquifer and surrounding aquitard. Electrical conductivity, or its inverse resistivity, is the proportionality factor relating the electrical current that flows in a medium to the applied electric filed. It is the ability of an electrical charge to move through a material. It has been correlated with porosity through the work of Archie (1942). A relationship often exists between electrical conductivity and the clay content or fluid type (Waxman and Smits, 1968). The relationships between conductivity and material properties of an aquifer have been discussed by Mazac et al. (1985) and observed relationships between resistance and the hydraulic conductivity of an aquifer have been given by Coetzee et al. (1992). Seismic velocity is related to the elastic moduli and the density of a material with compressional wave velocity also correlated to porosity (Wyllies's Equation) and fluid content (Gassman, 1951).

The successful use of each geophysical technique is dependent not only on the careful design of the survey but also on the consideration of a number of key geological and cultural factors together with the geophysical data. These factors include:

Nature of the target: The target geophysical signature must be different to that of the background geology or hydrogeology.

Depth of burial of target: The depth of burial of the feature of interest is important as different techniques have different investigation ranges. The depth range is technique dependant however there is always a trade off between penetration depth and resolution of the technique with respect to the feature of interest. A technique that will look deep into the earth generally has lower resolution than a technique that is only looking to shallow depths

Target size: An estimation of the target size is necessary prior to selecting appropriate techniques. The target size should be considered in conjunction with the depth range for individual techniques.

Measurement station interval: This will depend on the burial depth, target size and technique selected. Geophysical surveys have traditionally been conducted along line profiles or on grids and therefore the station spacing along the lines must be calculated together with the line separation in order to not miss a particular target size or to result in spatial aliasing the target (Reynolds, 1997). A rough rule of thumb is that a geophysical anomaly will be approximately twice the size of the object causing the anomaly so this will give the maximum line and station spacing.

Calibration of the data: The key to success of any geophysical survey is the calibration of the geophysical data with both hydrogeological and geological ground truth information. Calibration data may be provided by both down-hole geophysical logs in boreholes, samples derived from boreholes by continuous sampling and through measuring the groundwater flux.

Magnetic (or geo-magnetic) Techniques

Magnetic techniques measure the remnant magnetic field associated with a material or the change in the Earth's magnetic field associated with a geologic structure or man-made object. They have been used for regional surveys since the early 1900's in the hydrocarbon industry and for longer in mineral prospecting however little use has been made directly for groundwater studies. This is mainly because groundwater does not have a magnetic signature. The main use for regional groundwater investigations has been as part of combined surveys with gravity for defining large-scale basin structures. A basic description of their use can be found in Hinz (1985). Babu et al. (1991) describe the use for mapping bedrock topography, and in particular possible groundwater reservoirs in hard-rock (igneous and metamorphic) terrains. Other use of the magnetic technique together with resistivity surveys in volcanic terrain has been described by Aubert et al. (1984). Magnetic surveys are also often used to locate the cause of contaminated groundwater by surveying for buried metallic objects such as hydrocarbon storage tanks, and chemical containers (ref) however these uses are not discussed further.

Magnetic surveys have also been used to identify basement faulting and other locations of crustal weakness that may represent preferential fluid flow paths. Large areas can be covered using airborne magnetic surveys with line and station spacing tens of metres wide. Results of magnetic surveys are usually presented as line profiles or magnetic anomaly maps. An example of this airborne use of magnetic surveys is given by Combrinck et al. (2001). In this study, a regional appraisal of potential fracture and fault zones was made prior to conducting the geophysics. The airborne magnetic and electromagnetic surveys were then conducted with a 100m line spacing in order to identify the major structural controls and geologic boundaries. The airborne geophysics was followed by a ground-based programme of magnetic and electromagnetic surveying. The results showed that the major fault and shear zones provided highly fractured, higher yield aquifers which could be mapped in relatively sparse groundwater regions. A recommendation to conduct future airborne mapping at 50m line spacing was made. The application of magnetic surveying for unconsolidated sequences has been somewhat limited as the magnetic signatures for different sediment horizons are often weak.

Gravity

Common uses of gravity or micro-gravity surveys have been to record the changes in density of materials. While gravity methods have not been widely used for groundwater applications, there are some notable examples of its use for mapping the location of low density rocks (typically sedimentary sequences) within more dense basement rocks. Yuhr et al. (1993) used a combination of electromagnetics and microgravity to design a strategic approach to mapping karstic features. Other common applications are the detection of voids within the subsurface where the small changes in the Earth's gravitational attraction caused by such contrasts in density can be recorded with modern instrumentation. Interpretation of gravity data however is difficult as the causes of the changes in gravitational field can be many and varied. In addition, the collection of gravity data is typically a slow process and thus expensive. The results of gravity surveys are presented as gravity maps and 3D models in a similar manner to those of magnetic data.

Notable early gravity work includes that of Hall and Hajnal, 1962, Spangler and Libby, 1968, Carmichael and Henry, 1977. Buried valley alluvium aquifers were mapped using gravity by Lennox and Carlson (1967), and also by van Overmeeren (1980). A more recent study on an aquifer draw-down scheme by

Allis and Hunt (1986) used measurements of micro-gravity changes to monitor the draw-down in the steam zone in the Wairakei geothermal field. Van Overmeeren (1975) used a combined approach of micro-gravity and seismic refraction for groundwater evaluation near Taltal province, Chile with a similar study including the use of electrical resistivity to study groundwater in Sudan (van Overmeeren, 1981).

Electrical

Electrical and electromagnetic techniques have been extensively used in groundwater geophysical investigations because of the correlation that often exist between electrical properties, geologic formations and their fluid content (Flathe, 1955; Zohdy, 1969; Flathe, 1970; Ogilvy, 1970; Zohdy et al, 1974; Fitterman and Stewart, 1986; McNeill, 1990). Most electrical techniques induce an electrical current in the ground by directly coupling with the ground. The resulting electrical potential is then used to measure the variation in ground conductivity, or its inverse, resistivity. Different materials, and the fluids within them, will show different abilities to conduct an electric current. In general, sequences with high clay content show higher conductivity as do saturated sequences and especially sequences where saline (or sometimes other contamination) fluids are present. Common field practice for electrical surveying relies on directly placing an electrical current into the ground (direct current electrical resistivity surveying) and measuring the response (the electrical potential drop) to that current over a set distance.

The typical results of electrical surveys are electrical profiles or geo-electric images and geo-electric depth soundings. The profile or transect method for mapping lateral resistivity changes is now largely replaced by electromagnetic techniques as the electrical technique is slow (when probes have to be placed directly into the ground) and thus is not cost effective relative to the electromagnetic techniques (MacDonald et al., 2001, McNeil XXX). Electrical methods are still widely used however for conducting soundings and electrical cross-sections.

Electrical techniques can be divided into a number of types based on the configuration of the electrodes that are used to input the electrical currents into the ground and the nature of the electrical signature. Only the basis of direct-current electrical resistivity techniques will be discussed here without a review of the different electrode configurations.

Direct Current Resistivity

The direct-current (DC) electrical resistivity method for conducting a vertical electrical sounding (VES) has proved very popular with groundwater studies due to the simplicity of the technique and the ruggedness of the instrumentation. An excellent example of the use of the technique was shown by Reynolds (1997) in a survey for a rural water supply in northern Nigeria. Before the vertical electrical sounding were used a failure rate of over 82% was recorded for boreholes. With the geophysics and a combination of geological and photogeological inspection this was dramatically reduced to less than 20% failure. Van Overmeeren (1989) showed the use of electrical measurements in mapping boundary conditions in an aquifer system in Yemen. Beeson and Jones (1988), Olayinka and Barker (1990), Hazell et al. (1988 and 1992), Barker et al. (1992) and Carruthers and Smith (1992) all have demonstrated the use of electrical techniques for siting wells and boreholes in crystalline basement aquifers throughout sub-Saharan Africa. Other similar examples are given by Wurmstich et al. (1994), Yang(1998), and Yang et al. (1994). Paul (1977) demonstrated a useful development of electrical techniques by considering the conductance of the DC section as a guide to overall aquifer potential for mapping groundwater resources in the Kalahari Basin. This type of approach may find applicability in many mafic-basin groundwater studies. Sauck and

Zabik (1992) have demonstrated a development of the sounding technique by conducting azimuthal surveys. This method was successfully used to assess the directional variation in hydraulic conductivity of glacial sediments in Switzerland. A similar approach has been tested by Marin et al. (1998).

During the late 1990's methods were developed for continuously acquiring electrical data by using a pulled electrical array (Sorensen, 1996). These techniques use a static electrical array that is pulled across the ground surface for continuous coverage of the subsurface along 2D profiles. A favourable comparison of the pulled array with that of a static 2D array has been given by Moller et al. (1998). Christensen and Sorensen (1998) have demonstrated the potential of these techniques when combined with those of TDEM soundings for regional schemes of hydrogeophysical investigations. They illustrate this approach using large-scale surveys in Denmark where widespread problems exist in supplying increasing quantities of high quality drinking water to expanding populations. Of particular note in these studies is the ability to obtain high data coverage over densely populated areas where cultural noise and man-made conductors make geophysical surveys difficult. Also, they demonstrate the efficient nature of the surveys where 10 to 15km of data can be obtained by a two-person crew per day.

The vertical sounding techniques are typically limited in the near surface to exploration depths less than 50m due to the spacing of the electrodes and the strength of currents required. (Young et al., 1998). Also at any greater depths the large electrode spacing mean that there is considerable lateral smearing of results.

Recent advances in computing power have led to developments in electrical techniques that have opened up the possibility of conducting true 2D geo-electric cross-sections (Barker, 1981, 1996a and b) and more experimentally 3D volumes. The 2D geo-electric methods are very effective at measuring sections down to 10m with some recent results shown from deeper penetration. Results for electrical surveys are usually presented as geo-electric, conductivity or resistivity sections, line profiles or maps and volumes. A good example of this for groundwater exploration is shown by Dahlin and Owen (1998) using 2D resistivity surveys with an ABEM Lund Imaging System together with a ground penetrating radar in shallow alluvial aquifers in Zimbabwe. The results were used to build conceptual geological/hydrogeological models of the aquifers as a basis for guiding the drilling programme. Olayinka and Barker (1990) used similar micro-processor controlled resistivity traversing techniques for siting boreholes in Nigeria.

Most recent surveys tend not to rely on the electrical method alone for data but rather to integrate it with other geophysical techniques. Examples of the multi-technique approach using electrical and electromagnetic techniques include those by Beeson and Jones (1988), Zonge et al. (1985), Bartel (1986), Buselli et al. (1988, 1992), Hazell et al. (1988), Saksa and Paananen (1992), Sorensen and Sondergaard (1999), van Overmeeren et al. (1981, 1989 and 1998).

Dannowski and Yaramanci (1999) used ground penetrating radar together with electrical measurements to estimate the water content and porosity of formations. Yadav and Abolfazli (1998) also tried to establish relationships between hydraulic parameters and geo-electric results in semi-arid regions of Jalore, northwestern India, and this approach is likely to see increased interest in the future. Kalinski et al. (1993) used electrical sounding techniques to establish relationships between hydraulic conductance within an aquifer and its protective aquitard (a clay layer). They followed by conducting profiles that were calibrated with the soundings to apply the relationships over a larger area that contained the aquitard.

Very Low Frequency

Very low frequency (VLF) survey methods rely on eleven major stations that transmit continuous VLF electromagnetic waves distributed throughout the world. The interaction of the electromagnetic plane waves emitted from these transmitters can be measured as the waves impinge on different material conductors in the earth. Vertical sheet conductors are particularly sensitive the waves. Examples of vertical sheet conductors include faults, dykes and fracture or joint zones. These features are often associated with enhanced fluid (groundwater) flow. Survey profile lines conducted perpendicular to the conductors show a strong response to the conductor. The method is generally inexpensive with final data output from the instrument providing a direct indication of linear conductor anomalies. The method is often conducted as a recognisance survey as large areas of ground can be rapidly covered. A full review of VLF methods has been given by McNeill and Labson (1991) and a good recent example of locating bedrock wells in water bearing fracture zones for contaminant migration prevention has been given by Covel et al. (1996). The VLF method is typically used in conjunction with other follow-up techniques such as DC resistivity. An example of this was given by Benson et al. (1997). Michaud and Covel (1998) have demonstrated the technique together with that of downhole logging during a hydrogeologic study of an island in Narragansett Bay, Rhode Island.

Electromagnetic

Electromagnetic techniques have been extensively developed and adapted over the last 15 years to map lateral and vertical changes in conductivity with some spectacular examples of their use being shown for groundwater studies. While the final output is similar to that from electrical techniques, several advantages with the electromagnetic techniques result in an increased resolution and more cost-effective application.

Kaufman and Keller (19) have given an extensive background to electromagnetic geophysics and a number of important contributions were also published in Electromagnetic Methods in Applied Geophysics - Applications part A and B, a special publication by the Society of Exploration Geophysicists, Tulsa (Nabighian, 1991).

Two types of electromagnetic survey are currently practised, i) time domain electromagnetic (TDEM) surveys which are mainly used for depth soundings and recently in some metal-detector type instruments, and ii) frequency domain electromagnetic (FDEM) surveys that are used predominantly for mapping lateral changes in conductivity. In both electromagnetic survey techniques no direct contact is made by electrodes with the ground and thus the rate of surveying can be far greater than for electrical techniques where electrode probes must be placed in the ground for every measurement. Both techniques measure the conductivity of the ground by inducing an electric field through the use of time varying electrical currents in transmitter coils located above the surface of the ground. These time-varying currents create magnetic fields that propagate in the earth and cause secondary electrical currents which can be measured either while the primary field is transmitting (during frequency domain surveys) or after the primary field has been switched off (for time domain surveys). Instrumentation exists to survey to a range of depths (see appendix A) in either transect mode or as discrete soundings.

Frequency-domain Electromagnetics (FDEM)

Published reports on the use of FDEM profiling in groundwater exploration using the Slingram method have been given by Palacky et al, (1981) and for measurements at low induction numbers by McNeill (1980a and b, 1983, and 1986). The technique is usually used to measure lateral conductivity variations along line profiles either as single lines or grids of data. Further recent improvements in FDEM has seen the integration of GPS technology with the FDEM instruments which has led to a dramatic increase in the rate at which electromagnetic surveys can be accomplished. A number of manufacturers offer FDEM equipment that vary in physical size, ease of operation and survey depth. An example is given of Geonics Ltd. equipment in table XX. Typically survey results for FDEM surveys are presented as contour maps of conductivity and 2D geo-electric sections showing differences in conductivity along a line profile. Changes in conductivity are often associated with differences between lithological sequences (see Table 2) and over disturbed ground such as faulted or mineralised zones. A comparison of electromagnetic techniques for reconnaissance groundwater mapping has been given by Richards et al. (1995).

A useful example of FDEM for groundwater studies has been given by Godio et al. (1998) in a mountainous area in north-eastern Italy. Here a frequency domain survey using 20m and 40m coil separations gave information on the electrical resistivity for locating a number of water wells. The FDEM resistivity values were calibrated using the results of vertical electrical soundings and significant features noted along the FDEM traverses were collaborated with VLF profiles. Van Lissa et al. (1987) demonstrated the use of FDEM for mapping lateral geological changes and water bearing faults and fractures in the Nyanza Province, western Kenya. A methodology was developed that first located potential fault and fracture zones from aerial photographs and satellite images. These were then targeted with the FDEM together with resistivity profiling and vertical DC-resistivity electrical soundings. The combined use of the three geophysical techniques resulted in a success rate of over 80% for borehole locations with the depths for the boreholes determined by the geophysics at only about half that for traditional boreholes and with yields of 140% of the traditional holes. Moreover, it was estimated that the relatively low survey costs for the geophysical methods approximated 3% of the construction costs of a borehole, and thus were more than justified by the increase in yield and success rates.

A similar approach was adopted by Edet (1990) in a study of basement terrain in northwestern Nigeria. The crystalline basement in this region can only be exploited where there are extensive fractures and faults. These were first located using lineament analysis from air photographs with follow-up surveys using ground based electromagnetic measurements. It was found during a subsequent drilling programme that borehole yields generally increased with increase in electrical conductivity and fracture density. Taylor et al. (1997) also used electromagnetics to locate shallow water wells in highly fractured aquifers. Beeson and Jones (1988) and Hazell et al. (1988 and 1992) have also demonstrated a combination of FDEM and vertical electrical soundings to locate zones of enhanced groundwater yield from fractures in arid areas.

Time-domain Electromagnetics (TDEM)

TDEM techniques produce one-dimensional and two-dimensional geo-electric cross-sections in a similar manner to electric cross-sections. Survey depths for TDEM are from 5m to in excess of 100s of metres with high vertical and lateral resolution. The techniques do not however give high resolution from 5m to the surface. It is also possible to conduct electromagnetic surveying using logging tools in non-metal cased boreholes. This procedure has been shown to be extremely sensitive to lithological changes and is important for the calibration of the surface geophysics with sub-surface geology (Ref Savannah river). Additional correlation between electrical/electromagnetic measurements and physical samples can be obtained by measuring resistivity in the laboratory on borehole samples. Background information on the method is extensively discussed by Kaufman and Keller (1983) and McNeill (1990)

Many regional case histories are now available to demonstrate the utility of TDEM for groundwater exploration with background work on salt water intrusion given by Stewart (1982), Goldstein et al. (1990), Fitterman and Stewart (1986), Hoekstra and Evans (1986), Mills et al. (1988), Hoekstra and Blohm (1990), Miamone et al. (1989), Hoekstra et al. (1992), Wolfe et al. (1999), Jensen et al. (2000) and Fitterman and Hoekstra (1994).

Hoekstra and Blohm (1990) used TDEM to map different levels of saltwater intrusion into three different aquifers near Monteray Bay, California. The increase in total dissolved solids in the fluid showed the progress of saltwater intrusion where the deepest aquifer had the least amount of abstraction and was least intruded by the saltwater. The shallowest aquifer, with greatest abstraction rates, showed the greatest salt water intrusion inland. Hild et al. (1996) used a similar approach to map the fresh water lens floating on the saltwater beneath the island of Guam in the Northern Mariana Islands, western Pacific. This approach has seen much success in these types of groundwater exploration projects (Hild et al., 1996). In these types of study (see also the work of ....for other examples) use ismade of the Ghyben-Herzberg principal (Davis and DeWiest, 1966) where a basal lens of fresh water floating on denser salt water has a thickness which forces the freshwater-saline water contact to a depth below sea level that is 40 times the elevation of the top of fresh water above sea level. The fresh water/saline water boundary shows a high electrical contrast that is easily mapped with TDEM techniques especially in resistive bedrock. This freshwater resource is a significant one for many of these islands where water storage is poor and water demand is on the increase.

Maimone et al. (1989) demonstrated the use of TDEM in urban areas for mapping the freshwater-saline water boundary with surveys around Southern Nassau County, Long Island NY. The use of TDEM for mapping other groundwater systems includes that for karstic aquifers (Alwail, 1996), work on small pacific islands (Hild et al., 1996), integration with borehole data (Paillet et al., 1999) and investigations of block-faulted terrains (Petersen et al., 1989).

The successful use of TDEM in arid environments is also demonstrated by the work of Young et al. (1998) in Oman where over 30% of the population rely on groundwater extracted from alluvium aquifers on the Batinah Plain on the coast of the Gulf of Oman. Their work along over 400km of profiles defined three zones within the aquifer and a wedge of saline intrusion up to 10km from the coast. Taylor et al., (1992) showed the use of TDEM with simple 1D, closely spaced soundings to define local hydrogeology in an arid alluvial environment near Reno, Nevada. The results were used to reduce the total number of wells required to characterise the groundwater system.

Meju et al, 1993 demonstrated the powerful use of combining TDEM methods with audiofrequency magneto-telluric methods for stratigraphic and hydrogeologic mapping in the southeastern part of the Parnaiba basin, Brazil. A 400km traverse showed the techniques to be in excellent agreement with the borehole data and known geology of the area. Their results also showed that the major formations could be distinguished based on resistivity and a preliminary groundwater resource evaluation indicated that the major aquifers contrasted from the surrounding rocks with higher porosity and permeability. The AMT method was useful for mapping the deeper (100m plus) aquifers with the TDEM giving higher fidelity for aquifers that were shallower than this.

The integrated use of TDEM methods has very successfully been demonstrated recently with the regional mapping programmes undertaken by the Danish Survey and reported by Christensen and Sorensen (1994, 1998), Sorensen et al. (2000). Goldman and Neubauer (1994) also showed an integrated use of TDEM together with electrical and nuclear magnetic resonance tomography. This work was continued by Shtivelman and Goldman (1998) with a combined study of coastal aquifers in Israel using both TFEM and seismic reflection.

Airborne electromagnetic systems have been tested over a number of regions for hydrogeological investigations. Traditionally, frequency and time domain electromagnetic systems have been used for mineral prospecting but there has been an increased hydrogeological interest in these techniques particularly in urban areas over the last decade (Sengpiel and Siemon, 1998, Paine et al., 2000). The advantage of airborne systems is the rapid data acquisition over large areas and thus the techniques are ideally suited to regional studies (Jackson, 1993; Paine 2000; Christensen et al., 2000; Wynn and Gettings, Slade, 1999; Smith and Keating, 1996). However, the disadvantages are the poor horizontal resolution, a narrow bandwidth giving reduced vertical resolution and the susceptibility of the systems to environmental noise. The techniques are always applied together with ground surveying for calibration such as ground based TDEM, borehole logging and the integration with other geological information. Future work will determine if the technique is one that will find widespread use within groundwater evaluations. Another application of EM airborne techniques has been to map the depth to basement beneath aquifers. Wynn et al (2000) demonstrated the increase in resolution obtained from this type of survey over the more traditional gravity data in the San Pedro Valley, southern Arizona. In this study, a number of difficulties were encountered with human cultural interference (power lines, pipelines etc) and also static geologic noise from Tertiary volcanic flows that would require further processing in the future. Gamey et al. (1996) demonstrated airborne techniques for mapping the thickness of clay for irrigation canals using airborne surveys

Other electrical and electromagnetic methods

Three other methods have had limited use for groundwater studies, namely induced potential, spontaneous potential and telluric methods. The measurement of induced polarisation (IP) is made using conventional electrical resistivity electrode configuration where the voltage between electrodes is measured as a decay function with time after the current has been switched off or as the current is switched on. The technique has found most use in the search for mineral deposits but has had some limited success in groundwater applications. Two case histories have been provided by Vacquier et al. (1957) where measured rations of IP values 5sec and 10sec after current shutoff. The higher rations were associated with finder grained material I a buried channel aquifer. Further studies are given by Draskovits et al. (1990), Ruhlow et al. (1999) and for contamination studies by Sanberg et al. (1998).

The method of spontaneous potential or self potential geophysics uses naturally occurring ground potentials from mineral bodies, geochemical reactions, and groundwater movement. The techniques have most often been used in exploration for mineral deposits and successful applications have been seen for groundwater surveying in association with geothermal systems (Corwin and Hoover, 1979; Fitterman and Corwin, 1982). The methods have also been used recently to investigate the leakage of systems such as landfill sites and natural dams (Llpois, 1990; Jansen et al., 1994).

Telluric methods that utilise natural fluctuations in the Earth's magnetoshpere causing low frequency currents within the ground have been developed for regional (deep) geologic studies over the last 30years (AMT methods, for a review see Vozoff, 1986). In the early 1970's controlled sources were introduced to the method (CSAMT) for increasing the reliability of the source signatures (Zonge and Hughes, 1991). Examples of the use for deep groundwater surveys have been given by Vozoff (1983), Giroux et al. (1997), Bernard et al. (1990), Miele et al. (2000) for deep aquifers of Senegal where it not only was used as a method to find the base of the local Maestrichtian aquifer but also to estimate porosity values, Nichols et al. (1994), and Ritz et al. (1997) who showed that it could be used to measure the water content and quality in Reunion Island. Meju et al. (1993) demonstrated the use of CSAMT methods in conjunction with time domain electromagnetic surveying.

Seismic

In seismic methods measurements are made of acoustic energy propagation within a medium. The velocity of acoustic energy in the form of compressional and shear waves is related to the dynamic elastic moduli and density of a material. The use of seismic surveys in groundwater exploration have traditionally relied on seismic refraction techniques using compressional waves which show increasing velocity with density. This contrasts with the use of seismic in the hydrocarbon industry where the reflection technique dominates exploration. This is mainly due to the high costs associated with acquisition and processing reflection data. An extensive review of seismic refraction techniques has been given by Haeni (1988). The review highlights the major use of refraction seismics to map the depth and geometry of bedrock surface underlying unconsolidated (drift) sediment. A further use of compressional wave seismic is demonstrated for mapping the water table as there is significant velocity increase across the water table from un-saturated to saturated material.

Wallace (1970) conducted studies in deep alluvial basins with varying water table depths and Visarion et al. (1976) have investigated complex karsted limestone sequences in Romania. A good example of the combined use of seismic refraction with other techniques have been given by Wachs et al. (1979) for finding depth of bedrock and depth of watertable in arid zones using seismic refraction and electrical resistivity. Bates et al. (1992) demonstrated the use of both compressional and shear waves seismic refraction at a number of sites in the US and also showed the pitfalls associated with seismic refraction and in particular the hidden layer problem for groundwater evaluation. El-Behiry (1994) used both refraction and electromagnetics to investigate a confining layer, which can often act as a hidden layer, in central New Jersey.

Seismic refraction has also been used to infer aquifer properties such as porosity. Duffin and Elder (1979) used seismic refraction to determine empirical relationships for estimating total porosity in sand aquifers in south Texas. In a similar manner van Zijl and Huyssen (1971) used compressional wave refraction to evaluate the relationship between velocity, porosity and depth of burial for a sand aquifer in South Africa. Haeni (1986) showed the application of refraction methods in groundwater modelling studies in various locations in New England. Vilas et al. (1998) showed the combined use of seismic refraction, electrical techniques and GPR for investigating a complex catchment scheme in Catalunya. The results were used to determine the subsurface topography and 3D soil volume in order to be able to provide the hydrological model with correct flow parameters for the hydraulic behaviour of the aquifers.

Recent studies for groundwater evaluation include those of Holman et al (1999) at the Pleistocene Crag aquifer in northeast Norfolk, England. The seismic survey provided information on the internal structure of the aquifer which shows layers of clay and silt strata that limit the overall vertical permeability of the aquifer. Young et. al (1998) used high resolution seismic reflection for defining the structural control and the base of alluvium aquifers on the Batinah Plain, Gulf of Oman. Shtivelman and Goldman (1998) used an integrated study of high-resolution reflection and TDEM at several sites along the Mediterranean coast of Israel to define the coastal aquifer of Quaternary marine and continental deposits. The interpretation of the combined geophysical data sets allowed the discrimination of the higher porosity sand sequences from the lower porosity/permeability clay sequences. This discrimination was important in order to manage the salt water intrusion.

An interesting study using the reflection technique has been shown by Woodward (1994) who demonstrated the information that could be gained by re-processing deep hydrocarbon exploration data for the near-surface hydrogeological information at an area in Abu Dhabi Emirate. This approach may offer a means of conducting preliminary investigations in many arid areas in the Middle East and parts of Africa where hydrocarbon exploration has already been conducted.

Ground Penetrating Radar

Ground penetrating radar has seen a significant increase in use through the 1990's in near surface investigations with a number of case histories now recorded for groundwater surveys. The increase in use has in part been stimulated by an increase in computing power and the decrease in cost of computing. Ground penetrating radar is an electromagnetic technique for measuring the displacement currents in the ground. Displacement currents are defined by the movement of charge within the ground by polarization and can be related to the applied electrical field by the electric permitivity of the ground or the dielectric constant (Annan, 1991).

Traditional uses for mapping geological sections with excellent reviews have been given by van Overmeeren (1998), Davis et al. (1984), Vaughan (1986) and Benson et al. (1983) and the specific use for hydrogeologic properties by Knoll and Knight (1993) and Rea and Knight, (1995 and 1996). Although the technique often results in spectacular, high resolution sections of the earth, some degree of caution is recommended with the GPR as the technique can be limited to penetrations of less than 50cm when the surface ground electrical conductivity is above 30 mSm-1. Unfortunately such values are often reached in clay and clayey-silt soils or 100% saline saturated soils and therefore a measure of the near surface conductivity is recommended before embarking on a GPR survey. The water table is often also a strong GPR reflector, as shown by the work of Trenholm and Bentley (1998), which can limit the penetration depth of the signals. Arcone et al. (1998) have demonstrated the use of the GPR in permafrost areas for mapping the bedrock and groundwater in zones where the permafrost shows a discontinuous nature and thus may act as a barrier to fluid migration. Harari (1996) demonstrated the high resolution possible with the technique in imaging a sand dune aquifer complex in the Eastern Province of Saudi Arabia.

Greenhouse et al. (199?) have given good examples of the use of GPR in conjunction with VLF and FDEM at sites near Ontario, Canada . At one site near the city of Ontario a contaminant plume from a landfill was further described by Cosgrave et al (1987) who showed that where the background conductivity is low the method provides a means of monitoring contaminant plume flowing through glaciolacustrine sands. The results of monitoring the Borden site were discussed earlier. And are detailed in Faulkner, 1983 and Greenhouse et al. 1985. A similar set of monitoring was conducted with a range of geophysical techniques including both downhole and surface GPR at a shallow alluvial aquifer in the Boise Hydrogeophysical Research Site, Boise, Idaho (Clement et al., 1999; Peretti et al., 1999; Peterson et al. 1999). Olheoft (1986) has demonstrated the use of GPR together with complex resistivity measurements to detect hydrocarbon and other organic chemicals in groundwater. Similar studies have been conducted for the detection of hydrocarbons by Saunders et al. (1993), Ulrych et al. (1994) and for monitoring pumping tests by Endres et al. (1997).

Other important work has been done with the use of GPR to produce 3D images of the subsurface (see for example Roberts and Daniels, 1992), however once again, again this use within groundwater studies is likely to be cost prohibitive. Green et al. (1995) demonstrated the integrated use of the GPR with that of 3D seismic reflection for mapping glaciolacustrine and glaciofluvial sediments in Switzerland.

Summary

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Appendix A – Additional Notes on Electrical and Electromagnetic Methods for Groundwater Contamination Studies

Environmental studies of groundwater contamination have received the attention of a number of studies using electromagnetic techniques. These include the work of Greenhouse and Slaine (1983, 1986) who demonstrated the use of electromagnetic techniques for contamination migration studies of groundwater and Lahti and Hoekstra (1991) showed its use in tracing brine migration from evaporation pits and ponds in Texas. Smith et al. (1997) also demonstrated the combined use of FDEM, resistivity profiling and resistivity soundings for mapping saline waters associated with the Brookhaven Oil Field, Mississippi.

Eddy-Dilek et al. (1996) demonstrated the use of TDEM for mapping the continuity of confining layers within a critical confining zone at a contaminated site in Washington State. El-Behiry (1994) showed the use of TDEM together with seismic reflection for mapping a confining layer in an aquifer in central New Jersey.

The use of electrical and electromagnetic methods to distinguish conductive organic and inorganic contaminant plumes in groundwater has been shown by a number of authors (Palacky, 1988, Hoekstra brine pit, Vanhala et al., 1992, Buseli et al., 1990) and the SEG edition by Ward is recommended for good selection of papers. The majority of these studies rely on the fact that a conductive plume, with its increased total dissolved solids within the pore fluid, tends to cause a decrease in the overall resistivity of the ground. Over the last 20 years successful case histories have been given for a number of investigations in the US associated with the clean-up of environemntally contaminated sites. It is anticipated that in the future much more use may be made of geophysics for monitoring contamination of the groundwater using permanently installed geophysical sensors in boreholes and perhaps both within and on the ground surface. Examples of this are given below.

Ruhlow et. al. (1999) performed a number of DC resistivity and IP measurements near an open air petrochemical storage complex in Brazil where liquid organic and inorganic waste was disposed. Through the use of 1D inversions and 3D forward modeling on the resistivity data together with correlations to borehole results the potential contamination plume was distinguished from clay aquitards at the site.

Geophysics has been used in attempts to map hydrocarbon contamination plumes however the effects of hydrocarbon within near surface soils and rocks is complex. In some studies hydrocarbon was found to decrease the resistivity of the rocks it had contaminated (Vanhala, 1997) but the reverse has also been found with biodegradation resulting in highly conductive groundwater (Bailey et al., 1973)

One noteable piece of experimental work has been conducted at the Borden Site in Canada by a group under Prof. John Greenhouse at the University of Waterloo. The main aim of project conducted at this site was to determine how well different geophysical methods could directly detect a LNAPL plume. An experimental XbyXm "tank" was constructed which contained a pure grade of sand. This confined tank was then instrumented with a number of geophysical sensors both surface and down hole. The site was then contaminated with a known product and the migration of the product was traced over the following hours and days. The results of this work showed that the contaminant plume could be traced using a number of geophysical methods with particular success shown with the electrical and radar techniques. The real power of the geophysical methods was demonstrated in this experiment by the time-lapse nature of the study with information of the site both before and after the infiltration of the contaminant. Unfortunately, it is rarely possible to have data from both before and after a contaminant pollution event but this does demonstrate the utility of geophysical methods as monitoring tools. A further example of a time-lapse type study was given by Merrick (1997) showing the use of both downhole and surface electrical and electromagnetic techniques to monitor fresh water injection to a salt-filled aquifer. See Olofsspm et al (1997) for a similar study.

Other notable monitoring efforts have been shown on many of the contaminated military sites in the US. For example, from 1994 through 1995 over 30,000 gallons of DNAPL consisting of mainly TCE was extracted from the Hill Air Force Base, Utah (Newmark et al., 1999). The removal was monitored by fiberoptic chemical sensors, neutron logs and electrical resistivity tomography. The ERT showed a decrease in electrical resistivity during pumping which was interpreted as a direct reduction in the DNAPL and replacement by relatively lo w resisitiviy groundwater. Studies where an integration of a number of geophysical methods have been used include those by Farrell et al. (2000) at the Yucca Mountain site, Nevada where TDEM, IP, DC resistivity and magnetic methods were all combined to map the spatial continuity of the hydrostratigraphy and water table elevations for constructing regional groundwater models.

Ardau et al. (2000) used gravity and electrical surveys in the coastal plain of south-eastern Sardinia, Italy to map the saltwater intrusion and thickness of sediments through the regional aquifer. In addition, the seismic and electrical surveys proved effective for recognizing deep aquifer characteristics and in particular the seismic stratigraphy.

Seismic Shear Wave

A number of workers have indicated the increased resolution that is possible with shear wave techniques due the slower wave velocities (Dobeiki etc). Clark et al. (1994) demonstrated the high resolution possible with shear wave reflection at a number of site in the US. Considerable success has been shown with the use of seismic reflection for groundwater contamination studies on sites particularly in the US. In this publication, Clark (2000) demonstrated the use of high redundancy compressional wave refraction and high resolution shear wave reflection at a site in Nebraska to delineate the saturated zone and bedrock topography. The high resolution of the shear wave proved particularly successful in providing information on the shallow soil stratigraphy.

Initial work in this field was conducted by Hasbrouck (1987, 1991). Bates et al. (1992) used a shear wave refraction method to map the depth to bedrock and the fracturing of the bedrock surface at a site in Colorado and one in Florida. A similar study was conducted by Richard et al. (1992) to locate preferential fracture orientations in a limestone near two oil-producing wells. For both sites the location of fracture zones was critical to the subsurface investigation as the fracture zones represented preferential fluid migration paths with enhanced groundwater flow and the potential of transmitting contaminants at greater rates. Bates and Phillips (2000) described a regional study of fractured rock in Wyoming and overconsolidated clay in England using shear waves. At both sites the regional hydrogeology was greatly influence by a dominant rock anisotropy.