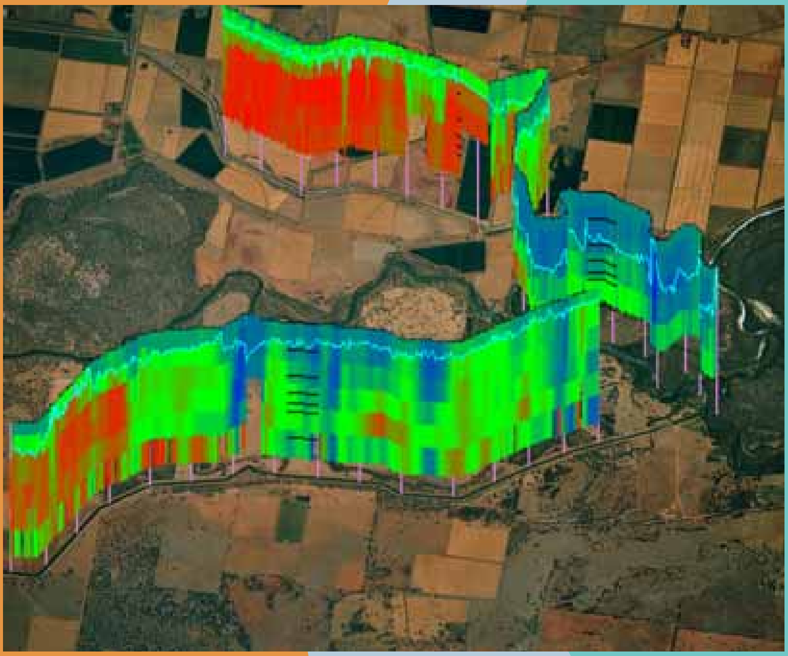
IRRIGATION
INSIGHTS
NUMBER 7



GEOPHYSICS FOR THE IRRIGATION INDUSTRY

Dr David Allen, Groundwater Imaging Pty Ltd

Case studies by D. Allen, J.Clarke,
G. J. Street, K. Lawrie, A. Fitzpatrick,
H. Apps, W. Lowis, M. Hatch, A. Price,
P. Wilkes, D. Dore, S. Abbott and K. Beckett.

NATIONAL PROGRAM FOR
Sustainable Irrigation

Cover Image

Imaging of aquifers beneath irrigation canals flanking the Murrumbidgee River (Allen, 2006). Funded by the CRC for Sustainable Rice Production. See Case Study 3 (p. 134) for further details.

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NATIONAL PROGRAM FOR
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The National Program for Sustainable Irrigation

The National Program for Sustainable Irrigation focuses research on the development and adoption of sustainable irrigation practices in Australian agriculture.

The Program has 14 funding partners: Land & Water Australia (managing partner); Sunwater, Queensland; Horticulture Australia Limited; Goulburn-Murray Water, Victoria; Cotton Research and Development Corporation; Harvey Water, Western Australia; Lower Murray Water Authority, Victoria; Wimmera Mallee Water, Victoria; Ord Irrigation Cooperative, Western Australia; Australian Government Department of Agriculture, Fisheries and Forestry; Department of Natural Resources, Mines and Water, Queensland; Department of Primary Industries and Resources South Australia; Department of Environment Water and Catchment, Western Australia; and Department of Agriculture and Food, Western Australia.

CONTENTS

GLOSSARY

Aquitard	A zone within the earth that restricts the flow of groundwater from one aquifer to another. Aquitards are composed of layers of either clay or non-porous rock with low hydraulic conductivity.
Apparent EC or Resistivity	This is equal to true ground bulk EC or resistivity if an instrument is situated over homogeneous ground. Over inhomogeneous ground, it is a weighted average of the signal contributions of each portion of ground in the instrument sampling volume. With most instruments, some portions of ground are negatively weighted so erratic apparent EC values occasionally occur. It is derived from field data using a simple formula. It is sometimes referred to as bulk soil EC, however, bulk soil EC should, technically, refer only to unweighted averages of EC of the portions in sampling volumes.
Artefact	A geophysical artefact is a feature present in a geophysical image that bears no sensible relationship with real features.
Bird	A streamlined object attached by a cable beneath an aircraft.
Bouguer gravity	This is the gravity value obtained after correcting observed absolute gravity for drift, tides, latitude, elevation and terrain. Elevation correction includes the free-air and Bouguer corrections. The Bouguer correction allows for the material between the gravity station and the datum – usually sea level.
Bucking coil	a “bucking coil” removes (or bucks) the primary field from the receiver coil. This technology, and the associated technology of fixing receiver coils so as to null couple with the primary field, has been important in enabling TDEM helicopter-borne electromagnetic systems to be developed.
Bulk EC	See Apparent EC.
Complex resistivity	See Induced polarization.
Conductivity	Conductivity may be either electrical or hydraulic and so in groundwater and soil studies electrical conductivity is generally termed as EC. Conductivity is the ability of a medium to allow the flow of current (either fluid or electric).
Data integrity	See ‘Integrity’.
DAW	Deficit available water – a percentage indicating unsaturated soil moisture content in the range between plant wilting point and where water logging starts to occur. (see also RAW).
Dielectric Permittivity	Dielectric Permittivity is an electrical property that determines the force that can be achieved between

	charged particles. It is principally and clearly related to water content. It is important in ground penetrating radar and soil moisture probes but its variation also is sometimes detectable, but not isolatable, in IP and EM techniques.
DEM	Digital elevation model - Computer-based representations of the topography of the surface of the Earth. They usually comprise a grid of regularly spaced elevation values that can show the surface in three dimensions (Spies & Woodgate, 2005).
Duty cycle	Where a periodic wave form is used in a transmitter and when the current is not always on, duty cycle (usually expressed as a percentage), refers to the fraction of time within one cycle that the current is switched on.
EC	Electrical conductivity typically measured in mS/m, µS/cm or dS/m is the inverse of resistivity.
EC_a	See apparent electrical conductivity.
$EC_{1:5}$	EC of a saturated paste of soil measured after diluting with 5 parts distilled water for 1 part paste. The measurement is corrected for dilution. This is the standard way of measuring soil EC in the laboratory.
Effective depth	The depth above which 50% of signal received by a device is contributed if the device is situated on the surface of an homogeneous halfspace.
FDEM	Frequency domain electromagnetic – refers to a system that transmits one or more frequencies from one or more transmitter coils and measures in-phase and quadrature response at one or more receiver coils spaced a fixed distance away – see chapter 3 introduction for further explanation.
FEM	See ‘FDEM’.
EM sounding	A technique to determine variations in electrical conductivity with depth, usually assuming horizontal layering. A frequency domain sounding uses multiple frequencies with the lower frequencies providing greater depth penetration. A time domain sounding measures over a range of time. Unless otherwise stated these soundings use a fixed transmitter and receiver geometry. Soundings can also be made at a single frequency by varying the spacing between transmitter and receiver. These are referred to as geometric soundings.
Equivalence	Equivalence occurs where single parameters of geological models cannot be determined accurately on their own but only as part of entire geological models. Electromagnetic data typically exhibit equivalence such that conductivity multiplied by thickness of conductive layers can be well defined

	but the thicknesses and conductivities of those layers cannot be well defined independently. Synthetic datasets created from numerous geological models can be created which match a single field dataset within a specified error tolerance limit. Equivalence is important to consider in all geoelectric and electromagnetic exploration techniques.
Field capacity	Water content of soil at which the soil cannot contain any more water. See also DAW and RAW.
Gamma log	This is a borehole log of the natural radioactivity of the material in and surrounding the borehole. Natural radioactivity of rocks and soils is due to the presence of Potassium, Uranium and Thorium and the decay products of these elements. The log responds mainly to material within a radius of 30 cm from the borehole. Rocks and soils have different concentrations of these elements and can in some cases be distinguished by these differences. Shales are usually more radioactive than sands.
Geophysics	Geophysics uses the methods of physics to provide understanding of the geology of the surface and subsurface of the Earth. The use of ground-based and airborne geophysical devices to measure the electrical conductivity of the earth can yield detailed information on size and depth of aquifers, salinity of aquifers and the mineral composition and depth of the soil. Most geophysics applied to irrigation is in the form of imaging conducted by moving various devices over the ground while some involves insertion and monitoring of sensors within the ground.
GPR	Ground penetrating radar – a device that images soil layering due to changes principally in dielectric permittivity which correlate strongly with water content.
GPS	Global Positioning System. A GPS receiver calculates its position by measuring the distance between itself and three or more GPS satellites. Measuring the time delay between transmission and reception of each GPS radio signal gives the distance to each satellite, since the signal travels at a known speed. The signals also carry information about the satellites' location. By determining the position of, and distance to, at least three satellites, the receiver can compute its position.
Halfspace	A geophysical term referring to the half of space below the ground (as opposed to above it). A mathematical model which is bounded only by one plane surface, usually the ground surface. The

	model is so large in other dimensions that only one boundary affects the results.
HCP	Horizontal coplanar – refers to the plane of transmitter and receiver coils in electromagnetic equipment, both being horizontal and aligned in the same plane. HCP coils are useful for flat lying or shallow dipping conductors. This configuration is also referred to as vertical dipole, as the axes of the coils are vertical. Some confusion has occurred when some authors have confused planes of axes and of coils (See Figure 3.7).
Induced polarization	A technique that may be added as an enhancement to geoelectric DC resistivity imaging. Induced polarization measures capacitive effects between clay particles (or metallic particles if present) and therefore can give an indication of clay distribution. It involves measurement of a property called chargeability which is in practice taken as the voltage shortly after turn off of current in a geoelectric system divided by the primary voltage immediately before current turnoff. There are numerous variations such as frequency domain IP where IP is a measure of phase shift in geoelectric systems operating at high frequencies; also complex resistivity which indicates resistivity from geoelectric equipment as measured at multiple frequencies.
In phase	Refers to an electromagnetic or electrical component of a received signal that is in phase with transmitted signal. For pure sinusoidal signal, maximum in phase response occurs when peaks and troughs in the signals coincide in time.
Integrity	The *a priori* expectation of data quality in terms of accuracy, correctness and validity. Loss of integrity usually results from failure to take into account all parameters affecting the data and/or the use of oversimplified algorithms to transform the data.
Inversion	See ‘Parameter estimation techniques’.
IP	Apart from standing for intellectual property, in geophysics IP abbreviates induced polarization – see induced polarization.
LIDAR	stands for ‘light detection and ranging’ and describes both a technique and equipment for detecting and measuring positions of objects using lasers. LIDAR systems flown in aircraft are used to produce very accurate digital terrain data.
Matrix inversion	See ‘Parameter estimation techniques’.
Magnetic permeability	This is the ability of a medium to propagate magnetic fields. Its variation is significant in EM surveys where ferrous minerals and metals are

	present in the ground.
Magnetometric resistivity/IP	This is a method that combines a geoelectric transmitter and electromagnetic receiver.
Magnetotellurics (MT)	A natural-source, electromagnetic geophysical method of imaging structures below the earth's surface. Natural variations in the earth's magnetic field induce electric currents (or telluric currents) under the earth's surface. The ratio of the electric field to magnetic field can give simple information about the subsurface conductivity. Because of the skin effect phenomenon that affects electromagnetic fields, the ratio at higher frequency ranges gives information on the shallow Earth, whereas deeper information is provided by the low-frequency range.
Moment	Magnetic moment or magnetic dipole moment is a measure of the strength of a magnetic source. In EM systems this is the product of transmitter loop area x current x number of turns of wire in the loop. Increased moment means that more energy penetrates the ground, enabling readings at greater depth.
MPS	Multi phase saturation is a geoelectric survey technique patented by Water Prospecting.
Neural network	An Artificial Neural Network (ANN) is an information processing paradigm that is inspired by the way biological nervous systems, such as the brain, process information. The key element of this paradigm is the novel structure of the information processing system. It is composed of a large number of highly interconnected processing elements (neurones) working in unison to solve specific problems. ANNs, like people, learn by example. An ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process
NMR	Nuclear magnetic resonance. See Proton Magnetic Resonance.
Parameter estimation techniques	Parameter estimation techniques (or inverse modelling) refers to the iterative process of deriving from field data a geologically plausible model that is consistent with the data. In each iteration, a geological model is proposed and synthetic field data are calculated and compared with the true field data before another model is proposed and the process iterates again. The process generally is stopped when the field and synthetic field data are deemed to match acceptably. Parameter estimation techniques can include neural networks and other optimisation methods and do not always require matrix inversion. Models are computed such that we

	work towards minimising the difference between observed and modelled response.
PDA	Personal digital assistants (PDA) are handheld computers that were originally designed as personal organizers, but became much more versatile over the years. PDAs are also known as pocket computers or palmtop computers.
Permittivity	Permittivity is the capacity of a material to store electrical charge when an electric field is applied. A material with high permittivity can store more charge than a material with lower permittivity. Dielectrics are insulators with high permittivity. The ratio of the permittivity of a material to that of free space is called the dielectric constant which is sometimes called dielectric permittivity. In SI units permittivity is measured in farads per metre.
Pitch	Rotational motion of a boat or aircraft about a horizontal axis perpendicular to the direction of travel.
Primary field	In electromagnetic systems this is the magnetic field in the earth and air that exists due to current transmitted into the transmitter loop.
PRP	Refers to the perpendicular array of two dipolar coils. This FDEM coil configuration is used by the DUALEM instrument and some airborne systems. The plane of the transmitter coil is horizontal while the plane of the receiver coil is vertical and perpendicular to the direction to the transmitter coil.
Proton magnetic resonance	Also termed nuclear magnetic resonance or NMR, PMR is an exploration technique by which rock water content, and an indication of permeability can be measured with respect to depth remotely.
Pseudo-section	A vertical cross sectional plot of electrical measurements or calculations, often of apparent resistivity or conductivity as a function of horizontal position and electrode spacing.
PVC	Poly Vinyl Chloride plastic.
Quadrature	Refers to an electromagnetic or electrical component of a received signal that is 90 degrees out of phase with transmitted signal. For pure sinusoidal signal, maximum quadrature response occurs when peaks in transmitted signal occur simultaneously with troughs in received signal.
RAW	Readily available water is the water that a plant can easily extract from soil and ranges from the water percentage that starts to cause waterlogging stress up to field capacity. See also DAW.
Regression	The statistical process of determining a mathematical relationship between a control variable (or variables) such as electrical

	conductivity and a response variable such as soil clay content.
Resistivity	The property of a material which resists the flow of electrical current. The inverse of electrical conductivity i.e. 1 divided by electrical conductivity.
Roll	Rotational motion of a boat or aircraft about the axis of the principal direction of travel.
Saturated paste	This is a soil sample that has had water added to it until it can hold no more without increasing in volume when under pressure (i.e. excluding volume increases due to absorption by clay minerals). Saturation normally is determined empirically. It is used to determine $EC_{1:5}$ values.
Scintillometer	A device which counts the light scintillations caused by radiation interacting in a scintillator which is usually made of Sodium Iodide. Radiation loses energy to the scintillation detector and creates light pulses which are converted to voltage pulses by a photomultiplier attached to the detector. A counting circuit counts the number of pulses detected per second. A refinement is the Gamma Ray Spectrometer which is described next.
Spectrometer	The spectrometer is a special form of scintillometer where the pulse height voltages are measured and counted within preselected voltage ranges. The voltages are directly proportional to the energy lost by the radiation in interacting with the detector. The energy loss spectrum is related to the energy spectra of the incident radiation. Potassium, Uranium and Thorium and their decay products have different gamma ray spectra and after suitable calibration and measurement procedures, gamma spectrometer measurements can be converted to geochemical concentrations of these three elements.
Stacking	A composite record made by combining multiple readings of the same dataset. Selective stacking eliminates extreme readings which fall outside one standard deviation of the mean. In airborne and towed systems, stacking duration multiplied by vehicle speed determines station spacing.
TDEM	Time domain electromagnetic – refers to systems that measure ground response to a transient pulse of current flowing through a transmitter loop over a range of time. Receiver voltages are measured during the time intervals between current pulses. i.e. while the transmitter current is off. See chapter 3 for a thorough explanation.
TEM	Transient electromagnetic is the same as TDEM.
Turn-off time	This is the time it takes for a TDEM system to turn

	off transmitted current and is usually measured in microseconds. Fast turn-off times and clean turn-off ramps are critical for shallow exploration.
VCP	Vertical coplanar refers to the plane of transmitter and receiver coils in electromagnetic equipment both being vertical and aligned in the same plane. VCP coils are useful for steeply dipping or vertical horizons but are used in soil exploration due to their ability to return adequate signal while sampling principally topsoil. This configuration is also referred to as horizontal dipole.
VLF	Very low frequency – refers to radio transmission in the range 3 to 30 kHz used for communication with submarines and for radio-positioning. In exploration, this signal is used by a method of the same name which measures distortion of VLF signals by ground EC variation and therefore may map out features that can constrain groundwater flow.

Note a useful source of descriptions of abbreviations is Sheriff, 1991. Some of the above descriptions are modified from this source.

1. INTRODUCTION

Why and how this document was created

Geophysical techniques involve the use of ground-based and airborne geophysical devices to measure physical properties of the earth. They can assist in the planning and management of irrigation developments by identifying the size and depth of aquifers, the connectivity between surface and ground water, the salinity of aquifers, the mineral composition and depth of the soil and the chances of successful water boring.

Most geophysics applied to irrigation is in the form of imaging conducted by moving various devices over the ground, or by insertion and monitoring of sensors within the ground. This book provides an introduction to various geophysical techniques for water managers, including irrigators, engineers and staff of water and catchment authorities and all those involved in various aspects of the irrigation industry from design through to implementation and monitoring.

The last generation advanced irrigation largely by the intelligent application of fossil fuels. This generation has the opportunity to advance irrigation by the intelligent application of electronics and information technology. Such applications include methods of precision irrigation and groundwater management that can only be made possible using new geophysical technology.

In 2004, the ANCID/NPSI[1] Travel Fellowship was awarded to David Allen for the purpose of conducting an international survey of over 100 geophysical instruments applicable to irrigation problems. Irrigators were using geophysical equipment to solve some problems but the diversity and complexity, and therefore true potential, of geophysics was overwhelming. This document provides background information on geophysics, listing and grouping currently available commercial equipment to assist irrigation professionals to see the potential and pitfalls of various devices. The book gives irrigators some basic geophysics so that they can ask the right questions of geophysical contractors, consultants, government agencies and university researchers[2].

The principal author, David Allen, visited equipment manufacturers and researchers in Canada, Denmark and Sweden after attending the Symposium on Application of Geophysics to Engineering and Environmental Problems in Atlanta, Georgia, USA in April 2005. He was also able to discuss with overseas manufacturers and researchers his PhD work on electrical conductivity imaging of aquifers connected to

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[1] ANCID – Australian National Committee on Irrigation and Drainage
NPSI – National Program for Sustainable Irrigation

[2] ASEG – the Australian Society of Exploration Geophysicists (Appendix 1) can provide contact details.

watercourses.

Structure of this document

The document is organized into chapters which describe generic types of geophysical equipment. The order of chapters is for convenience and starts with an introduction to survey planning and interpretation (Chapter 2).

Chapters 3 to 7 all discuss electrical conductivity imaging equipment and each have introductory sections that describe the basic principles of how each class of instruments work.

Chapters 3 and 4 describe ground electromagnetic equipment working in the frequency domain (FDEM) and time domain (TDEM) respectively. Chapter 3 includes most common soil mapping tools. The primary focus of this book is on the high resolution devices typically used for farm scale surveys.

Airborne electromagnetic systems are described in chapters 5 (FDEM) and 6 (TDEM) and assume that the reader has read the introductory sections of chapters 3 and 4. Airborne systems may be mounted on fixed wing aircraft or slung from helicopters. The fixed wing systems generally fly higher and faster than the helicopter systems and typically have less spatial resolution on the ground. They have transmitter loops fixed between aircraft wing tip and nose, and wing tip and tail. The airborne systems are generally more suited to regional or larger area surveys whilst the ground systems (and waterborne adaptations) are generally better suited to detailed, high resolution, local or task-oriented surveys.

Chapters on airborne devices are necessarily technical and brief but suitable as a guide, showing the basic potential of commercial airborne equipment. Irrigation professionals are advised to seek impartial geophysical help regarding airborne surveys.

Chapter 7 describes geoelectric or ‘DC resistivity’ systems. Resistivity is the inverse of electrical conductivity i.e. resistivity = 1 / electrical conductivity. It should be noted that some of the equipment described in chapters 3, 4 and 7 has also been adapted for use in waterborne applications.

Chapter 8 covers some borehole geophysical equipment. These systems are very useful for obtaining *in situ* physical properties e.g. electrical conductivity. Natural gamma logs are also very useful in recognizing different lithologies or variations in weathering.

Chapter 9 briefly describes some other geophysical techniques which may have relevance to irrigation studies.

Chapter 10 describes some software products that help in displaying data acquired for some of the systems described in the earlier chapters.

Within each chapter, equipment is listed alphabetically by manufacturer name. This makes it easy to see whether particular equipment is included. The order is purely alphabetic and not in order of perceived applicability to irrigation projects.

Chapters 11, 12, 13 and 14 are case studies of the application of geophysical technology to soil and groundwater investigation.

Appendix 1 provides contact details for equipment manufacturers and geophysicists.

Appendix 2 provides useful tables on costs and some operational details for the electromagnetic and geoelectric systems described in chapters 2 to 6.

Other useful documents

It should be noted that there are some other useful sources of information that describe geophysical equipment and methodology for environmental and/or near surface applications. The reader's attention is drawn to the book by Spies and Woodgate (2005) entitled 'Salinity mapping methods in the Australian context', which summarises in two documents – a book and user guide – the methodology and equipment used in salinity mapping. The CRC for Landscape Environments and Mineral Exploration (CRC LEME) has also produced a useful summary document, edited by Papp in 2002, which describes geophysical and remote sensing methods for regolith exploration. These are available on the world wide web (see the References for details).

This book covers some similar material but differs in that it focuses much more on detailed soil imaging and on listing and comparing commercial equipment. Anyone involved in commissioning airborne surveys is strongly advised to gain a thorough understanding of at least the Spies and Woodgate (2005) book.

A classification of techniques

It is much easier to select equipment if you have a good idea of what is fundamentally similar or different between various commercial devices. The following set diagram (Figure 1.1) categorizes the various fundamental principles of relevant geophysical equipment that will be explained throughout this document.

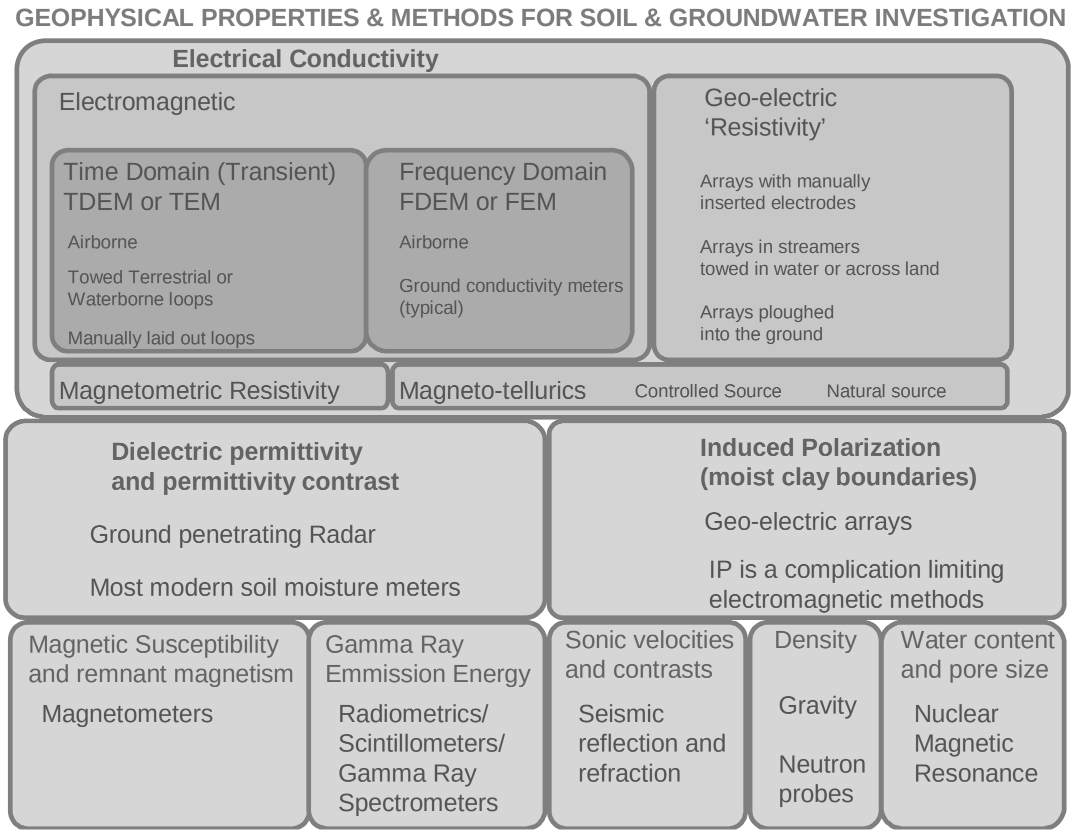

Figure 1.1 A grouping diagram of fundamental geophysical properties and methods for soil and groundwater investigation.

What is electrical conductivity?

Conductivity is simply the measure of a material's ability to conduct an electric current, and is measured in the S.I.[3] unit Siemens per metre (S/m). These units can be scaled depending on the material's conductivity. For example the electrical conductivity of groundwater is often measured in micro-Siemens per cm (µS/cm) or similarly deci-Siemens per metre (dS/m). Ground geophysical methods often display units as milli-Siemens per metre (mS/m). This report uses mS/m (100 mS/m= 1dS/m = 1000 µS/cm).

Resistivity is simply the measure of a material to impede current flow. Resistivity is the reciprocal or inverse of conductivity, and is measured in ohm.metres

The following equation relates conductivity to resistivity;

$$\sigma = \frac{1}{\rho}$$

Where ρ = resistivity (Ohm.m)
σ = conductivity (S/m)

Table 1.1 lists conductivity and equivalent resistivity values in mS/m and Ohm.m

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[3] S.I. International System of Units, universally abbreviated SI (from the French *Le Système International d'Unités*), is the modern metric system of measurement.

respectively.

Conductivity (µS/cm)	Conductivity (mS/m)	Resistivity (Ohm.m)	Example
100,000	10,000	0.1	Brine
10,000	1,000	1	Water Suitable for Sheep
1,000	100	10	Water causing wilting of crops
100	10	100	Good irrigation water
10	1	1,000	Unsaturated moist sand
1	0.1	10,000	Moderately dry sand or rock
0.1	0.01	100,000	Hard rock (no fractures)

Table 1.1 Electrical conductivity (in µS/cm and mS/m) and equivalent resistivity values (Ohm.m)

In terms of geophysical methods, it is common to express geoelectric or DC (Direct Current) measurements as resistivity and for inductive techniques (electromagnetic methods) as conductivity, although the terms can be interchangeable if the data are transformed accordingly. DC geoelectrical methods are typically classified as invasive, requiring electrodes to be placed into the ground, whereas electromagnetic methods are non-invasive and use coils of wire to induce current into the ground.

In this report, the abbreviation ‘EC’, rather than ‘conductivity’ which can be confused with hydraulic conductivity which is also very important in irrigation problems. Resistivity techniques have been labelled by their other common name ‘geoelectric techniques’. The second reason that the term ‘EC’ has been chosen is that the irrigation community is very familiar with it already as they are regularly measuring water EC and soil EC in units of µS/cm.

Apparent (or bulk) electrical conductivity (or resistivity)

Geophysical instruments measure electrical conductivity averaged over a bulk sample of the ground. However, the averaging is never uniform within the sampled volume. This means that each instrument type will report a different answer if the ground is heterogeneous. In this document, much effort has been made to explain the different bulk sampling distributions (or 3D footprints) of commercially available equipment and how these distributions affect resolution of each instrument. Figure 1-2 presents a schematic of the difference between real ground EC and apparent EC.

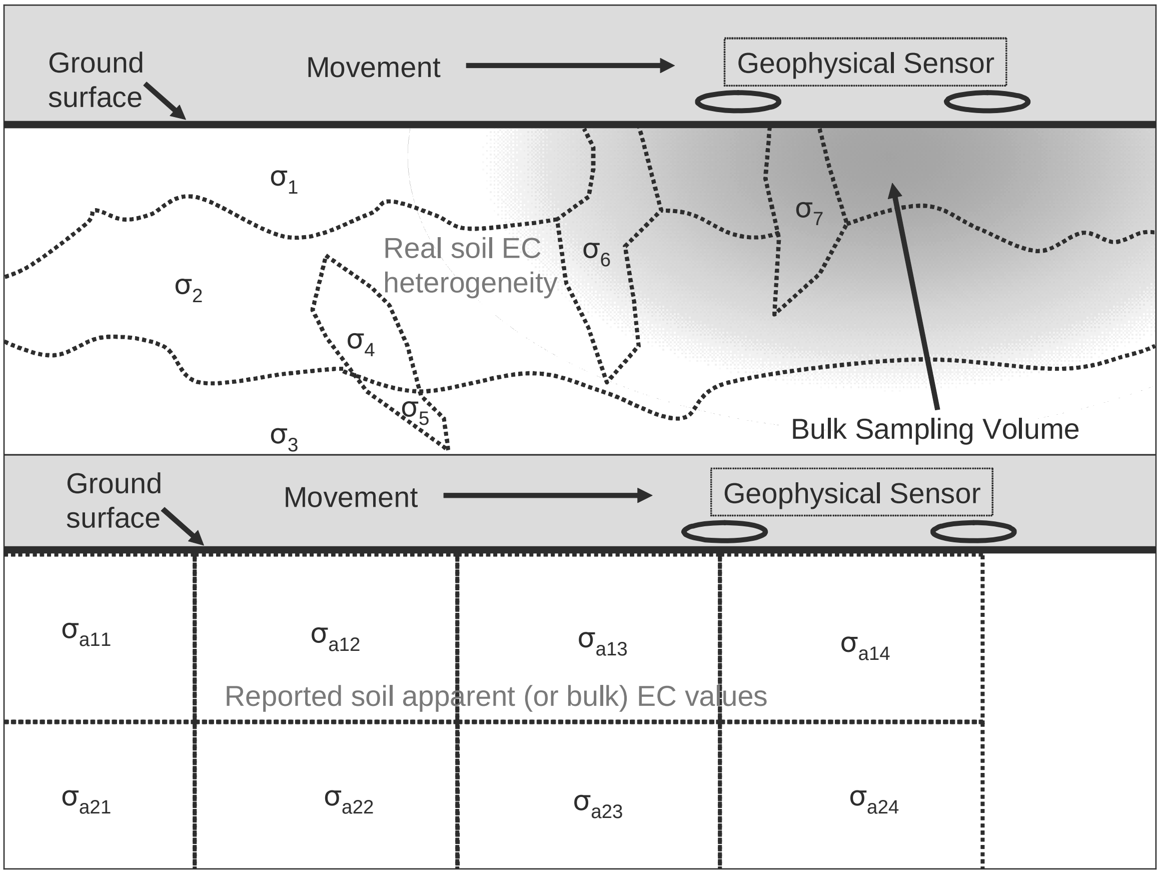

Figure 1.2 The concepts of apparent (or bulk) electrical conductivity and bulk sampling volume (or 3D footprint). The diagram shows how real soil EC heterogeneity is reported by geophysical sensors as 'averaged' regular blocks of apparent (bulk) EC. Signal contribution coming from different parts of the bulk volume sampled can vary markedly and is always a mixture of positive and negative contributions rather than just a simple smeared cloud as schematically suggested here. EC in some parts of the sampled volume will contribute negatively, and some positively. The way signal contributions are distributed is peculiar to each sensor type. EC values in the geological section are denoted by the symbol σ followed by a single number representing a particular geological entity. EC for each of the cells in the geophysical image are denoted by the symbol σ suffixed by *a* for 'apparent' and numbers representing rows and columns in the image.

Why measure electrical conductivity for groundwater resource evaluation?

Electrical conductivity of water is largely controlled by its content of dissolved salts, thus providing a good surrogate to infer the salinity of the water. The relationship between total dissolved salts and electrical conductivity is shown in Figure 1.3, taken from standard calibration water samples for an Oakton® salinity tester. In irrigation practice, the relationship between water salinity and EC is usually simplified by application of a simple conversion factor typically ranging from 0.58 to 0.68 µS/cm per mg/L depending on salt composition (Allen, 2006).

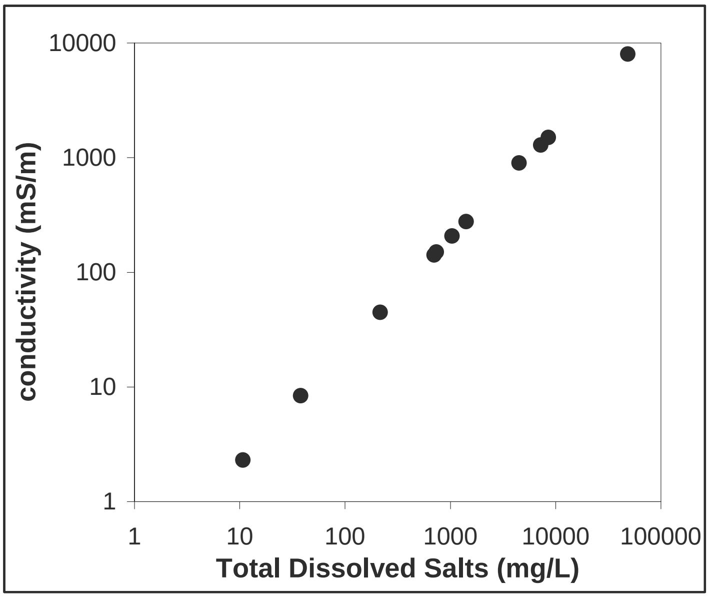

Figure 1.3 Total dissolved salts (NaCl) of standard calibration samples for the Oakton® salinity tester versus conductivity. Source http://www.4oakton.com/Con_to_TDS.htm

Geophysical electrical measurements not only measure the conductivity of the water, but measure the combined contribution of the water and soil/rock. Thus the interpretation of ground electrical methods can be complicated as the electrical conductivity of a rock is a complex function of a number of factors. Listed in order of decreasing importance (Hallenburg, 1984; Lane, 2002), these are:

- porosity and water content
- water chemistry (ie salinity)
- rock chemistry and mineralogy (ie clays)
- degree of rock alteration and mineralisation
- amount of evaporates
- amount of humic acids and
- temperature.

Thus interpretation is greatly enhanced when geophysical data is supplemented with other independent measurements e.g. geological logs, conductivity logs and EC measurements.

In soil, EC is principally affected by salinity, saturation and clay content. Conversion from EC of pore space water to bulk EC of saturated unconsolidated sediment of various textures (or clay contents) can be conducted empirically using factors obtained by Slavich and Petterson (1993) for Australian irrigation area soils. Rhoades et al. (1999) investigate factors affecting soil EC in great detail. Archie's formula, and its successors, empirically relate hard rock EC to pore water EC and porosity (Telford et al., 1990). Generally in soil, salinity, saturation and clay content all tend to change EC in the same sense, as shown in Figure 1.4, resulting in clear anomalies.[4]

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[4] Note that sections on electrical conductivity above have been contributed by Andrew

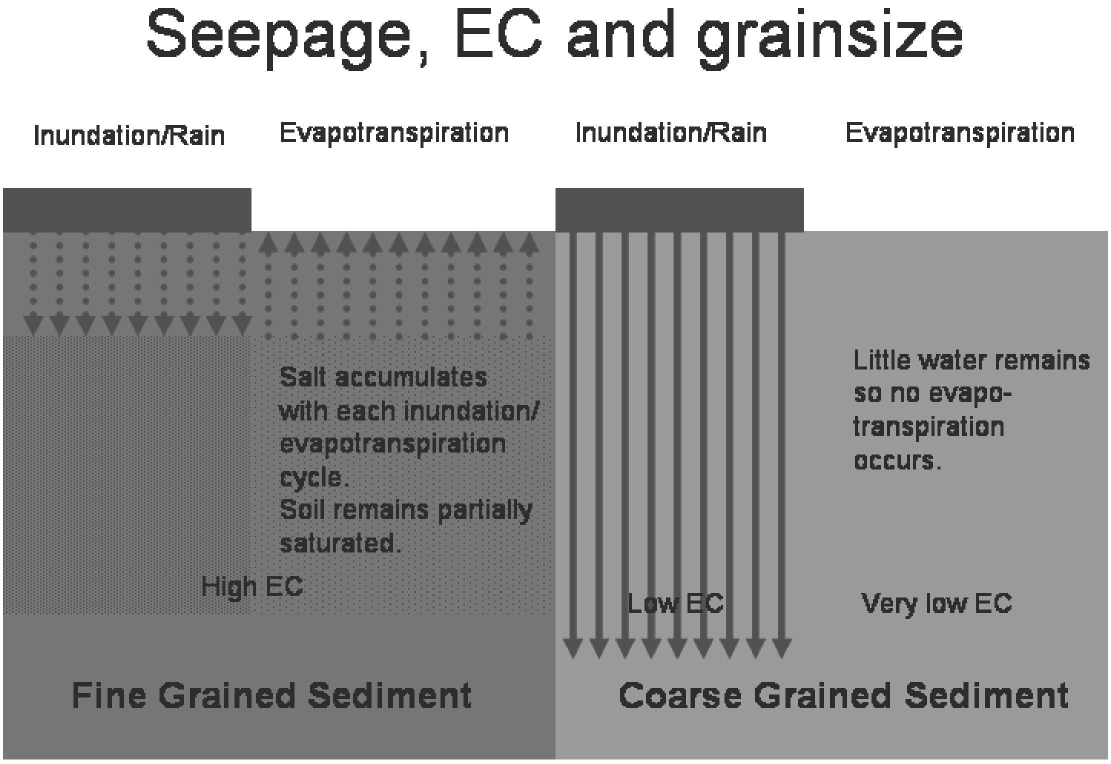


Figure 1.4 Percolation (seepage), EC and grainsize. Periodic Inundation/Rain and Evapotranspiration cycles tend to concentrate salt in near surface clay, but not sand, resulting in clear soil EC anomalies.

Some new approaches

The latest hydro-geophysical technology permits new approaches to water management. These new approaches offer new ways to make environmental and production gains on farm and at the catchment scale. They include:

- Imaging of shallow aquifers so that they can be developed reliably as underground water storages resulting in diminishing waterlogging and topsoil salinization problems. Using geophysical imagery, pockets of freshwater could be extracted from otherwise saline aquitards, reducing downward groundwater movement and mixing of mid level saline aquifers with deeper extensive freshwater aquifers.
- Imaging of connectivity of aquifers with surface water bodies (i.e. seepage and saline inflow) so that they can be conjunctively managed.
- Imaging of aquifers to improve bore siting and groundwater modelling.
- Multi-depth imaging of soil properties for management of water application and deep leaching.
- Borehole logging for responsible borehole development and detection of cross contamination of aquifers through poorly cased boreholes.

Fitzpatrick, CSIRO E & M and CRC LEME, and David Allen.

2. SURVEY PLANNING AND INTERPRETATION

Soil and groundwater scientists usually have limited geophysical training but if application of geophysical equipment to their respective disciplines is to be optimized then they must be involved in selection and utilization of that equipment. This chapter assists the irrigation industry with this process of selecting and utilizing geophysical equipment. It also attempts to distinguish between decisions that should and should not be made without the help of professional geophysicists.

Device selection procedure

In subsequent chapters, details on over one hundred devices are presented so the following device selection procedure has been prepared to help readers focus in on only those devices that will be most applicable to their requirements.

The device selection procedure is summarized as follows:

- Acquire information on the property that must be measured, site details, site obstructions, metallic object locations, and depth sections;
- Determine what geophysical properties correlate with the property you are interested in (e.g. water bearing capacity);
- Determine if the effect of other variables that correlate with a chosen geophysical property can be minimized, avoided or removed;
- Consider line and station spacing and device footprint;
- Consider depth range of interest;
- Consider depth resolution required;
- Consider what data integrity and ground truthing efforts are required;
- Consider interference from metal objects;
- Look at case studies and computer modelling;
- Sum up costs and consider value of any extra information that may be obtained;
- Consider processing options;
- Consider political and public relations issues.

In detail these steps are as follows.

Does your ground property correlate with a geophysical property?

Determine how EC (or other geophysical properties) relate to the property you are interested in – this is a task that soil and other environmental scientists should undertake in some detail, and most areas will have some preliminary surveys. If it relates clearly then proceed. You may need to do some research and field tests to determine the relationship at your particular site. Geophysicists will be able to advise on appropriate field tests.

Do other ground properties also relate to the selected geophysical property?

Determine other factors in your environment that relate to EC (or whatever geophysical property you intend to survey) and whether such factors can be stripped out of data collected. For example, unwanted correlation with variable soil saturation may be avoided by imaging deep enough to ensure saturation or by collecting multiple depth data so as to be able to see at what depth saturation effects disappear.

As another example, bedrock elevation response may be separated from cover sediment clay content response by increasing both vertical and horizontal resolution so as to identify and ignore bedrock elevation anomalies due to their shape and 3D position. For many applications, it may be that improved processing, rather than equipment choice alone, may provide the additional resolution that is necessary to identify variation in the variable you are interested in.

What horizontal resolution is needed?

There are two properties that may limit horizontal survey resolution. One is the device footprint and the other is the selected line and station spacings. Determine what horizontal line and station spacing and footprint your data needs to have in order to resolve the features in which you are interested. Limit your search to devices that can give such horizontal resolution affordably. Footprints of some geophysical devices such as fixed wing airborne EM systems will be too broad for some applications. Other devices may be effective but not economically viable at the spatial coverage density required. In most Australian irrigation areas, stringer sands (small palaeochannels) are very common. These may be only tens of metres wide and follow very irregular paths. As they are the dominant feature in many soils, failure to survey at a spacing and with a footprint that can resolve them may result in useless data.

What depth range must be sampled?

Determine what depth range the instrument must resolve and limit your search to such devices. Figure 2.1 indicates typical resolvable depth ranges of current EC survey technology. Figure 2.1 is an approximate guide and, eventually, modelling or case study comparison should be used to confirm the capabilities of a device. Depth ranges are strongly influenced by the EC of layers penetrated. EC imaging technology devices respond to variations in EC at various depths in very different and generally complicated ways so no one formula can be used to give the depth range of all types. For example it is easy to be caught by a conductive surficial layer at a site masking the readings from the survey depth of interest.

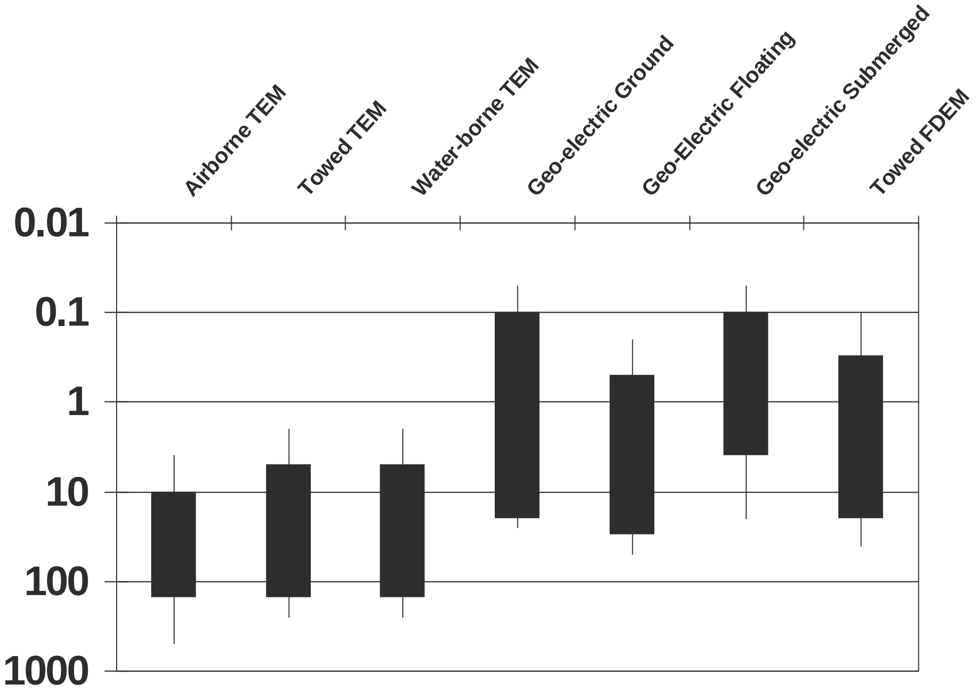


Figure 2.1 Ranges of detectable depths of various conductivity imaging devices (in metres). Note that airborne FDEM (not shown) has a range similar to but shallower than airborne TEM. This information is provided for ground with resistivity of approximately 50 ohm.m (typical of irrigation areas) and is somewhat subjective. Be aware that the minimum depth indicates the minimum thickness that can clearly be resolved without a priori (extra) information – not the minimum depth that is detected.

What depth resolution is necessary?

Determine what depth resolution is necessary to resolve features in which you are interested. Note that resolution can vary strongly depending on EC distribution and some technologies will resolve some features far better than others. For instance, geoelectric systems will easily resolve the thickness of resistive layers while TDEM systems will easily resolve the thickness of conductive layers but not vice-versa.

What ambiguity will need ground truthing?

Determine what integrity and accuracy the data needs to have. Some EC measuring techniques are affected by properties other than EC and therefore have less integrity (the *a priori* expectation of data quality in terms of accuracy, correctness and validity). Others are affected by difficult drift and calibration problems. Integrity of data can be increased with most techniques by use of ground truthing in some way but the need for, and cost of, such ground truthing needs to be considered.

A property called equivalence plagues most techniques that resolve multi-depth information. The same field data may be generated by a whole range of geological models. Various devices exhibit this property in different ways and to different degrees. Figure 2.2 presents an example. Equivalence is caused because compound properties (such as conductivity multiplied by thickness of conductive layers) are easy to measure accurately, but measuring the thicknesses and conductivities of those same layers independently may not be able to be obtained accurately, if at all. Consider what happens if we try to conduct multiple depth investigation with a device such as the EM31, designed to map a property over just a single depth range. A small change in EC at the focal depth of the instrument (about 1.5 m for EM31) will have the same result on the instrument as a huge change in EC at the limits of exploration depth of the instrument (about 6 m for EM31). This is an extreme case of equivalence. The equivalence can be greatly reduced if a multiple depth instrument, sampling many depths, is used. However, even then, because of accuracy limitations of practical instruments that measure from the ground surface, equivalence is still present to a degree, even after the best inversion data processing has been applied. Equivalence will be understood in greater detail by most readers once they have read the section below, entitled ‘Identifying models that match field data’, because it is only through processing, using parameter estimation techniques such as inversion, that equivalent models that equally fit the same dataset can be identified.

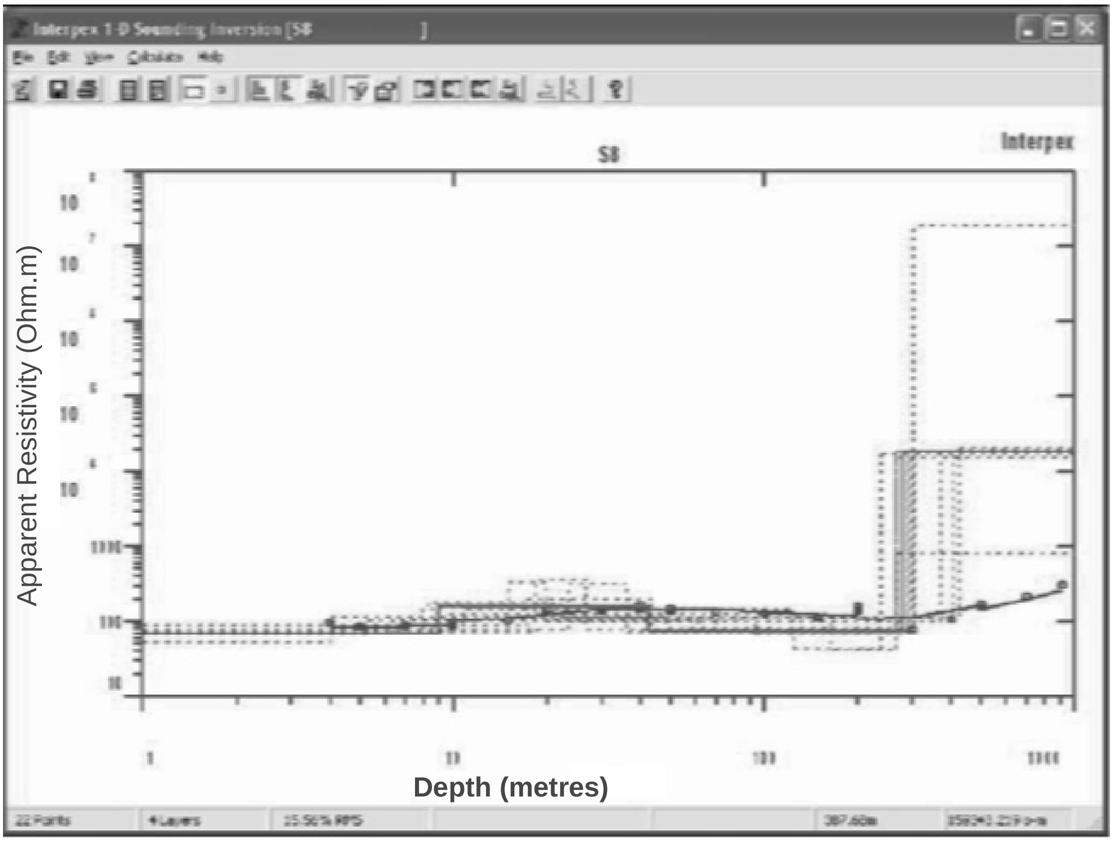


Figure 2.2 Equivalence can be most simply explained by an example of equivalence analysis conducted on multi-depth data collected at just one point. The smooth purple line is apparent resistivity (or 1/EC) data obtained from a geophysical instrument. The red line represents a model of horizontal layers of different resistivities. This model was identified by an inversion technique to be the most likely model that might have resulted in the field data presented in the purple curve. The collection of green dotted models are equally likely and are called equivalent models.

What effect will metal objects have?

Determine the potential interference from metal objects on the survey site. Most EC measuring devices are very strongly affected by metallic objects in their proximity. Shape and grounding of such objects may be very significant. For instance, an ungrounded fence, around a rectangular paddock, with a closed gate may not affect geoelectric devices but may cause problems for electromagnetic devices. Simply by opening the gate, the circuit through the fence may be broken resulting in negligible effect on electromagnetic devices. Similarly, a buried copper pipe may cause problems for a geoelectric device but have less effect on an electromagnetic device. In populated areas, where there is a lot of metallic infrastructure, much of which has power circulating through it, it is typical for geophysical datasets to be extremely difficult to interpret due to the effect of metallic objects. In such environments, it may be preferable to use gravity, seismic methods and ground penetrating radar to avoid these complications.

If a site contains metallic objects, whose locations are known or unknown, then account needs to be taken of these sources. One approach is to mark up, on the geophysical maps, known locations of metallic sources and allow for these in interpretation. A second approach is to try to remove the effects of metallic objects by editing the data but this requires that we know their locations and over what distance they affect the data. Some possible but buried sources may be recognised by the geometric form of their response e.g. linear due to pipelines.

In summary:
Some metallic objects may be seen in data from one geophysical method but not in others.
When metallic objects are present, accurate positional data is needed to aid in achieving a valid interpretation of the geophysical data.
Contracts should clearly specify whether survey lines are to be moved away from known metallic objects.
Contracts should specify whether the data should be edited to remove these effects, and/or whether the raw data with GPS positions of metallic objects are to be supplied.

What case studies and modelling are relevant?

Communicate with geophysical companies to verify if their products can provide what you require. Get them to confirm this with similar case studies and/or computer modelling. Beware of statistical incorporation of extra information for constraining case studies. Such constraints may be an appropriate way of providing a survey solution but it is important to know what constraints have been used and how this has been done. Decide which companies can provide solutions. Be very cautious of equipment performance that is verified by case studies alone because many geophysical instruments perform in drastically different ways with just small changes in boundary depths, layer combinations and conductivities of various sediment layers.

Price

Negotiate with the geophysical companies to get a competitive price for your size and type of survey.

Many devices will provide information that is redundant to your objectives. Carefully consider what extra information is available and whether you have future potential use for it. Consider this when selecting equipment as a little extra cost may provide a whole lot of extra value in your data that requires some lateral thinking to identify.

In Australia where labour costs are high, typically, the predominant cost of a survey will be the man and vehicle hours involved both in mobilization and survey rather than the costs related to the complexity of the equipment utilized.

What processing will be needed?

Processing and presentation of data will often be as important as the selection of the acquisition device. Ensure you are getting appropriate processing at an appropriate cost. For many specialized applications, it may be worth spending more on processing than on acquisition.

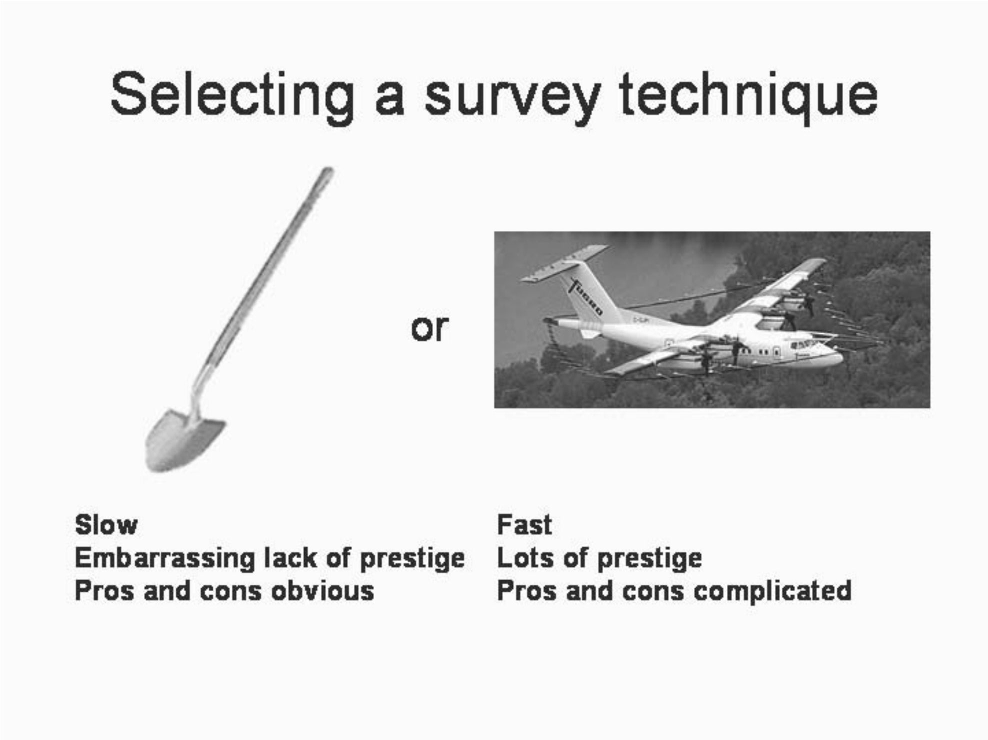
Public relations and commercial influences

Political and/or human nature issues may be significant factors influencing choice of technique.

Choosing the most appropriate geophysical technique requires a broad understanding of all of the systems available and their appropriateness for the survey objectives. Sub-optimal solutions have been applied in the past. For example there has been excessive use of tried and proven (but not necessarily particularly effective) techniques, survey designs and interpretation methodologies. On some occasions, expensive, tried and proven commercial techniques have been adopted straight from the mineral exploration industry without appropriate re-application for agricultural or environmental objectives.

Cheap simple techniques carry with them a lack of prestige and are often rejected, unfortunately, for that reason. Conversely, highly capable, complicated techniques with large start-up costs are often either ignored or oversold as their pros and cons are so complicated that decision makers struggle to assess their merits. A high degree of collective effort, organization, community education and funding collection is necessary for use of the more expensive techniques. These factors (highlighted in figure 2.3) typically also significantly influence choice.

Decisions on survey techniques are also highly dependent on who is involved with the survey. Ground surveys usually involve lots of communication and interaction with farmers and other on-site personnel. This interaction is often very useful for conveying the correct interpretation of the survey results. It is more difficult to achieve this one-on-one interaction with airborne surveys. However, airborne surveys enable catchment-scale surveys to be undertaken, and avoid the problems of obtaining permission to enter land.



Selecting a survey technique

or

Slow	**Fast**
Embarrassing lack of prestige	**Lots of prestige**
Pros and cons obvious	**Pros and cons complicated**

Figure 2.3 Human nature can often influence decisions on groundwater and soil investigation. This unrealistically extreme decision example highlights some awkward issues. A shovel and the four engine MegaTEM aircraft, normally used for very deep mineral exploration but capable of groundwater exploration, are simply chosen here as extremes (photo from Fugro website).

Further notes on modelling

Modelling and simulation can be conducted cheaply before surveying to highlight which survey instruments, if any, can supply viable information and at what cost. This survey of equipment, as well as various software tools, provides guidance on equipment applicability.

Software tools include:

- GeoPASS (www.Hygeia-eu.org) – free;
- HydroGeoImager geoelectric array configuration analyst (David@GroundwaterImaging.com) – free;
- Res2DInv, Res3DInv (www.Geoelectrical.com) – free;
- EMMA (http://www.geofysiksamarbejdet.au.dk/?id=201) – free;
- GeoTutor II Mag/Res/EM (www.PetRosEiKon.com) US$999 or US$499Academic;
- IX1D forward modelling capabilities (www.Interpex.com) – free; and
- Various tools and graphs supplied by reputable equipment suppliers.

These tools are for geophysicists to use – the non-geophysicist need only ensure that such tools are used where appropriate and that contracts for surveys are not finalized while there is still unnecessary risk that they may not identify what is required. The non-geophysicist may use diffusion and skin depth formulae quoted in introductions to chapters 3 and 5 and in Lane (2002) to give an approximate indication of depth of investigation of electromagnetic equipment except for ground frequency domain electromagnetic (ground FDEM) devices. There are limits to what modelling can determine. Minimum resolvable depth of exploration of most electromagnetic devices is generally determined by experimentation as many phenomena affecting it are not well understood or easy to quantify. Problems with three dimensional heterogeneity are typically identified, or inferred, only by complex modelling such as is reported in geophysical journals.

Survey design

Survey design will have been more or less completed in the process, given above, of choosing a suitable instrument. Some issues remain including choice of survey path and positioning.

Choice of survey path

Some surveys are best completed on a grid pattern while others are best performed on irregular survey paths logged by GPS. Irregular survey paths may be designed to cross relevant features at right angles and to provide denser coverage over areas that require it. A few well planned irregular transects of data with good vertical resolution may be enough to intersect various groundwater flow paths and provide groundwater development solutions but such data are only useful if they can be viewed in three dimensions, or at least vertical sections combined with a plan map (See for example, Figures 3 and 4 in Chapter 11).

Survey path is frequently limited by crop direction and natural and man made obstacles. Trimble and others have developed good GPS firmware for managing data collection close to obstacles, developed to respond to the demands of precision spraying and cultivation contractors.

Positioning

All surveys will need some form of positioning. This may range from manual measurement of grids using features on airphotos to dual frequency real time kinematic differential GPS. Soil surveys usually require differential GPS (real time or post processed) while deeper surveys can usually suffice with uncorrected GPS which usually has an accuracy of about 5 m and is better than 15 m 90% of the time. The remaining time constitutes GPS ‘blowouts’ which can be obvious to surveyors, should they be checking for them (Figure 2.4). Some GPS receivers contain features such as Trimble Everest multi-path rejection technique which significantly minimize ‘blowouts’ and can make marked differences to daily production. Differential GPS can give accuracies ranging from +/-1 m to +/-0.01 m. Higher accuracies are of limited use with geophysics due to the relatively large footprints of most geophysical sensors. Nevertheless users should be warned to differentiate between pass to pass and absolute (year to year) accuracies. For example, one metre pass to pass accuracy is useless if you must come back and drill a geophysical anomaly to an accuracy of 5 m and the absolute accuracy of the GPS used is not mentioned in specifications but happens to be +/- 15 m.

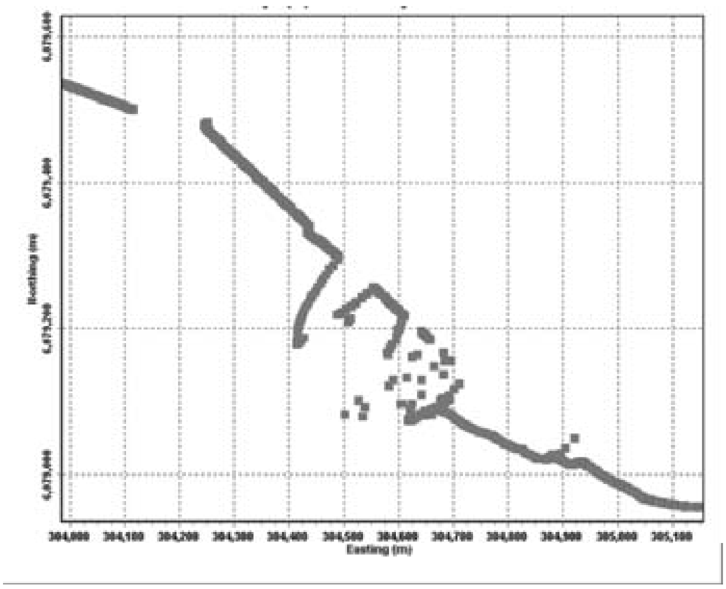


Figure 2.4 A GPS 'blowout' that occurred while surveying along a relatively straight canal. Grey points have been masked using instrument supplied GPS quality statistics. It is clear that the quality statistics (HDOP (horizontal dilution of precision) and number of satellites in this case) do not always correspond exactly with the 'blowouts'.

Survey interpretation

This section is intended to give those unfamiliar with geophysics an understanding of the processes and pitfalls of data processing and interpretation techniques.

Geophysical survey interpretation will generally involve the following steps:

- Organization and backup of the data;
- Geophysical transformations or parameter estimation techniques (such as inversion modelling that matches synthetic models to field data);
- Cleaning of the data – the identification and removal of spurious features resulting from metallic obstacle interference, operator error and equipment failure. Parts of this step are generally conducted both before and after the previous step due to the need to see the data in order to identify and diagnose errors in it.
- Ground truthing at spot sites and statistical extrapolation of the ground truthing using correlative procedures (either mentally or with the assistance of statistical algorithms);
- Gridding, grid processing and presentation
- Computer modelling
- An assessment of the final products.

Geophysical contractors should be responsible for the first three steps while the last four are usually left for interpretation consultants.

Geophysical transformations

Much geophysical data emerges from instruments simply as voltages. Various physical equations may be used to convert the voltages to desired physical parameters such as EC. Most equations used will be simplistic approximations valid only under certain conditions. The approximations often will result in less than ideal resolution, and under certain conditions, geophysical artefacts. The merits of many of the transformations are discussed in detail throughout this document. With most multi-depth instruments, a better result may be obtained using parameter estimation techniques as explained below.

Identifying models that match field data

The construction of models (or synthetic earth models) that match the geophysical field data can reveal much more than the raw field data on its own. Such models are produced by processes collectively known as parameter estimation techniques.

Two general approaches are common for producing such models: –
Inversion methods where geophysical response of an initial guessed earth model is used to seed an iterative process until a model of 'best fit' is achieved by convergence. In each iteration a forward model is generated which calculates the geophysical response from equations that use the geometry and physical property distribution of the model and the result is compared with the field data.

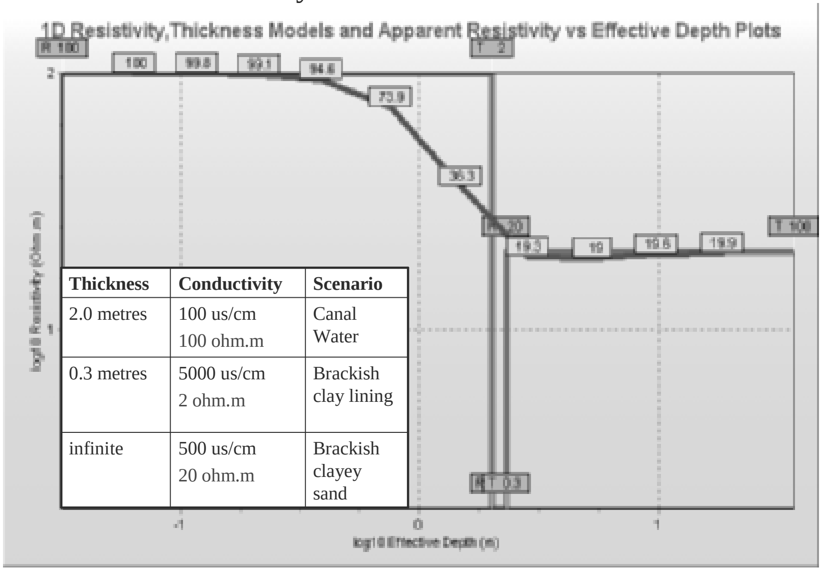
In contrast, neural networks use training datasets and geophysical responses as a guide to determining what earth model best matches each geophysical field dataset.

Some parameter estimation techniques resolve the substrate into smoothly varying models while others resolve it into discrete uniform layers or blocks. Discrete layer inversion works best in environments where sharp contrasts exist in the earth (e.g. clay – sand boundaries). It is common for such techniques to accurately resolve the depths of such boundaries in such a way that they can then be mapped. However, there are definite limits on the resolving capabilities of these modelling techniques and these must always be considered carefully when viewing the resultant datasets. For example, constraints may be added using assumptions or ground control (e.g. depths of layers known from borehole logs or other geophysical data). Such practices, conducted without care, tend to result in geophysical artefacts due to extrapolation of errors in the constraint data. An example is when airborne EM data is corrected for aircraft height above the ground, but the height sensor picks height above the trees. A second example might be when borehole conductivities and depths are used from a borehole that is not representative of the ground sampled by the 'footprint' of the geophysical device.

Inversion modelling methods use the following steps:

- acquire field data;
- input starting geological models that may fit field data;
- calculate synthetic field data for the models;
- compare the synthetic field data with the actual field data and determine what changes in the model parameters (eg. layer thicknesses and ECs) will cause the synthetic field data to become more like the actual field data;
- make changes to the geological models that may fit the data better, and
- iterate until satisfied that appropriate models have been chosen that fit the data.

A simple single sounding example of a three horizontal earth layer model and the corresponding smooth apparent EC (or resistivity) curve are presented in Figure 2.5. In Figure 2.6, a whole series of three layer models are presented stitched together in a 2D vertical section. Apparent EC curves were created from these and inversion was conducted on each curve giving the results in the lower 2D section. The limitations of the inversion are clearly evident.



Thickness	Conductivity	Scenario
2.0 metres	100 us/cm 100 ohm.m	Canal Water
0.3 metres	5000 us/cm 2 ohm.m	Brackish clay lining
infinite	500 us/cm 20 ohm.m	Brackish clayey sand

Figure 2.5 A comparison of a smooth apparent resistivity (or EC) curve and the corresponding physical three horizontal layer model that created the curve. Inversion is used to try to identify, from the apparent EC data obtained by survey instruments, what model is most likely. It is a technique that can greatly improve resolution of field data.

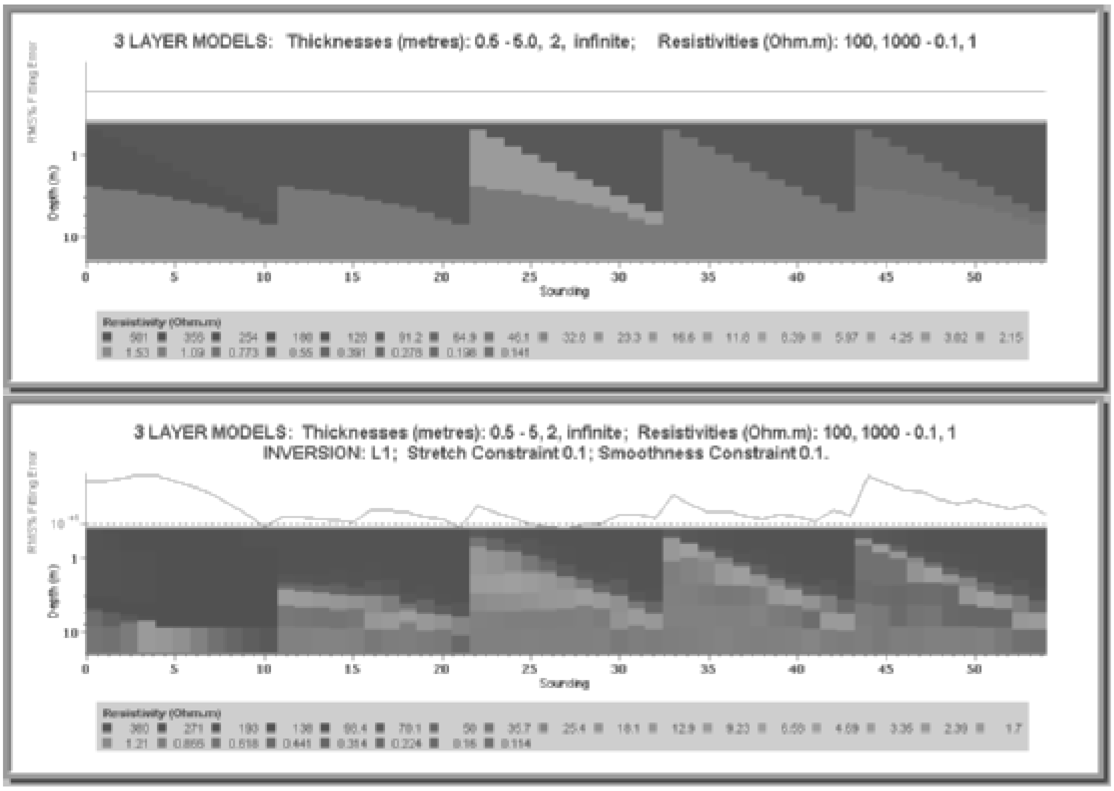


Figure 2.6 Stitched together three layer earth models presented in the upper 2D vertical section were used to create apparent resistivity curves for a geoelectric device (See Chapter 7). Each curve was then put through the inversion process (see HydrogeoImager in the software section) and the results are presented in the lower 2D vertical section. The resolving capabilities of inversion need to be taken into consideration when viewing images created by inversion.

Data cleaning

Data cleaning is an important issue with geophysical data. Most datasets must be manually edited to remove spurious data from instrument or operator malfunction and metallic and other object interference. Particularly with multi-depth datasets, careful identification and removal of the influence of low signal to noise ratio data must be undertaken in order to produce artefact-free presentations. This rudimentary part of processing tends to be particularly expensive due to its manual and unpredictable nature but it is always worth doing thoroughly.

Ground truthing ('calibration') and regression

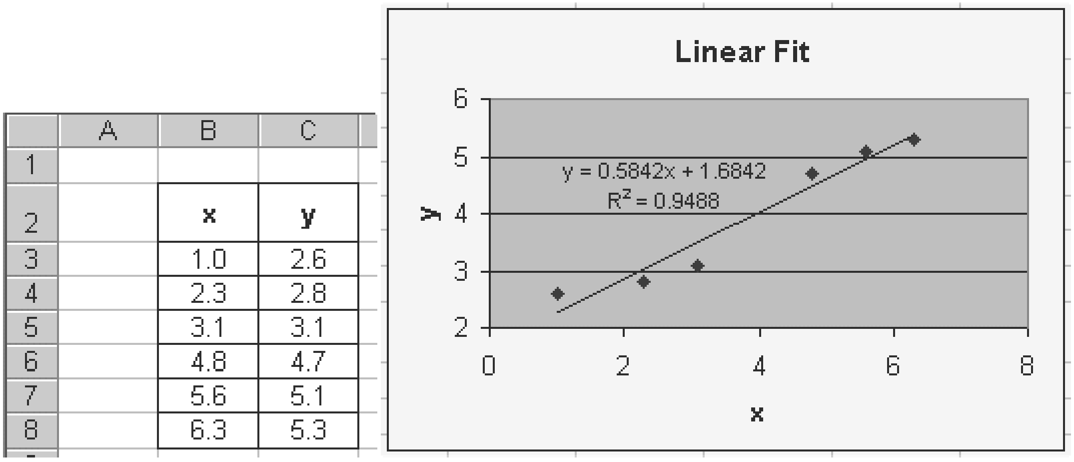
To get maximum benefit from geophysical interpretation it is necessary to take account of all other information known about the site. Geophysical surveys are normally used as a cheap way of spatially extrapolating information, known from bores or discrete locations into two- or three-dimensional maps or models of a whole area. Often, prior information about various sites in a survey exists and is useful for interpreting data. In other cases, it is common practice to use geophysical surveys to plan spot exploration (usually drill holes of some form). Spot exploration sites may target various features with particular geophysical signatures (e.g. long thin resistive bodies that are known to generally represent freshwater-bearing palaeochannels). Alternatively, spot exploration may be targeted to evenly represent all features in a geophysical dataset. This practice is commonly conducted when mapping soil. Such spot data can then be used with gridded geophysical data, by regression routines, to statistically extrapolate properties such as:

- soil salinity
- deep drainage
- pH
- clay percentage
- boron content
- soil depth over shallow substrate
- cation exchange capacity
- exchangeable sodium percentage
- infiltration

Obviously not all these properties will extrapolate well at every site. The integrity of the extrapolation will depend on both the integrity of the spot sampling procedure and the results of the regression analysis of each variable with respect to the geophysical and other data inputs.

What is Regression?

Regression is the process of determining how one variable relates to another. In environmental geophysical applications, a relationship between geophysical data and ground truthing is usually sought. The ground truthing may be of a parameter other than what the geophysical survey measured. Simple linear regression tries to identify a relationship such as $y=ax+b$ where a and b are constants. Multiple linear regression tries to find a relationship dependent on multiple variables. The input variable(s) x may not be actual data but rather a transformation of actual data. It is common to take the logarithm of data in order to reduce the influence of outliers. An example is presented in Figure 2.7.



	A	B	C
1			
2		x	y
3		1.0	2.6
4		2.3	2.8
5		3.1	3.1
6		4.8	4.7
7		5.6	5.1
8		6.3	5.3

Figure 2.7 A simple example of regression (from http://phoenix.phys.clemson.edu/tutorials/excel/regression.html)

In many cases a simple linear relationship will not exist i.e. the measured variables only partially explain the patterns in the data. Neural networks may be used, in place of regression, to more flexibly search for correlation.

Statistical extrapolation based on relationships obtained using regression should not be used blindly as problematic and wasteful results will usually occur.

It is a very worthwhile practice to search manually for correlation between geophysical datasets and ground truth spot measurements. Regression and statistical extrapolation need not be conducted if interpreters can visualize any correlations manually. The importance of this step should be emphasized. Interpreters should confirm that the spot data locations are distributed adequately across all the features in the spatial dataset. They should then look at values obtained and compare them to the geophysical data. For instance, one may be comparing clay content values in drill holes to EC mapped across a paddock and notice that in one portion of the image, high EC does not relate directly to an increase in clay content. This ill-defined portion of the image must be interpreted differently to the rest. Regression will not, however, be smart enough to do this.

Regression may be conducted using MS Excel, general purpose statistical packages or specialized products such as the US Salinity Laboratory's ESSAP (no longer web published but widely used in Australia). This package is generally used along with geographical information systems (eg. ESRI's ArcView) and/or gridding and mapping packages (eg. Golden Software's Surfer, The University of Sydney Centre for precision agriculture's Vesper www.usyd.edu.au/su/agric/acpa/vesper/vesper.html or Geosoft's Oasis Montaj). Passing data between the various programs and creating quality presentations is rather laborious at present as no product appears to be available that is capable of automating the whole process in an integrated holistic way.

Gridding and image processing

Gridding of geophysical data is important for presentation but brings its own pitfalls. Data may be inappropriately smoothed by gridding in such a way that the resultant grid appears to be reputable while the underlying data is noisy or important features in good data may be 'blurred out'. Gridding may extrapolate far away from known data and if data points are not posted over a grid, or the grid is not masked with an appropriate boundary, then viewers may be confused and/or deceived by the result. Masking of grids may create irregularly shaped images that present less elegantly than simple rectangular images but they may be more accurate. Various gridding algorithms are available with various important merits and demerits that will not be explained here.

Once data is gridded, a colour scale must be applied in order to image it. This is not a simple process. It is commonly claimed by image manipulators that they can make an image show whatever one wants it to show. They are referring to their ability to manipulate the application of colour scales in order to emphasise different features. Simple linear stretch of a colour scale over the range of data variation tends to highlight outliers and hide important variation in the image. A process called equal area distribution assigns each portion of the colour scale to an equal portion of the gridded data. This enhances variation across the image but, in order to avoid undue interest in insignificant features, should be used only in conjunction with a coloured histogram showing the distribution of the data across the colour scale. Once a survey technique is established in an area, it is common practice to select a common colour scale for all imagery obtained using that technique. It is only then that comparison of entire datasets is practical.

Various image enhancement techniques such as shading and the taking of derivatives may be used to make images easier to understand.

Final assessment of geophysical data

Finally, data products are mentally assessed. It is vital to take account of local knowledge and perspectives as possessed by local farmers and others involved in local irrigation. A knowledge of the landforms and underlying geology is also very important. Effective geophysical interpretation is often a team effort between a geophysicist and those with local knowledge.

3. GROUND FREQUENCY DOMAIN ELECTROMAGNETIC SYSTEMS

Basics

Many soil imaging devices are ground frequency domain electromagnetic (FDEM) devices, the most well known being the Geonics EM31 (Figure 3-1) and EM38. They are compact devices that can be passed over the ground without contact, resulting in very efficient survey. The EM31 has a maximum depth penetration of 6 - 7 metres whilst the EM38 has a maximum of 1 – 2 metres.

Figure 3.1 EM31 and DGPS set up for rice land classification. The boom is placed so as to straddle the quad bike. For production mode survey this placement is preferred by most Australian contractors, in preference to metal interference-free placement on a non-metallic trailer (from Shaw, 2001).

Maps of apparent soil EC are the most common output produced using these devices. They may indicate soil variations such as the presence of shallow palaeochannels as in Figure 3-2. Using additional information from auger holes, and image classification algorithms, the maps are often converted into simple soil classification maps such as in Figure 3-3.

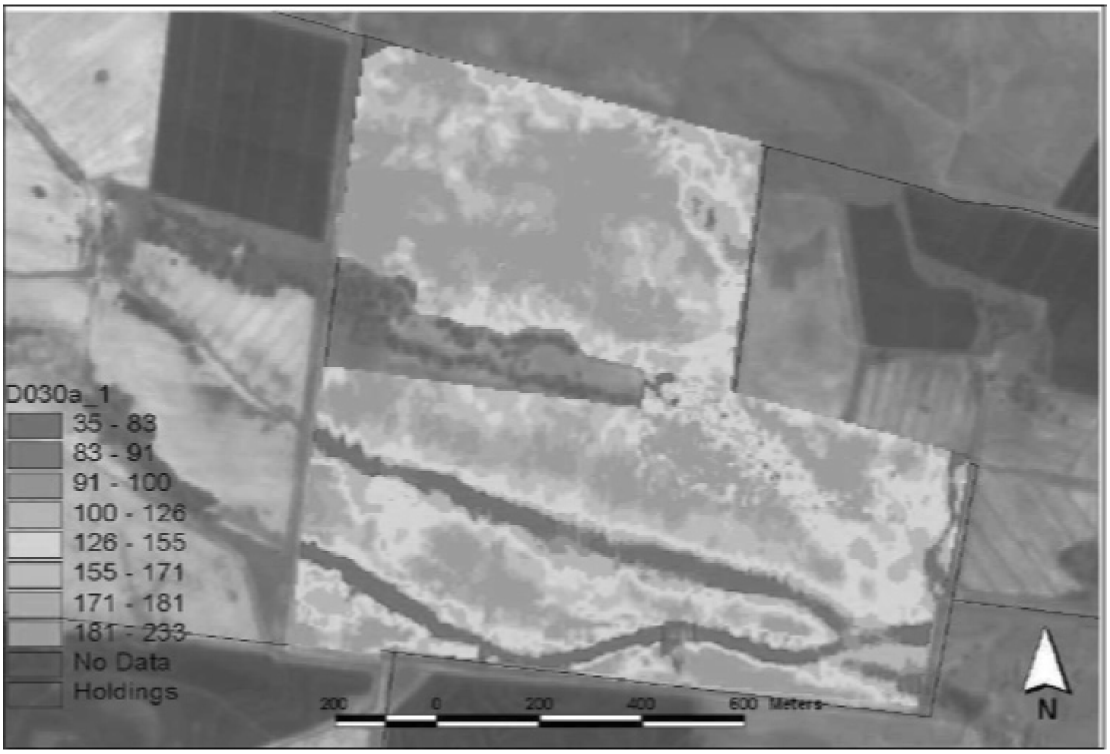


Figure 3.2 EM31 data collected at 20 m line spacing for rice land classification (from Shaw 2001).

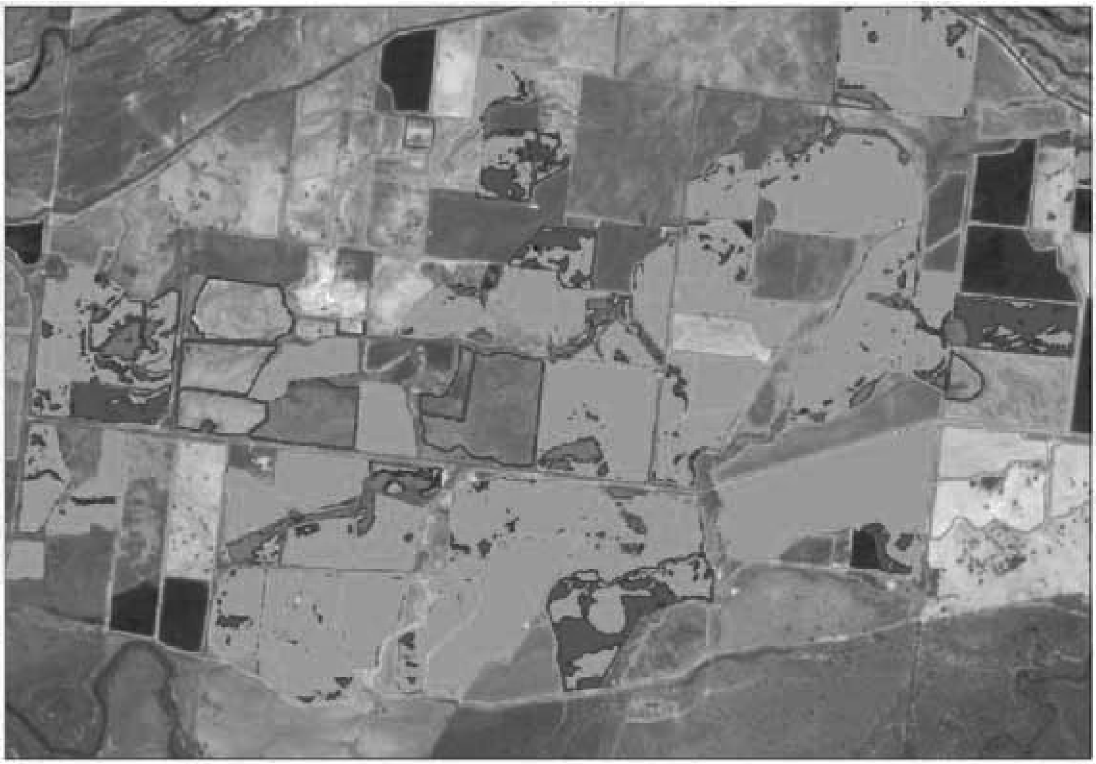


Figure 3.3 Rice land classification derived from EM31 surveying assisted by drilling and soil sampling. Red - Unsuitable, Blue - Suitable for crop rotation, Green – suitable (from Shaw 2001).

How do FDEM devices work?

Frequency domain ground systems operate with continuous transmitter waveforms, typically sine waves. Receiver coils are used to pick up change in the primary magnetic fields from the transmitter coils and change in the secondary magnetic fields from currents induced in the ground. Most coils are oriented horizontally but some systems also use vertical coils. A typical arrangement is presented in Figure 3.4.

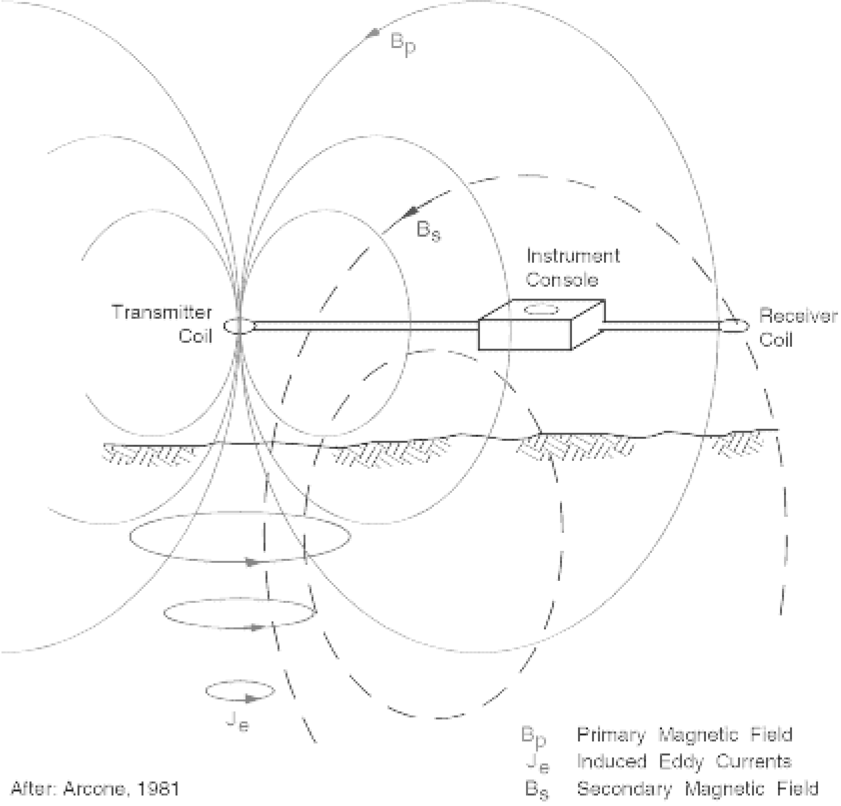


Figure 3.4 The principle of operation of a vertical dipole FDEM ground conductivity meter (from http://www.nga.com/Geo_ser_EM(FDEM).htm).

Frequency domain electromagnetic (FDEM or FEM) devices image electrical conductivity in a region of the earth under the instrument using electromagnetically induced ‘smoke rings’ of current that dissipate into the earth. Variable depths can be imaged by varying coil separation and/or orientation and the height of the instrument above the ground. Lower frequencies enable greater penetration into the ground. Higher frequencies provide shallower information. Spies and Frischknecht (1991) provide useful theory.

In contrast to helicopter slung FDEM systems, ground conductivity meter operating frequency has little effect on signal penetration. This is because, for pragmatic reasons, they are designed to operate at frequencies at which coil separation, rather than operating frequency, is the principal factor determining penetration. Figure 3.5 presents the principal difference between operation of helicopter slung FDEM and typical ground based soil imaging devices, which is that one principally uses coil separation to determine the bulk that is sampled while the other uses only frequency of operation.

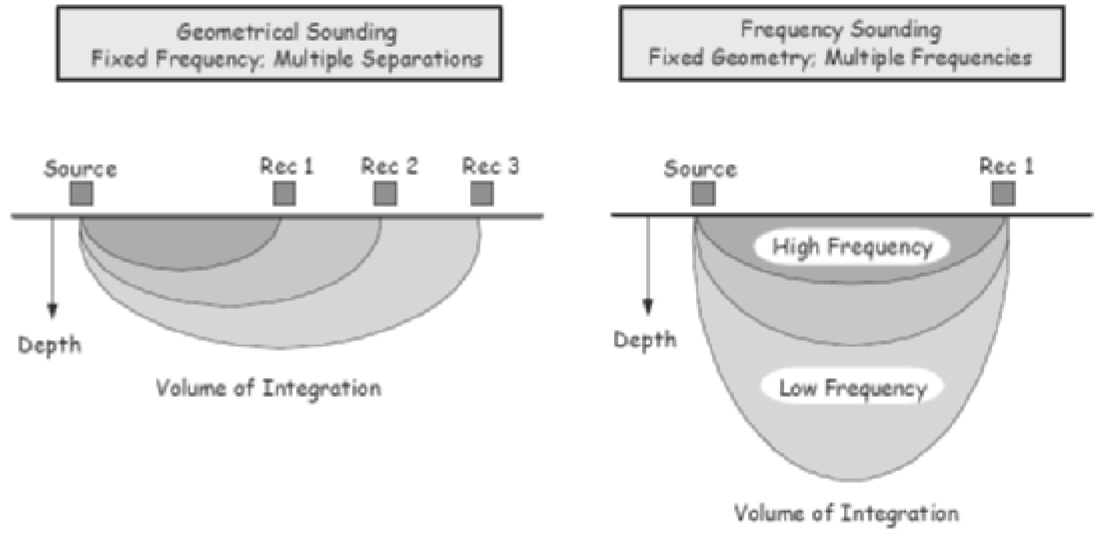


Figure 3.5 The difference between bulk sampled by geometric and frequency sounding devices. Typical soil conductivity meters operate principally by the geometric sounding principle while airborne FDEM systems operate entirely using the frequency sounding principle. (Diagram from Won, www.Geophex.com)

For efficiency of operation, FDEM instruments transmit a time-varying sinusoidal magnetic field. The receivers break received signal up into two components: signal in-phase with the transmitted signal and signal that is out of phase (quadrature) (See Figure 3.6). Behaviour of FDEM devices can be accounted for by simple equations (see insert), involving only the quadrature component, so long as they remain in what is called the low induction number approximation where electrical conductivity of the substrate is, conveniently, directly proportional to the quadrature signal. In-phase information is strongly affected by magnetic permeability as well as conductivity of the substrate and is rarely used in soil and groundwater investigation; it is typically used for detection of metallic objects , such as buried pipes, cables and steel drums.

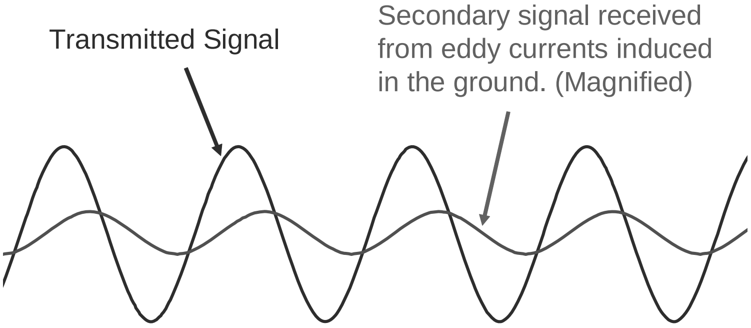


Figure 3.6 FDEM works by transmitting a repetitious signal (usually sinusoidal) into a transmitter coil. This induces an equivalent signal in a receiver coil (unless oriented so as to null it out) and this signal is of no use in subsurface investigation. A much smaller secondary signal however is also received by the receiver coil. As shown, there is a phase shift between the two signals. The instrument breaks up the secondary signal into two components. One component is the part of the secondary signal that matches the peaks and troughs of the primary signal (in phase) and the other component is the part of the signal that is left over (90° out of phase or quadrature). In most cases, bulk EC of the ground within the instrument 'footprint' is proportional to the quadrature component.

How EC is determined using common FDEM EC meters: - for the technically minded - Instruments designed to work with the low induction number approximation such as the Geonics EM31 and EM38 can report bulk EC simply after multiplying their quadrature data by a proportionality constant. The proportionality constant for VCP configuration instruments (see glossary) is obtained using the following formula:

$$\sigma_a = \frac{4}{\omega \mu_0 s^2} \left(\frac{H_S}{H_P} \right)_{QuadratureComponent}$$

where:

σ_a is apparent conductivity;

ω is angular frequency of the transmitted sine wave;

μ_0 is the permeability of free space;

s is the spacing between the coil centres;

H_S is the secondary magnetic field at the receiver coil; and

H_P is the primary magnetic field at the receiver coil.

Quadrature component is the received sinusoidal signal that is exactly out of phase with the primary transmitted sinusoidal signal.

For those with an aptitude for physics, the full formulae, valid even over conductive ground and at high frequencies of operation, is presented by Won (www.Geophex.com). Background theory helpful for understanding Won's papers is available in Nabighian (1987).

For the most commonly used instrument, the Geonics EM31 operating in the VCP mode (see section on configurations below) departure from the low induction number approximation begins to become significant once ground conductivity exceeds 100 mS/m (a value not uncommon in saline Australian soils) (McNeill, 1980). In borderline cases, this does not prevent operators from using FDEM data in a qualitative way – calibrated using soil samples. The limitations of the approximation can be partially overcome by using correction factors (for non-layered soil) or rigorous inversion software such as IX1D to process the data (for layered soil surveyed using multi-depth instruments).

Depth sensitivity of FDEM devices (operating in the low induction number approximation) is dependent only on coil separation and configuration. Some ground based FDEM instruments operate at multiple frequencies but they cannot, while keeping within the low induction number approximation, resolve multiple depths by doing so in the way achieved by airborne FDEM systems.

Low induction number approximation : - for the technically minded – a way of explaining the low induction number approximation is that the sampling volume remains solely dependent on geometry as long as the frequency of the field is consistent with the low-frequency-approximation where coil separation divided by skin depth is much less than one, as defined by Wait (1962.):

$$\left|(i\sigma_0\mu\omega)^{1/2}\rho\right| \leq 1/2$$

where i is the square-root of –1, σ_0 is the conductivity and μ is the permeability, respectively, of the material in the volume-of-exploration, ω is the angular frequency of the transmitted field, and ρ is the spacing between the transmitter and receiver (DUALEM website, 2005). Set i to 1 to use this equation for determining limits of the low frequency approximation. Further details are available in papers provided on the DUALEM and Geonics websites.

FDEM devices

The following frequency domain ground electromagnetic devices were reviewed:

- Apex Parametrics Max Min
- DUALEM 1, 2, 4 etc.
- Geonics EM31, 34, 38, 31Sh, 31-3multi, 34XL and 38DD
- Geophex GEM2 and GEM2H
- GF Instruments CM031, CM032, CM138
- GSSI Profiler EMP400
- Iris Instruments Promis-10
- L & R Instruments MiniEM
- Red Dog DT Barlow FEM-8 System

Geonics systems have been widely used in the FDEM soil mapping market for many years and are widely used in “precision agriculture” and temporal monitoring applications. DUALEM have more recently emerged as a company focussing on soil imaging. Between them, these two companies have supplied the majority of public domain information available on FDEM imaging.

FDEM Calibration

Calibration of FDEM instruments is difficult and critical to their operation since very small secondary fields must be detected in the presence of large primary fields. Noise shielding further adds to calibration sensitivity and noise shielding can be optimized only in instruments designed to operate at only one frequency.

Almost all Australian FDEM contractors currently place their instruments on metallic vehicles which add to the signal received by the devices, thus making precise calibration impossible. Over conductive ground, which is typical in Australia, this practice has been deemed acceptable by many who only use the data in a relative sense to show soil variation. Because Australian soils are relatively conductive, surveys conducted in Australia typically have low sensitivity to calibration errors.

Geonics and some others permit the user to re-calibrate their instruments when necessary. Geonics argue that frequent re-calibration of their FDEM instruments is appropriate. In field calibration is not possible, and claimed not to be necessary with the DUALEM instruments, MiniEM, Profiler EMP400 or the Geophex GEM2. Although these instruments are sealed, tamper free calibration is possible and simple – it just needs to be done, after conducting appropriate field tests, digitally on a computer after the survey. Geonics advise that the non-linearity of drift through even the course of a single survey can render such post-processing calibration ineffective.

Equipment manufacturers all claim anecdotal and informally gathered evidence suggests that there are significant variations between noise (spurious data introduced by any number of internal or external sources) and drift (real-time non-linear shifting of data caused primarily by interaction with the primary field) of each other’s instruments. Formal comparison is recommended but could not be conducted within the budget of this review. Because the response signal to the primary field decreases with the inverse square of the coil separation, the very shallow imaging tools are most susceptible to drift problems.

FDEM configurations and depth sensitivities

Three coil configurations are typically used in ground FDEM instruments for soil imaging (see Figure 3.7). The most common is horizontal co-planar (HCP) where both transmitter and receiver coil are in one horizontal plane. An example is the EM31 when operated upright. Vertical co-planar (VCP) is also common. An example is the EM31 when operated lying on its side. HCP is also referred to, confusingly, as vertical dipole because the axes of the coils are vertical. VCP is also referred to, similarly, as horizontal dipole. Complete confusion and ambiguity is sometimes introduced when the planes of the coil axes are referred to in HCP and VCP terminology rather than the planes of the coils – this must be avoided. Another configuration is patented for use by the DUALEM instruments and is called ‘Perpendicular’ or PRP. It uses the horizontal transmitting coil, also used in DUALEM HCP configuration, along with a vertical coil with an axis pointing along the length of the instrument. This configuration is null-coupled – that is no primary field is received at the receiver coil but such null-coupling creates sensitivity to orientation errors. The proposed Mini-EM also uses a method of introducing two non-interfering configurations using a common transmitting loop. It places the transmitter coil on a 45 degree angle so that components of its field can be used in both HCP and VCP configuration. Relatively stable simultaneous operation of HCP configurations of various spacings is practical but problems exist with optimizing operating frequency to each spacing.

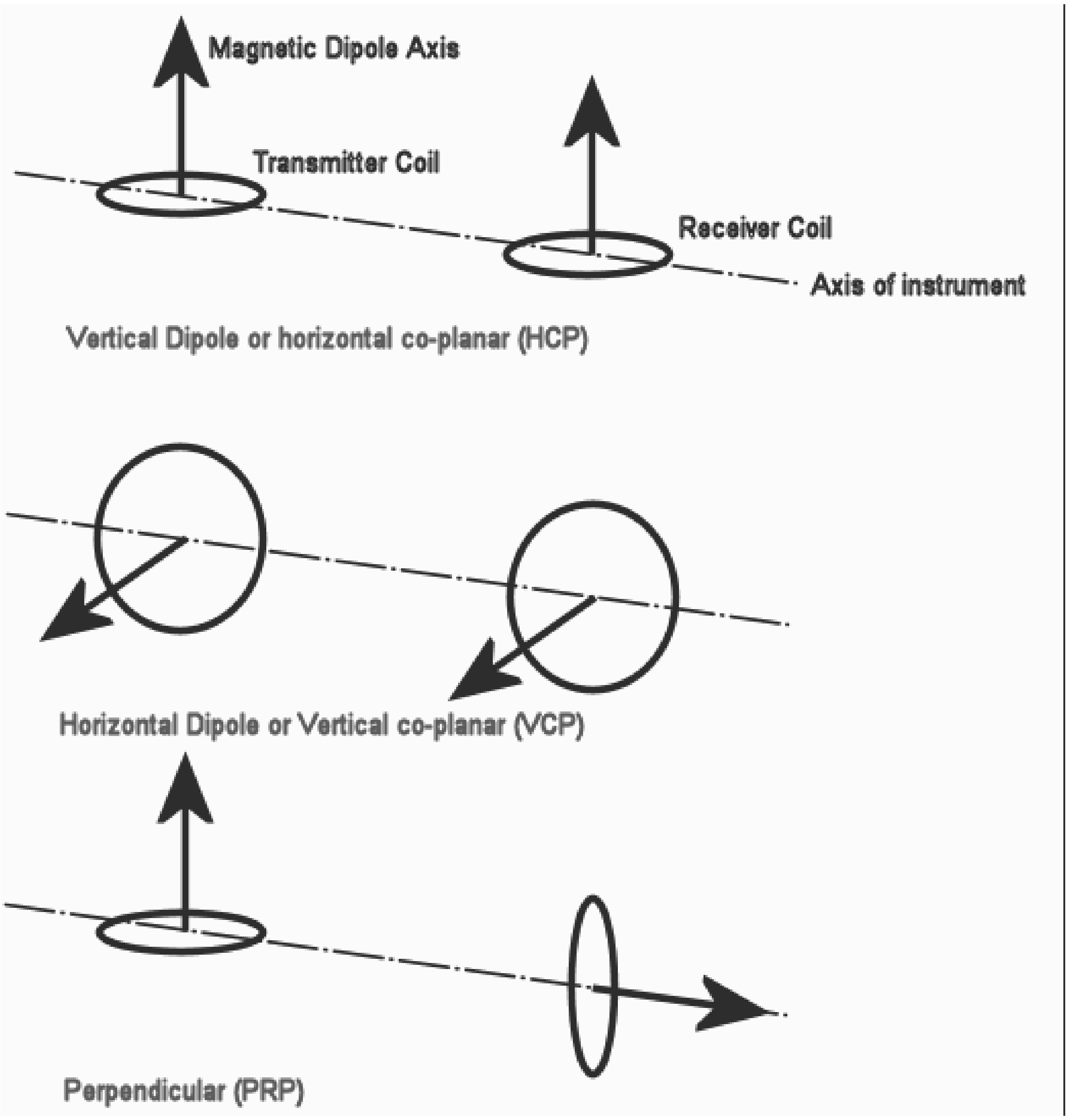
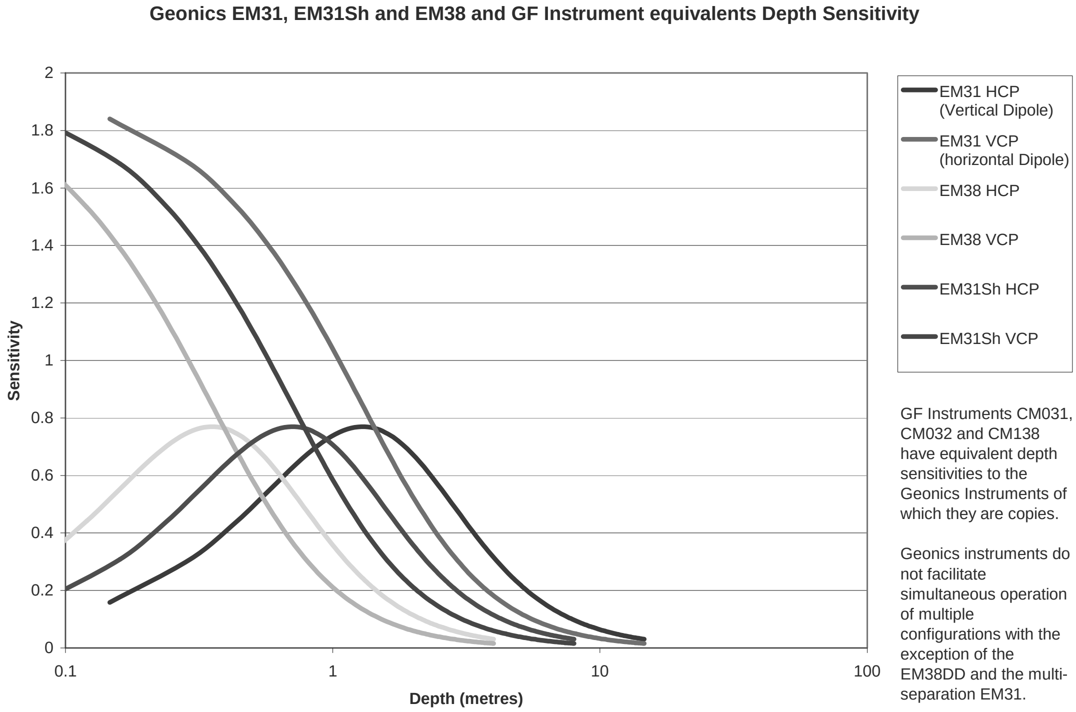


Figure 3.7 Common terminology describing coil configurations used in FDEM instruments.

Unique to this document is an attempt to plot the depth sensitivities of all known instruments on graphs of common scale. Depth sensitivities, and normalized cumulative depth sensitivities are determined, in the low induction number approximation, by the following functions of Z=depth of penetration normalized by dividing by transmitter coil to receiver coil separation:

Configuration	HCP	VCP	PRP
Depth Sensitivity	$\frac{4Z}{\left(4Z^2+1\right)^{3/2}}$	$2-\frac{4Z}{\sqrt{4Z^2+1}}$	
Cumulative Depth Sensitivity	$1-\frac{1}{\sqrt{4Z^2+1}}$	$1-\sqrt{4Z^2+1}+2Z$	$\frac{2Z}{\sqrt{4Z^2+1}}$
Multiplication factor for approximate sensitivity adjustment outside the low induction (low frequency) approximation.	$e^{-z/\delta}$ where *z* is depth in metres and δ is skin depth (depth to which *1/e* (37%) of signal penetrates). $\delta=\sqrt{\frac{2}{\omega\mu_0\sigma}}\approx\frac{500}{\sqrt{conductivity(S/m)\times frequency(Hz)}}$		

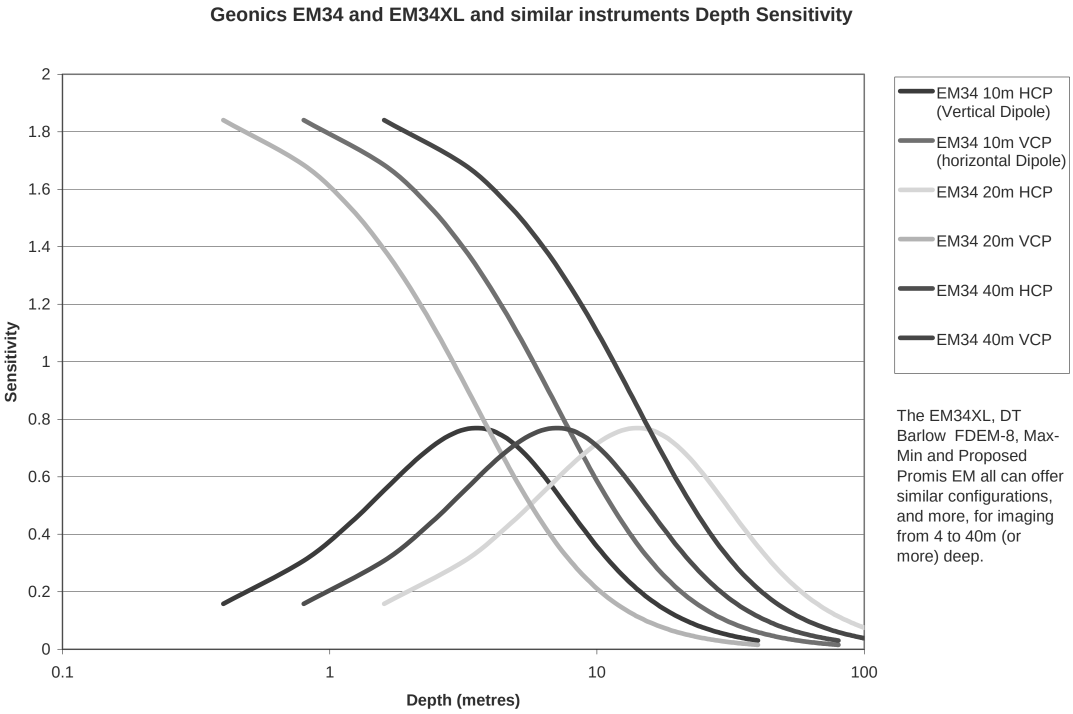
Depth sensitivities of the available configurations of the instruments reviewed are presented in the following figures (all plotted at the same scale).


Geonics EM31, EM31Sh and EM38 and GF Instrument equivalents Depth Sensitivity

GF Instruments CM031, CM032 and CM138 have equivalent depth sensitivities to the Geonics Instruments of which they are copies.

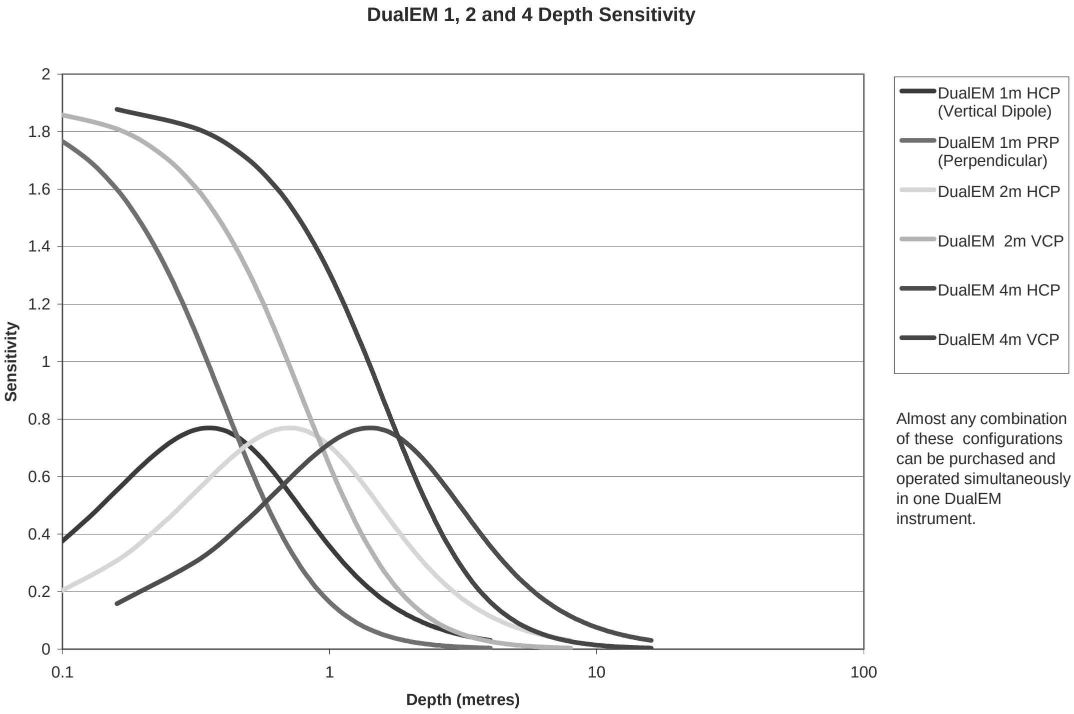
Geonics instruments do not facilitate simultaneous operation of multiple configurations with the exception of the EM38DD and the multi-separation EM31.

Figure 3.6 Depth sensitivity curves for Geonics EM31, EM31Sh and EM38 and GF Instruments equivalents.



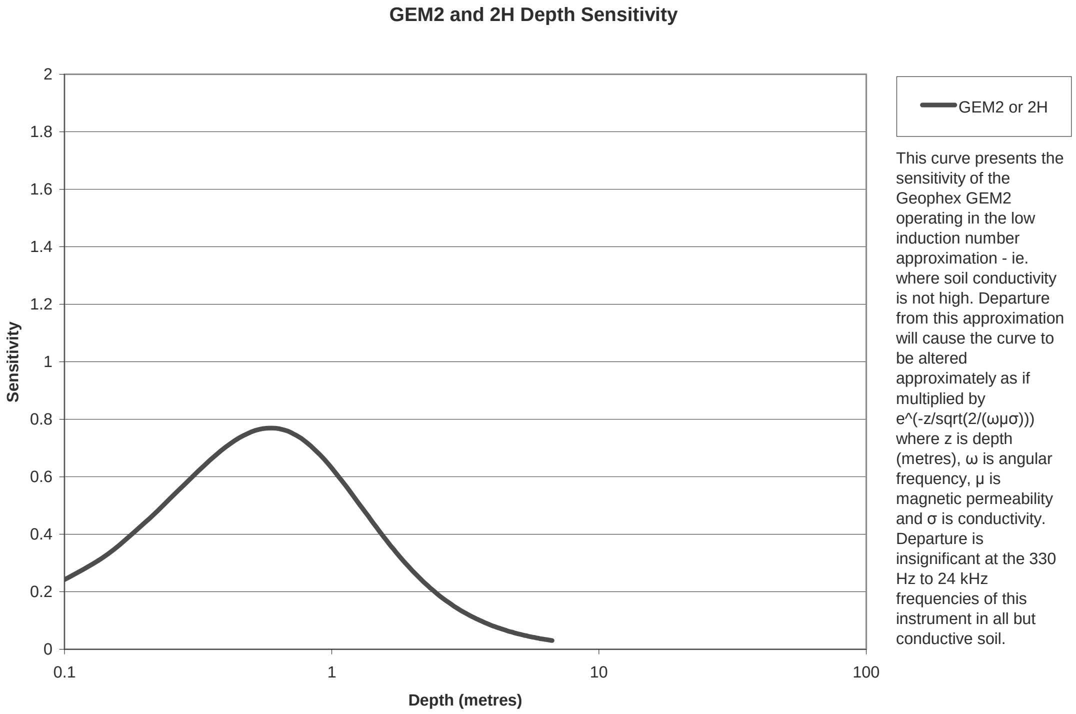
The EM34XL, DT Barlow FDEM-8, Max-Min and Proposed Promis EM all can offer similar configurations, and more, for imaging from 4 to 40m (or more) deep.

Figure 3.7 Depth Sensitivities for the Geonics EM34 and EM34XL and similar instruments



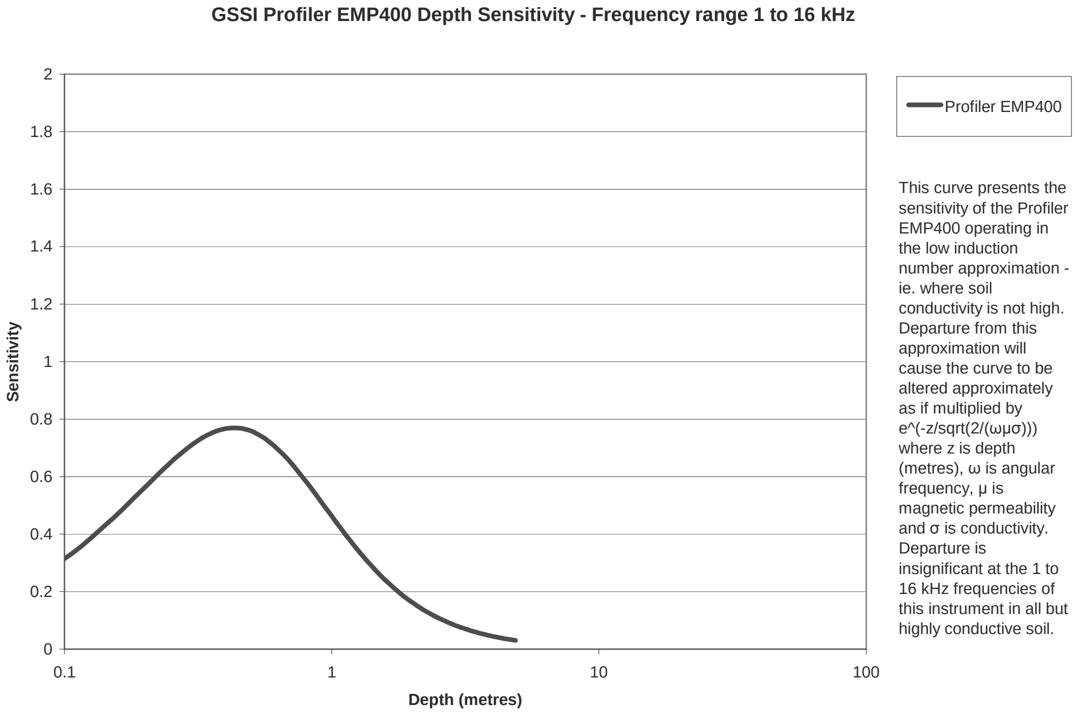
Almost any combination of these configurations can be purchased and operated simultaneously in one DualEM instrument.

Figure 3.8 Depth sensitivities of the DUALEM instruments' configurations



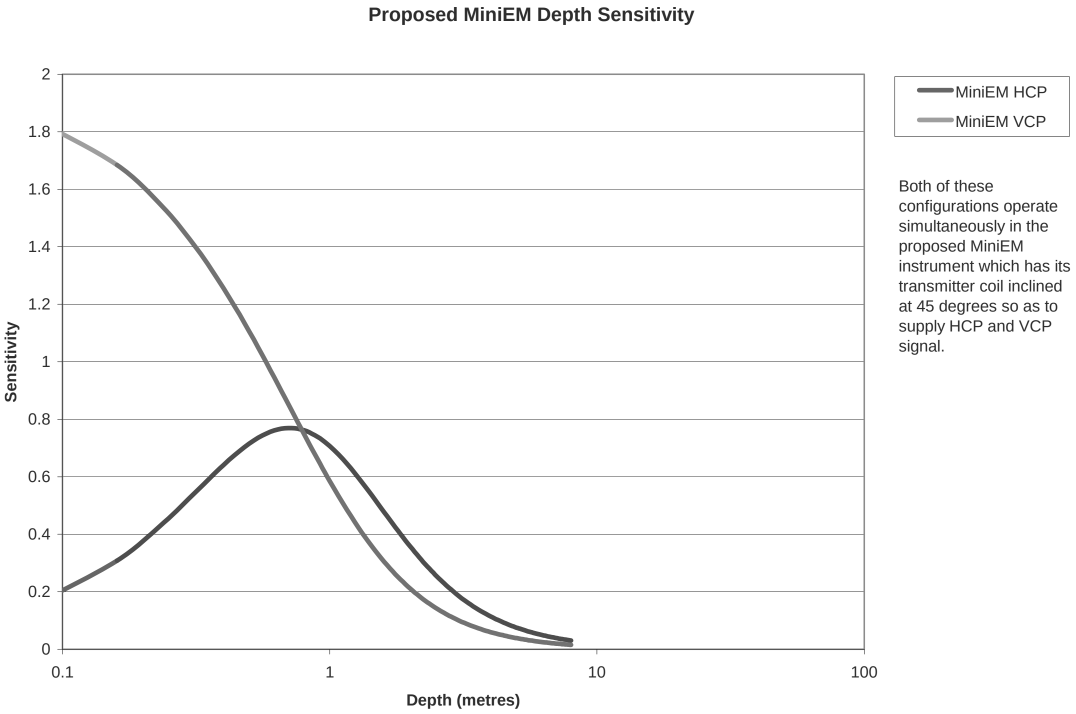
This curve presents the sensitivity of the Geophex GEM2 operating in the low induction number approximation - ie. where soil conductivity is not high. Departure from this approximation will cause the curve to be altered approximately as if multiplied by e^(-z/sqrt(2/(ωμσ))) where z is depth (metres), ω is angular frequency, μ is magnetic permeability and σ is conductivity. Departure is insignificant at the 330 Hz to 24 kHz frequencies of this instrument in all but conductive soil.

Figure 3.9 Depth sensitivities of the Geophex GEM2 and GEM2H



This curve presents the sensitivity of the Profiler EMP400 operating in the low induction number approximation - ie. where soil conductivity is not high. Departure from this approximation will cause the curve to be altered approximately as if multiplied by e^(-z/sqrt(2/(ωμσ))) where z is depth (metres), ω is angular frequency, μ is magnetic permeability and σ is conductivity. Departure is insignificant at the 1 to 16 kHz frequencies of this instrument in all but highly conductive soil.

Figure 3.10 Depth Sensitivity of the GSSI Profiler EMP400 - Frequency range 1 to 16 kHz



Both of these configurations operate simultaneously in the proposed MiniEM instrument which has its transmitter coil inclined at 45 degrees so as to supply HCP and VCP signal.

Figure 3.11 Depth Sensitivity of the proposed L&R Instruments MiniEM

FDEM instrument details

Apex Parametrics Max Min

The Max Min is an instrument that has been used in mineral exploration for many years. It is similar in design to both the Red Dog Barlow FDEM-8 and Geonics EM 34. It can operate at transmitter-receiver separations of up to 400 metres. (See information on the FDEM-8 and EM34). It is particularly effective for identifying vertical conductors such as hard rock fracture zones that hold groundwater.

DUALEM 1, 1s, 2, 2s, 4, 4s, 2/4, 2+4s and 1+2+4s

DUALEM instruments measure both in phase and quadrature signals to determine the conductivity and magnetic susceptibility of the ground, and detect buried metal. The patented DUALEM dual-geometry array simultaneously measures conductivity and susceptibility to two distinct and easily quantified depths.

DUALEM instruments are calibrated precisely and permanently at the factory using a patented technique, eliminating problematic ad hoc calibrations in the field. Precise calibration, base-level stability, high sensitivity and advanced digital signal processing give the instruments accuracy.

DUALEM instruments provide output to their RS-232 port in either NMEA0183-standard or DUALEM format. As NMEA0183 is the standard for GPS communication, a wide variety of GPS loggers and software can record DUALEM measurements and integrate them with GPS positions. This means that the signals can be fed into, and the device controlled from, Trimble (or other) DGPS systems such as are typically used in Australia for soil EC surveys.

The DUALEM-2 and DUALEM-4 are complete instruments, and the DUALEM-2/4 can be configured as either a DUALEM-2 or a DUALEM-4. The instruments incorporate monitors for applied voltage, temperature and configuration.

The DUALEM-1S, DUALEM-2S, DUALEM-1+2+4S and DUALEM-2+4S are sensors intended for use with external power and logging systems. The sensors incorporate monitors for applied voltage, temperature, pitch and roll. In common with all DUALEM instruments, the DUALEM sensors provide internal storage for time, grid position and measured quantities.

The following photos show how DUALEM devices are designed for use in production surveying.

Figure 3.12 DUALEM 2

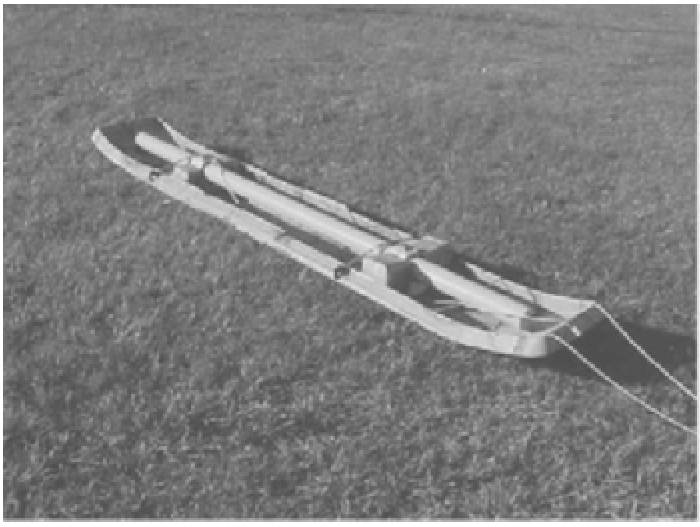


Figure 3.13 DUALEM 2s on a rudimentary sled (Photo: John Holman, USDA-ARS)

Figure 3.14 DUALEM 2 on a highly robust sled with lots of impact absorption for reducing movement related noise. (Photo: A. Schumann, University of Florida)

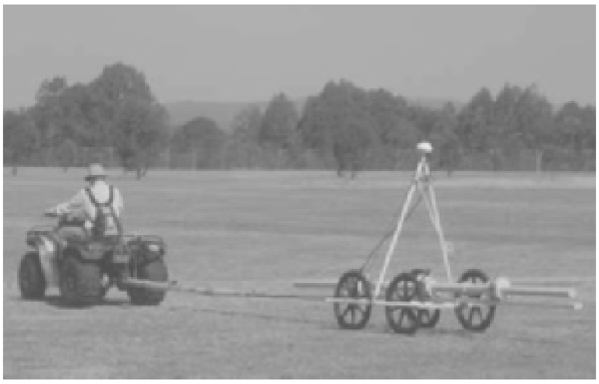


Figure 3.15 DUALEM 2/4 being operated on a non-conductive trailer. (Photo: Alpha Geoscience Pty. Limited)

The DUALEM-1+2+4s has six depth sensitivity curves for the six different sensors it contains. This makes it an ideal instrument for precise multi-depth soil imaging. The costs of the DUALEM-2+4s and DUALEM-1+4s are, however, much less and the author believes that these are the instruments that will take most of the soil mapping market in the near future. Because configurations with multiple depth sensitivity focii are sampled by these instruments, good processing (inversion) could resolve discrete layer conductivities and thicknesses. Although the raw data provide information focused at four different depths, presently a geophysicist is needed to enhance and make full use of such data as only technical multi-purpose geophysical programs are available for inversion and no software has yet specifically focused on this task.

The DUALEM-2+4S sensor has dual-geometry receivers at separations of 2- and 4-m from the transmitter, which provide four simultaneous depths of conductivity sounding, four simultaneous depths of susceptibility sounding, and detection of metal.

Users control the DUALEM-2+4S sensor through its RS-232 port and supply power through the same connector. Users typically integrate the NMEA-format measurements with GPS positions on a logger.

The several sounding-depths of the DUALEM-2+4S enable the analysis of layering in the top several metres of the earth. The DUALEM-2+4S is suitable for towing on a sled or cart, or for carrying at hip height.

Geonics EM31-Mk2, EM31-Sh

Geonics systems have been widely used in the FDEM soil mapping market for many years and are widely used in "precision agriculture" and temporal monitoring applications.

The Geonics EM31-mk2 has a focus depth of about 3 metres when used in horizontal coplanar mode. This means that 70% of signal comes from above 6 metres depth. It can also be rotated 90 degrees to operate in vertical coplanar mode with a much shallower focus depth but this cannot occur during continuous acquisition. It has been the instrument of choice for most irrigation water infiltration and salinity studies in Australia for many years, being the only instrument of its type on the market until recently. In Australia it is normally operated from a quad bike using Trimble DGPS and logging solutions along with a Trimble parallel swathing track bar, however, in Canada, the Geomar software used on an Allegro hand held computer is popular.

The EM31-Sh is a 2 metre long EM31 designed for slightly shallower exploration.

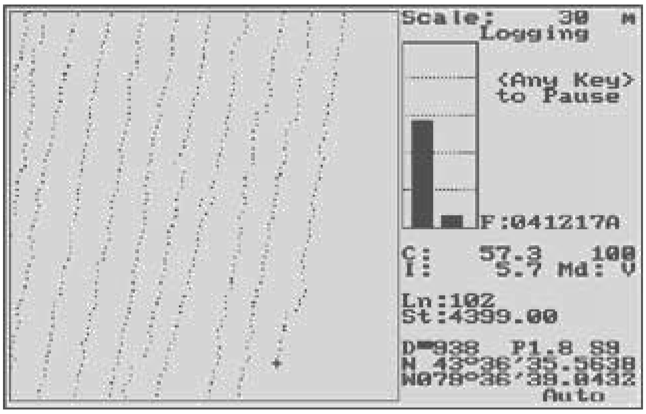
Figure 3.16 Geonics EM31 with GPS.

Geonics EM31-multi

Geonics have built a multi-spacing FDEM instrument – the EM31-multi with 1, 2 and 3.66 metre coil spacings but have not yet refined the design. The design still has legacy aspects due to being made out of barely modified EM31-Mk2 components. This instrument will hopefully become a replacement for the setup commonly seen in Australia where contractors have quad bikes rigged up with both an EM38 and EM31. It is yet to be seen if Geonics will modify the instrument for efficient trailer/sled based use rather than use carried on foot with the controller in the middle. When the controller is fixed into the middle of the instrument it is hard to rig it up for sled/trailer operation.

Geomar Software have developed the Multi31 program for logging of EM31-multi data simultaneously with GPS or DGPS data.

Figure 3.17 Allegro Pro4000 operating Geomar Multi31 (receiving GPS data and EM31 data from 3 different receiver coils).



```
Scale:     30   M
       Logging

        <Any Key>
        to Pause

       F:041217A
C:     57.3   100
I:      5.7 Md: V
Ln:102
St:4399.00
D=938   P1.8 S9
N 43°36'35.5638
W078°36'39.0432
           Auto
```

Figure 3.18 Geomar software – survey track plotting and signal level monitor for Geonics devices.

Figure 3.19 Juniper Systems Allegro handheld Windows CE computer used for new colour Geomar software currently in the process of being released. Here the Allegro is presented with the Trimble ProXH wireless connection GPS system.

Geonics EM34-3, EM34-3XL

The Geonics EM34 is a 10, 20 and 40 m separation instrument for investigating depths from 3 to 60 m. It can be used in horizontal or vertical coplanar mode so that six depths can be sampled. Unfortunately, each spacing and orientation combination must be set up one at a time at every sounding location. Towed mode operation is available by special order.

Consistent coil spacing is achieved conventionally by using the in-phase signal as a reference. This has the disadvantage that reported EC values deviate from reality in highly conductive environments which push the instrument out of the low induction number approximation. This is rarely a problem because, for each separation distance, a different frequency is used by the EM34 in order to optimize signal strength while keeping the instrument in the low induction number range for most typical soil ECs.

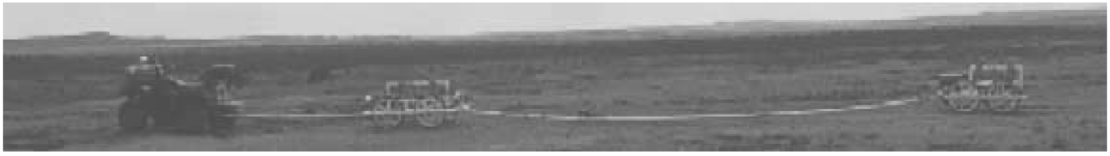


Figure 3.20 An EM34 automated and towed behind a quad bike – (courtesy of EchoTech, 2005).

Figure 3.21 Geonics EM34

Geonics EM38DD

The Geonics EM38DD has a vertical coplanar coil set separated by 1 metre and a similar set in a horizontal plane. This instrument and the DUALEM 1s are designed for topsoil and subsoil EC imaging. The two configurations of each of these instruments have focus depths of approximately 0.4 m and 1.0 m if operated at ground level, that is 70% of the signal comes from 0.75 m below the surface for the vertical coplanar or perpendicular configurations and 1.5 m below the surface for the horizontal coplanar (vertical dipole) configuration.

Figure 3.21 Geonics EM38DD

Geophex

Geophex have produced the GEM 2, pictured below. It is a 2 metre long FDEM device that operates at multiple frequencies in order to visualize multiple depths as well as resolve metallic targets. Geonics have presented theory that shows that multiple frequencies are of very limited use for vertical resolution in such an instrument (see McNeill, 1996 and Geonics, ~1997) however one can observe a vertical image created using the rigorous Interpex IX1D program and data from a GEM 2 displayed in the Interpex section below. Note that this image is highly constrained. If it was not for the constraint, a multitude of alternate imagery could fit the data with equal or lesser error.

Geophex offer a PDA with software that images GEM 2 data on the fly as you watch your track, as logged by GPS, on the screen. This can help a lot with quality control in the field.

Figure 3.22 Eric White (USGS, OGW, Branch of Geophysics), conducting a geophysical survey in Nebraska using a Geophex GEM 2 multi-frequency electromagnetic sensor.

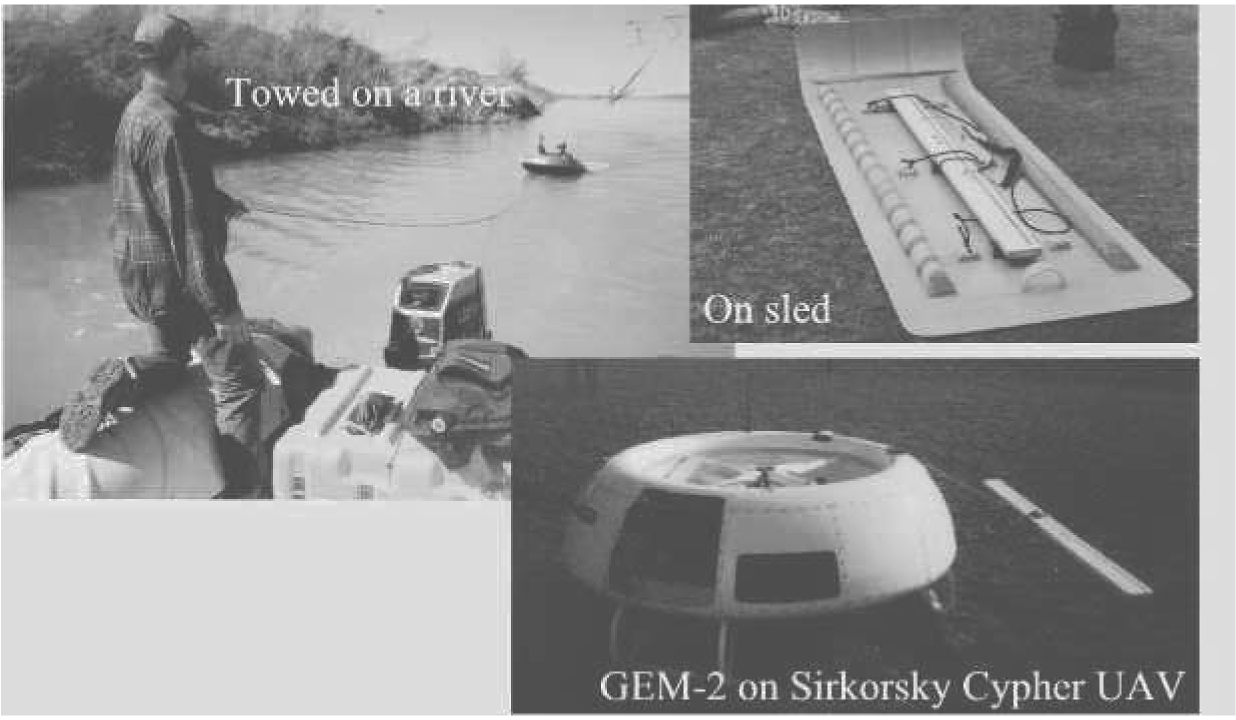


Figure 3.23 Various field implementations of the Geophex GEM 2.

GF Instruments

Instruments with very similar specifications to the Geonics EM31, EM38 and EM31s can be purchased from GF Instruments of Czechoslovakia – (see **www.gfinstruments.cz**) but at a cheaper price. It has been suggested that rigidity of these devices is less than that of Geonics devices. They use a HP calculator as a data logger. No mention of simultaneous GPS logging was found on the GF Instruments' web site.

Figure 3.24 GF Instruments CM-031

Figure 3.25 GF Instruments CM-032

Figure 3.26 GF Instruments CM-138

GSSI Profiler EMP400

Geophysical Survey Systems Incorporated have recently introduced to the market the Profiler EMP400. This is a 1.2 m long HCP FDEM device that operates from 1 to 16 kHz simultaneously measuring up to 3 frequencies. The device is designed to work with the Trimble RECON handheld computer. Comments above on the GEM 2 apply all the more to this device as it has an even smaller range of variable frequencies combined with a shorter length. This puts the frequencies further into the realm where depth sensitivity is insensitive to frequency. It is crucial that the equipment is optimized to stabilize drift. Nevertheless the device appears to be professionally made. Further information is available at www.geophysical.com .

Figure 3.27 The GSSI Profiler EMP400

Iris Instruments PROMIS-10

The Promis-10 is an instrument that is very similar to the Apex Parametrics Max Min except that it has a 3 component receiver. It has a digital controller and diagnostic display. It also is good for defining aquifers in fractured rock. Iris Instruments were not ready to market the Promis -10 when this report was written.

Figure 3.28 Iris Instruments Promis-10 wide coil spacing triple orientation receiver coil FDEM instrument

L&R Instruments - MiniEM

The MiniEM is a FDEM device that is proposed to be on the market by March 2007 (see **www.L-and-R.com**) It is a 2 m long FDEM device with a transmitter coil set at a 45 degree angle to horizontal and receiver coils in both the vertical and horizontal planes. This is a smart way of cheaply and robustly providing data at two depths by emulating both horizontal coplanar and vertical coplanar modes of operation.

Figure 3.29 L&R Instruments MiniEM

Red Dog DT Barlow FEM-8 System

The DT Barlow FEM-8 system is a very cheap South African substitute for the Geonics EM34 but has an automated reading procedure that takes about 15 seconds for all 8 frequencies scanned. Unlike the Geonics EM34, only a single pass/separation is needed to obtain multi-depth data but this is frequency sounding data. If considering this instrument, see Geonics Technical Notes TN30 and TN31 (McNeill,1996 and Geonics, ~1997) regarding frequency sounding. The large separations used with this instrument leave much of its data well out of the low induction number approximation. Also unlike the EM34, it uses a cable to determine separation so in-phase data can be collected. Software for inversion that does not require low induction number approximations such as IX1D is needed to make sense of vertical differences in this data. For plotting of a simple map, data collected at just one optimal frequency would be chosen. In areas where cheap labour is available, this instrument could be the most cost effective for imaging shallow aquifers adequately to enable borehole siting, at least in fractured rock areas.

In South Africa the instrument is used to find dykes, sills, and other features that constrain groundwater.

For more details, contact **reddog@geoafrica.co.za** or look at **www.geoafrica.co.za/reddog/barlow/emsystem.htm** .

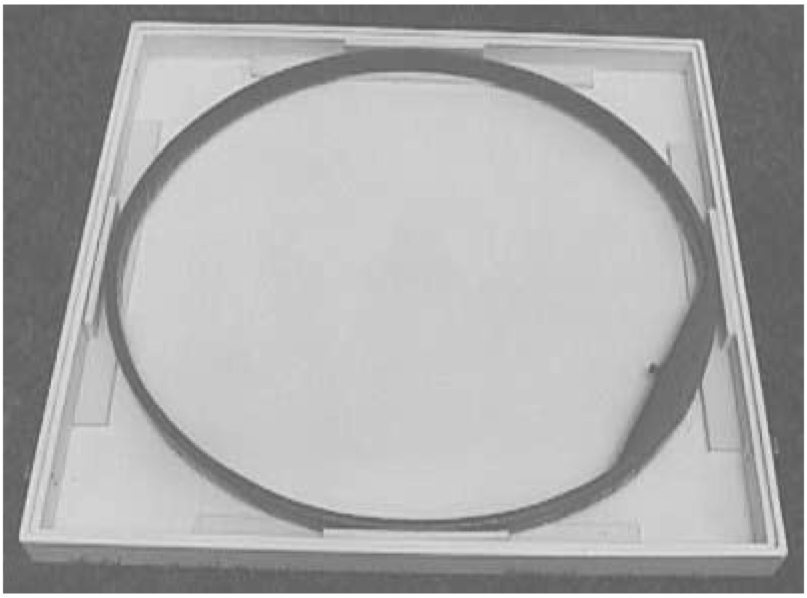


Figure 3.30 Red Dog's DT Barlow FEM-8 system coil. The system uses two coils, a transmitter and a receiver, like the Geonics EM34 but has some advantages over the EM34 including affordability.

4. GROUND TIME DOMAIN ELECTROMAGNETIC SYSTEMS

Basics

The principles of time domain electromagnetics (TDEM) are schematically represented in Figure 4.1

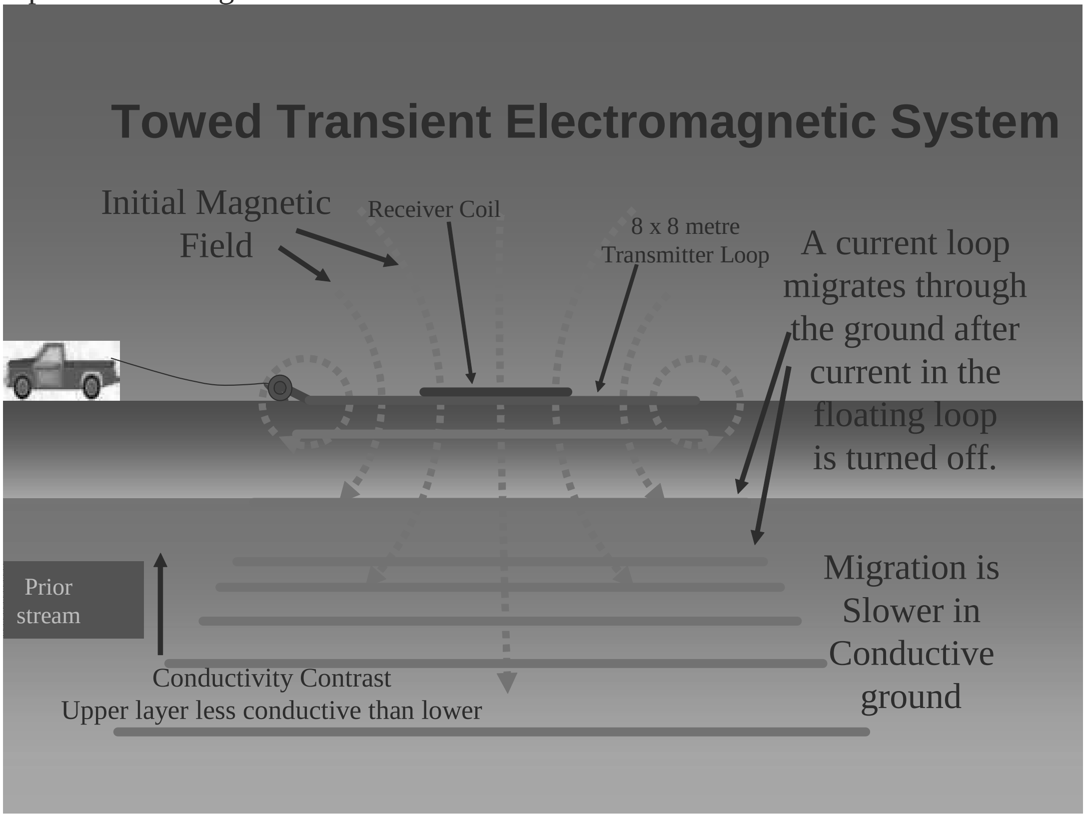
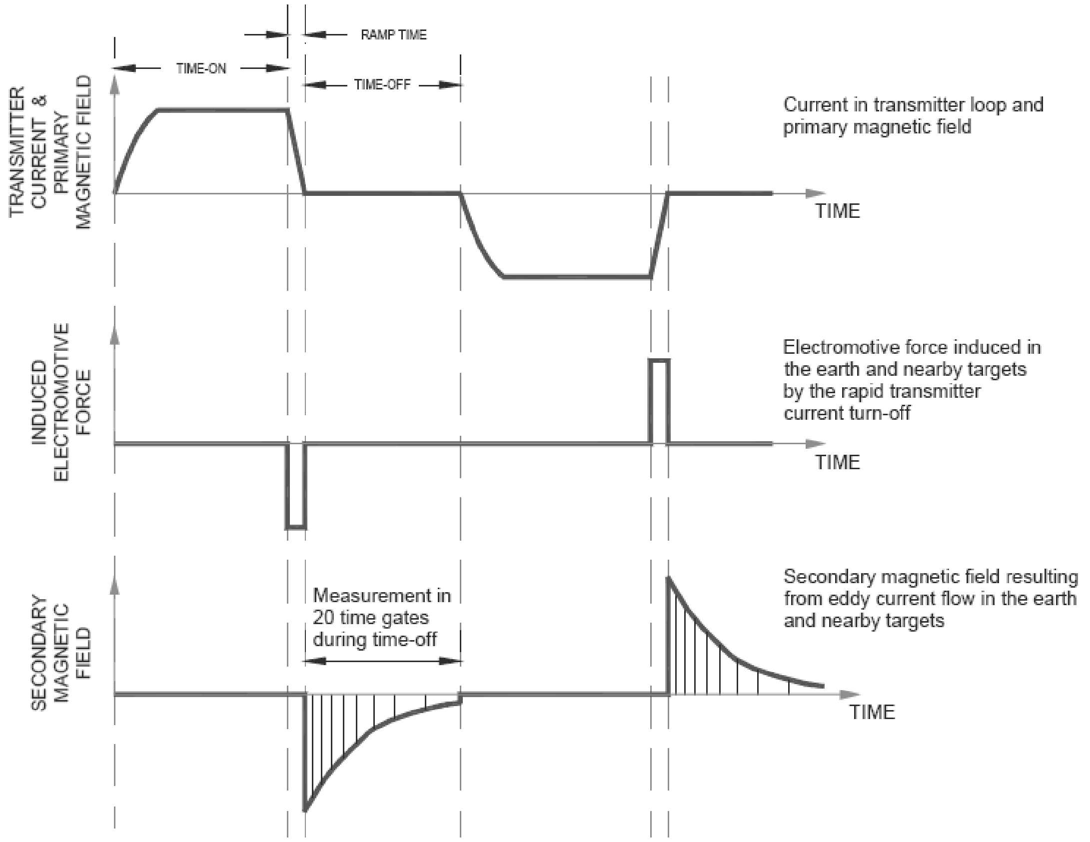


Figure 4.1 A time domain electromagnetic imaging device. A decaying magnetic field induces a 'smoke ring' of current in the ground which produces its own decaying magnetic field which is monitored at the surface.

In time domain electromagnetic surveying, also called transient electromagnetics, the basic principle is that a square loop of wire is laid out on the ground, or a towed platform, and a transmitter is used to put current into the loop. The current is pulsed as shown in the accompanying figure 4.2. During the time-off periods, ground response is measured as a secondary magnetic field. This is measured either by current induced in the same or a similar loop as used for current transmission or in an electrostatically shielded multi-turn coil. The decay curve characteristics are dependent on ground conductivity. Resistive ground has faster decays than conductive ground. The decay curves can be converted to apparent conductivity data as a function of depth or inverted (i.e. matched to appropriate synthetically generated models). Ground TEM systems share all the same technical issues, and solutions, as do airborne TEM systems with the exceptions of elevation error, stacking time limitations and, in some cases, high primary field rejection issues. Because ground systems are operated from the ground there is no elevation error, or associated aircraft movement and orientation errors. A lot of signal and footprint resolution is lost in airborne systems due to aircraft elevation (Reid et al., 2006). Ground based systems, even if towed, do not have the high flying time overheads of airborne systems. They need much less power to image to the same depth because they can be operated cheaply at slow speed, allowing the instrument to stack data for a long period of time over a short distance and because they do not have a loss of signal coupling with the ground due to altitude.



after: McNeill, 1990

Figure 4.2 Waveforms in time domain electromagnetic systems. Note that EMF and secondary magnetic field produced by on time rise are not shown. (From http://www.nga.com/Flyers_PDF/NGA_TDEM_TEQ.pdf)

TDEM Instrument details

Systems reviewed here are :

Aarhus University – PATEM[5]
Electromagnetic Imaging Technology - SMARTem
Geonics – Protem 47 and 57
Monash University – TerraTEM

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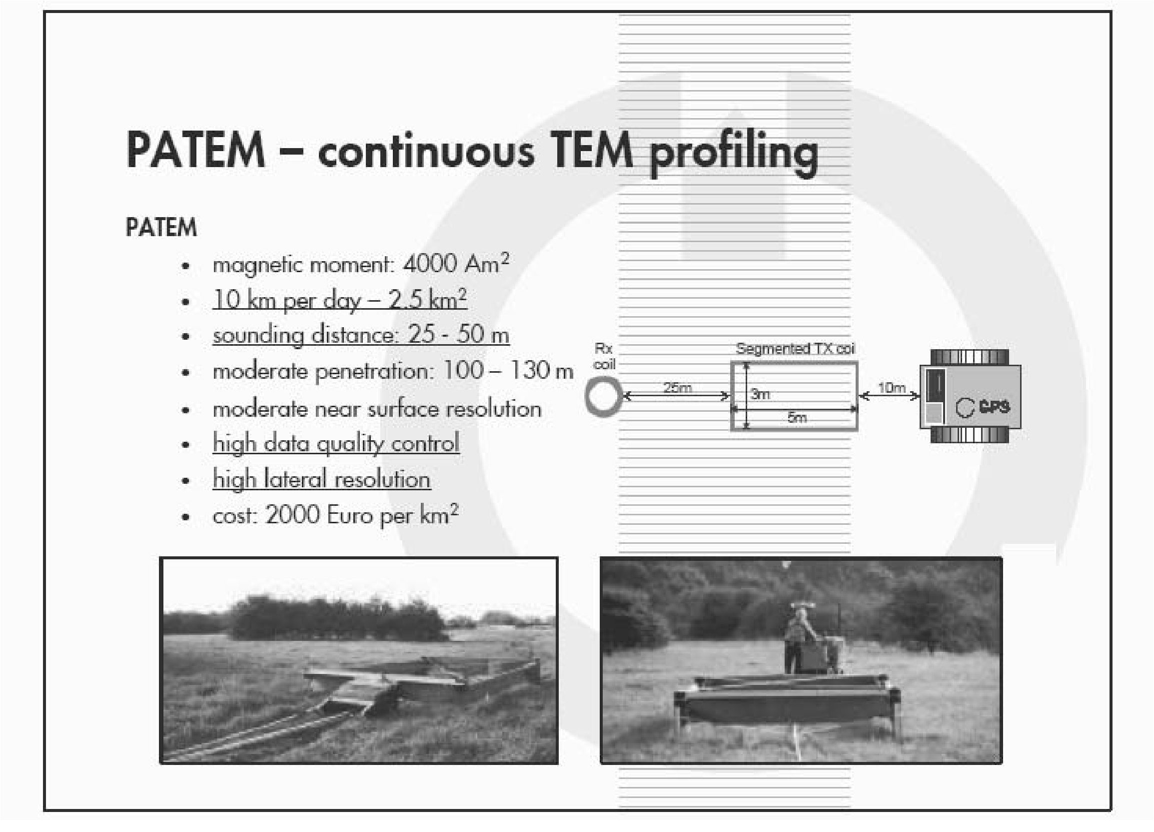
[5] Disclosure: The principle author is constructing a system similar to, but larger than, the PATEM.

Zonge – Nanotem

Aarhus University, Denmark - PATEM

Aarhus University Hydrogeophysics Group have been towing a large TDEM device across the ground in Denmark for some years and have conducted tens of thousands of soundings with the device. The device can image over 100 metres deep with multiple layer resolution. They have now moved PATEM technology into their airborne TDEM system – SkyTEM. In Denmark, numerous fences and land access issues make PATEM surveying less efficient than SkyTEM. The environment in Australia is very different and so PATEM, or similar devices, have potential here for aquifer imaging. It was found that the PATEM system, which has its receiver coil towed behind the transmitter coil, coped poorly with lateral inhomogeneities. PATEM has a low and high moment transmission that allows both shallow and deep data to be imaged.



PATEM – continuous TEM profiling

PATEM

- magnetic moment: 4000 Am^2
- 10 km per day – 2.5 km^2
- sounding distance: 25 - 50 m
- moderate penetration: 100 – 130 m
- moderate near surface resolution
- high data quality control
- high lateral resolution
- cost: 2000 Euro per km^2

Figure 4.3 PATEM continuous profiling system

Electromagnetic Imaging Technology (EMIT) - SMARTem

SMARTem developed by EMIT in Western Australia is a receiver only device. It must be used in conjunction with a separate transmitter made by another company, such as Geonics, Iris Instruments or Zonge. Geoforce of Western Australia set up a very small towed loop system with this device and called it TinyTEM.

Geonics - PROTEM 47 and 57

The Geonics Protem 47 system is designed with fast response like the Zonge NanoTEM (see below) so that it can be used to map shallow aquifers. Geonics have only supported continuous acquisition by special order, rather than routinely, so PROTEM units currently in Australia are not currently equipped for towed TDEM surveying. They are, however, ideal for moving loop surveys over deeper aquifers where loops must be laid out manually. In Denmark, 45,000 such 40 x 40 m loops were laid out in order to image shallow aquifers before the SkyTEM system was put into production there.

Protem has a very clear real time display of data that saves a great deal of time in field data acquisition and facilitates thorough quality control. Comparative tests of noise levels of various instruments have shown that the Protem can collect low noise data. Protem 57 is a more powerful version of Protem 47 and can image to greater depth.

Figure 4.4 Geonics Protem

Monash University - TerraTEM

TerraTEM is a very new instrument produced from Monash University and marketed by Alpha Geoscience. It has capabilities very similar to the Zonge NanoTEM (see below) but with slightly slower response time (500 kHz compared to 800 kHz). It is a suitable instrument for towed TEM surveying and has a small transmitter in the box with the receiver/controller. It has a high resolution colour display for real time display. For shallow and deep imaging it may be used with a high power fast turn off VESCOR transmitter but for mid-depth transmitting, as is required for investigating 5 to 80 m deep aquifers, the incorporated transmitter is sufficient.

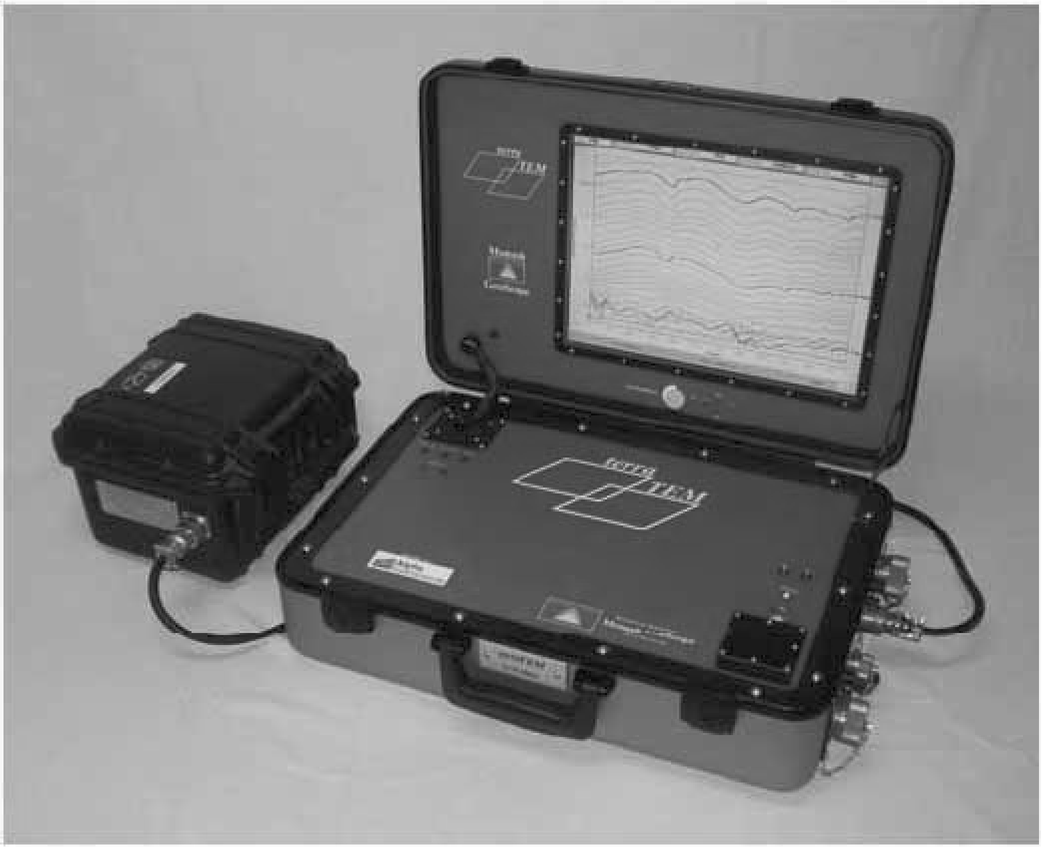


Figure 4.5 The TerraTEM system incorporating a TEM transmitter, receiver and controller with a colour touchscreen (battery on left).

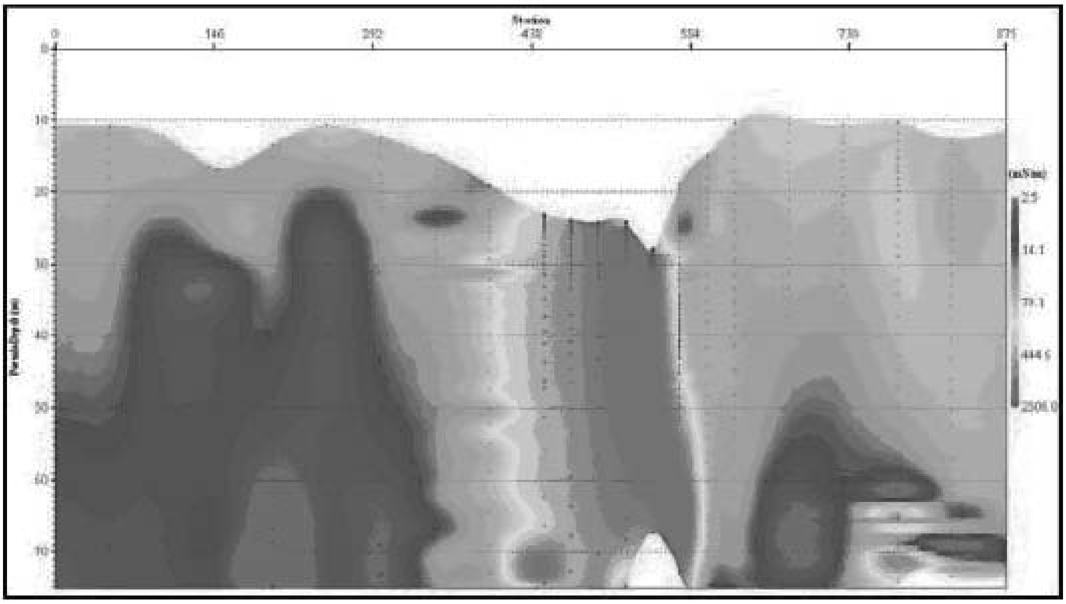


Figure 4.6 A vertical section of data collected, using TerraTEM, over a groundwater hosting fault.

Zonge - NanoTEM

Zonge have produced the NanoTEM system for shallow TEM exploration – typically 5 to 100 m depth. Barrett et al. (2003) and Zonge used it with a floating loop towed behind a boat to image salinity beneath the Murray River in South Australia. Allen & Merrick (2005b) compared this data with waterborne geoelectric data in the IAH conference proceedings in December 2005. The NanoTEM system is robust and includes channels as early as 1.2 microseconds after turn-off so that it can resolve shallow features.

The author has successfully used the NanoTEM with a towed 8 x 8 m loop to find and resolve depths of prior streams in the Murrumbidgee Irrigation Area. 25 kilometres could be surveyed in one day. CRC LEME have commenced similar experiments towing a 3 x 3 m loop over ground to investigate the top 10 metres.

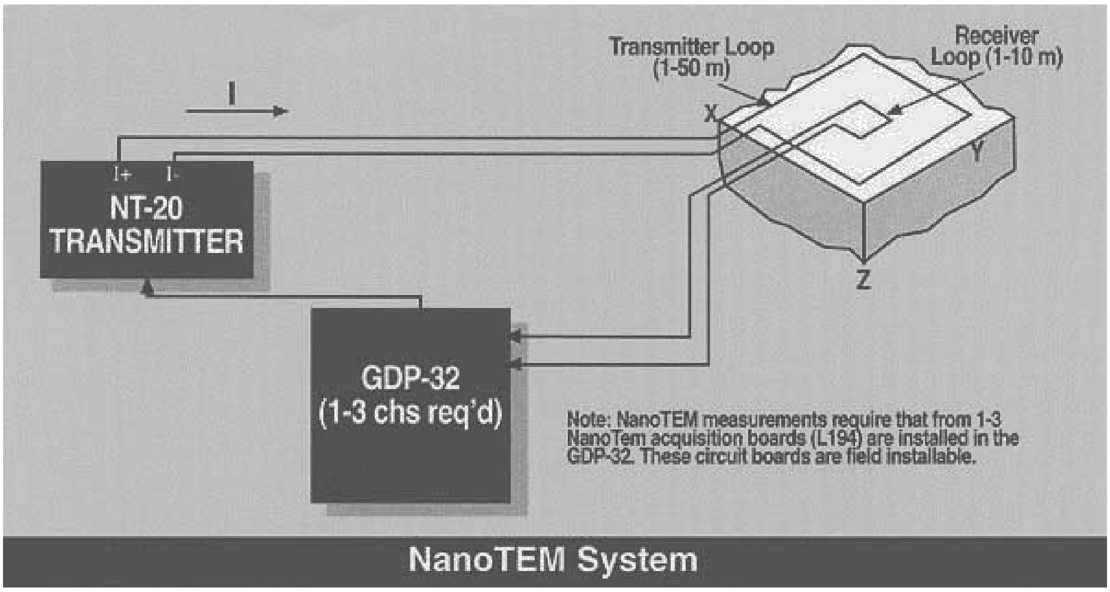


Figure 4.7 A schematic of the NanoTEM system in operation.

Figure 4.8 The Zonge GDP32-2 with an embedded NanoTEM Transmitter.

5. AIRBORNE FREQUENCY DOMAIN ELECTROMAGNETIC SYSTEMS

Basics

Basic principles of airborne FDEM devices are the same as those presented in Chapter 3 for FDEM ground conductivity meters.

Airborne frequency domain systems operate with continuous transmitter waveforms, typically sine waves, at a number of frequencies (up to six in present systems) operating simultaneously. Receiver coils are used to pick up the primary fields from the transmitter coils and the secondary fields from currents induced in the ground. Most coils are oriented horizontally but some systems also use vertical coils. The horizontal coils are most useful for horizontal conductors / layers, whilst the vertical coils are better suited to vertical conductors. Ground penetration is greater with the lower frequencies whilst the higher frequencies provide more shallow information.

A useful concept is skin depth which is approximately equal to depth of penetration.

Skin depth (in metres) = 503 x square root of (resistivity in ohm.metres divided by frequency in hertz)

(from Parasnis, 1997).

Airborne EM systems are useful for geological mapping and definition of large aquifers and aquitards.

With suitable software, data can be converted to conductivity sections and images. Definition of the top few metres is often unreliable.

Airborne FDEM instrument details

The following helicopter frequency domain (FDEM) systems have been reviewed:

- Aeroquest Impulse
- Fugro Resolve
- Geophex GEM 2A Broadband
- Geotech Hummingbird

Aeroquest - Impulse system

Aeroquest have designed airborne FDEM and TDEM systems and have optimized their designs for the mineral exploration and un-exploded ordinance detection market. Their Impulse system is displayed below in Figure 5.1.

Figure 5.1 Impulse helicopter-borne frequency domain electromagnetic system.

Fugro - Resolve

Resolve (previously known as Dighem Resolve) has been used in Australia, Europe and Namibia for investigation of aquifers and aquitards. In South Australia it was used successfully to map the thickness of the Blanchetown Clay, an aquitard, through proper calibration and constrained modelling which used borehole conductivity and lithology information (Brodie et al., 2004). In Namibia, it resolved locations of paleochannels suitable for extraction of fresh water. In Germany it identified salty aquifers adjacent to aquifers filled with fresh water from melted snow.

The Resolve system is a frequency domain electromagnetic instrument with separate transmitter coils for separate frequencies. The Resolve system has five coplanar horizontal coils operating at frequencies ranging from approximately 380 Hz to 106,000 Hz and one set of vertical coaxial coils operating usually at about 3,300 Hz. It is primarily designed for layered earth geology resolution but has also been successfully used in diamond exploration. The vertical coaxial coils are helpful in detecting vertical structures. It is claimed to be capable of imaging up to depths of 150 m in some resistive terrains, eg Canadian Shield. It must be lifted with a moderately large payload helicopter (eg. Eurocopter AS350B Squirrel) and components housed in and on the helicopter must be certified in each helicopter they are installed in. The instrument has a 30 – 50 m footprint.

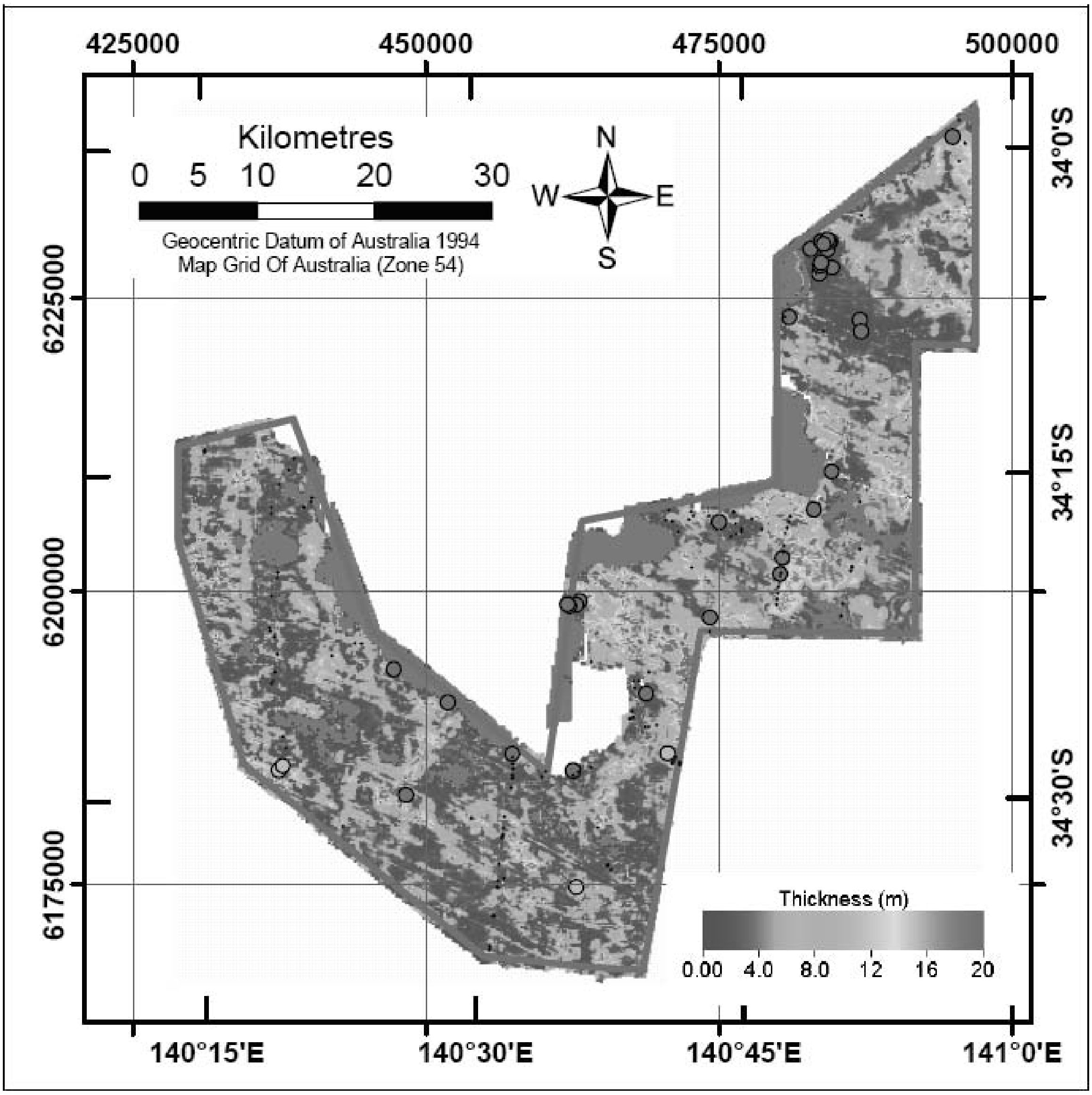


Figure 5.2 Thickness of the Blanchetown Clay (Berri-Loxton – South Australia) as inferred from Resolve data and Geonics EM39 borehole logs (from Brodie et al., 2004)

Figure 5.3 A Fugro Resolve 'bird'.

Geophex - GEM 2A Broadband

Geophex have produced a multi-frequency broadband helicopter-borne FDEM device in which all frequencies are transmitted from one coil and received by two others, thus simplifying design and drift correction but compromising electronics optimization. It uses up to 7 frequencies from approximately 270 to 47,970 Hz. (but during surveying typically only 4 or 5 frequencies are used - due to the design of the system for every extra frequency used the moment is decreased) Transmitter receiver separation is 5.1 metres. The GEM 2A (Figure 5.4) has one significant advantage over Resolve - lower weight and therefore usually lower operating costs. However its disadvantage is the narrower bandwidth - thus it is not as good at resolving shallow depths.

Figure 5.4 The GEM 2A broadband FDEM device weighing only 110 kg.

Geotech Airborne - Hummingbird

Geotech Airborne have produced two airborne instruments – the time domain VTEM device and a frequency domain system called Hummingbird (see Figure 5.5). Neither device has been designed specifically for groundwater exploration however they have sometimes been used for these applications. In Australia, Fugro operate the Hummingbird and Resolve systems. Resolve is generally preferred for near-surface salinity-groundwater investigations. The bandwidth of the system is limited for near surface mapping. The same is true for the Geophex GEM - 2A system.

Figure 5.5 Hummingbird

Specifications (from the Geotech website):

Frequency Range:	880 Hz, 980 Hz, 6600 Hz 7000 Hz, 35 kHz
Coil Orientation:	Horizontal coplanar and vertical coaxial coil sets
Output:	Inphase and quadrature samples (ppm)
Transmitting Power:	Up to 250 NIA (loop turns x current x loop area)
Sampling Rate:	40 Hz
Noise Level:	2.0 ppm or less
Time Constant:	Adjustable under software control
Filters:	50/60 Hz power line and sferic rejection 4th order digital, 15 Hz 2nd order analog and 5 Hz Low Pass 6th order digital
Console Computer:	Lightweight industrial Intel Pentium CPU
Display:	Detachable sunlight visible TFT 10.4 inch colour LCD
Data Acquisition:	540 MB removable PCMCIA Hard Disk
Power Requirement:	22-28 VDC, maximum 30 Amps
Operating Temperature:	-40 C to + 45 C
Magnetometer:	Geometric Cesium Vapour
Navigation:	GPS GEONAV with differential capabilities

6. AIRBORNE TIME DOMAIN ELECTROMAGNETIC SYSTEMS

Basics

The basics of airborne TDEM systems are the same as those presented in Chapter 4 for ground TDEM systems.

In time domain electromagnetic surveying a wire loop is either configured between nose, tail and wingtips of a fixed wing aircraft or suspended below a helicopter. A transmitter is used to put current into the loop. The current is pulsed as shown in figure 4.2. During the time-off periods ground response is measured as a decay of secondary magnetic field. This is measured in a receiver coil. The decay curve characteristics are dependent on ground conductivity. Resistive ground has faster decays than conductive ground. The decay curves can be converted to apparent conductivity data as a function of depth. A variety of different transmitter waveforms are used. They are not necessarily square as shown in figure 4.2

The relative merits of airborne systems depend on numerous technical issues all of which must be effectively dealt with. Most performance differences relate to methods of reliably detecting the very small ground response without undue influence from the huge primary field generated by the transmitter. FDEM devices measure the secondary response as a fraction of the primary response and rely on accurate frequency control, extremely sensitive calibration and extremely rigid instrument geometry to detect the small secondary signal in the presence of the primary field. TDEM instruments on the other hand attempt to measure secondary ground response with the primary field turned off. In practice, primary field is never completely turned off, particularly on fixed wing systems where eddy currents continue to flow through the aircraft well after current in the transmitter loop is turned off. Fixed wing systems minimize the problem by placing the receiver in a bird a long way beneath the aircraft but this results in geometric instability and reduced coupling between the transmitter loop and the ground due to the necessity to fly high enough for the bird to clear the ground. Helicopter-suspended TDEM systems generally use methods of null coupling the receiver loop with the transmitter loop to minimize the amount of primary field detected. Stable null-coupling requires geometric stability in key parts of the suspended structures. In contrast to FDEM devices and fixed wing TDEM devices, such null-coupled systems need only remove a tiny portion of primary field by calibration procedures and so are often referred to as ‘absolutely calibrated’.

A second technical issue that must be dealt with is the ability to turn off the primary field very cleanly and quickly. A quick turn-off permits resolution of shallow EC variations in the ground. Such variations must be stripped out of data to clearly resolve deeper variation. A good airborne TDEM system is capable of clearly detecting signal from a large range of times after turn-off with good linearity and primary field removal.

Fixed wing systems

Fixed wing time domain systems known to the author are Geotem, Megatem and Tempest. All of these are flown by Fugro Airborne Surveys.

The Tempest system has been used for many extensive salinity and groundwater investigations, particularly in Australia, but also in Africa and South America. Through proper calibration and validation with ground measurements the Tempest system has been shown to map near surface conductivity variations (0 to 5 metres), correlating well with ground EM systems such as Geonics EM31, as well as mapping down to 150 metres. It should be noted, however, that there is a big difference between detecting near surface variations and resolving them from deeper variations. The advantage of the fixed-wing systems is speed of operation, despite being twin or four engine aircraft and requiring more operating personnel than helicopter systems, they may be more cost effective than helicopter-borne systems (per line kilometre). The Geotem is designed similarly to Tempest, but uses a different waveform designed for deeper exploration, and thus near surface resolution is reduced, The Megatem system is larger and requires a 4 engine aircraft, but is claimed to image down to 500 metres, and is suitable for deep aquifer investigations.

There are numerous Australian case studies that were conducted using ‘Saltmap’ a system designed by World Geoscience Corporation. This system pre-dated the development of the systems described here.

TEMPEST – Fugro Airborne Surveys

Fugro Airborne Surveys offer a range of time domain electromagnetic systems on fixed wing platforms. Of most interest to groundwater investigators is the TEMPEST system (Figure 6.1). Some specifications are given below.

Figure 6.1 Fugro TEMPEST fixed wing airborne time domain electromagnetic system.

Base frequency	25 Hz
Transmitter area	186 m^2
Transmitter turns	1
Waveform	Square
Duty cycle	50%
Transmitter pulse width	10 ms

Transmitter off-time	10 ms
Peak current	300 A
Peak moment	55,800 Am^2
Average moment	27,900 Am^2
Sample rate	75 kHz
Sample interval	13 microseconds
Samples per half-cycle	1500
System bandwidth	25 Hz to 37.5 kHz
Flying Height	120 m (subject to safety considerations)
EM sensor	Towed bird with 3 component dB/dt coils
Tx-Rx horizontal separation	122 m (nominal, actual value determined)
Tx-Rx vertical separation	37 m (nominal, actual value determined)
Stacked data output interval	200 ms (~12 m)
Number of output windows	15
Window centre times	15 windows from 13 microseconds to 16.2 milliseconds
Magnetometer	Stinger-mounted cesium vapour
Compensation	Fully digital
Magnetometer output interval	200 ms (~12 m)
Magnetometer Resolution	0.001 nT
Typical noise level	0.1 nT
GPS Cycle Rate	1 second

Helicopter systems

The following helicopter time domain EM systems have been reviewed:

Aarhus University, Denmark - SkyTEM
Aeroquest - Aerotem
GeoTech - VTEM
GPX - Hoistem

SkyTEM -Aarhus University, Denmark

SkyTEM (Figures 6.2 and 6.3) is an airborne EM system designed specifically for imaging aquifers. It has a combination of technological advances not present in other airborne systems. This combination gives it the ability to resolve shallow aquifers just as well as ground based TDEM systems, such as the PROTEM 47, while also resolving deep aquifers – sometimes as deep as 250 m. It can transmit alternately through low and high moment loops so as to detect both deep and shallow ground features. Its X and Z component receiver coils are situated in a null-coupling arrangement and the transmitter loop is rigid, resulting in good primary field rejection and very low noise levels. The X component data improves resolution of upper layers if correctly processed. Patented methods of keeping primary field turnoff clean and rapid, even when high moments are being transmitted, have resulted in very good shallow imaging characteristics. Kevlar and timber 3D truss construction have resulted in weight of 300-350 kg - low enough for the equipment to be operated beneath a Eurocopter EC120 Colibri (sling load limit of 700 kg) or Bell Jet Ranger or, in hot climates, a Bell Long Ranger helicopter. An operator is not required in the helicopter thereby saving weight and increasing time available for production. Data are continuously transmitted to a follow car present in the survey area as well as the field office so field planning can be conducted on the fly.

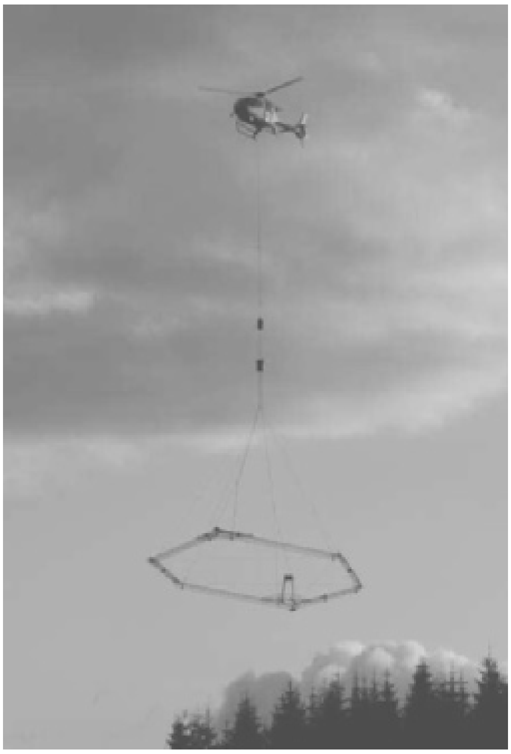


Figure 6.2 SkyTEM rigid helicopter-borne transient electromagnetic system with null coupled receiver coil.

The Aarhus Hydrogeophysics Group have an extensive interactive processing system developed for processing SkyTEM data. This system allows trained operators to selectively remove interference from fences and transmission lines from datasets so that they only reflect aquifer properties (Figure 6.4). Processed SkyTEM data then appears as shown in Figure 6.5.

Technical specifications: SkyTEM has dual moment transmission which means that it can transmit with a 100,000 amp x metres squared moment (higher if a larger generator is used) with a 34 microsecond turnoff and then transmit a low moment signal with a 3 microsecond turnoff. Survey speeds of up to 100 km /hour have been achieved. Speed is determined by helicopter power and desired flying height, which both affect resolution. SkyTEM has multiple altimeters and tilt meters on it. Data are processed to remove altitude effects as well as tilt effects. Although helicopter power can be used to operate SkyTEM, it is best to supply power to it using a sling loaded generator. A thorough, but outdated, appraisal of SkyTEM features is given in Sørensen and Auken (2004) and more up to date details are available from www.Skytem.com .

Figure 6.3 SkyTEM being launched.

Figure 6.4 SkyTEM interactive processing (simultaneous map, decay and profile display).

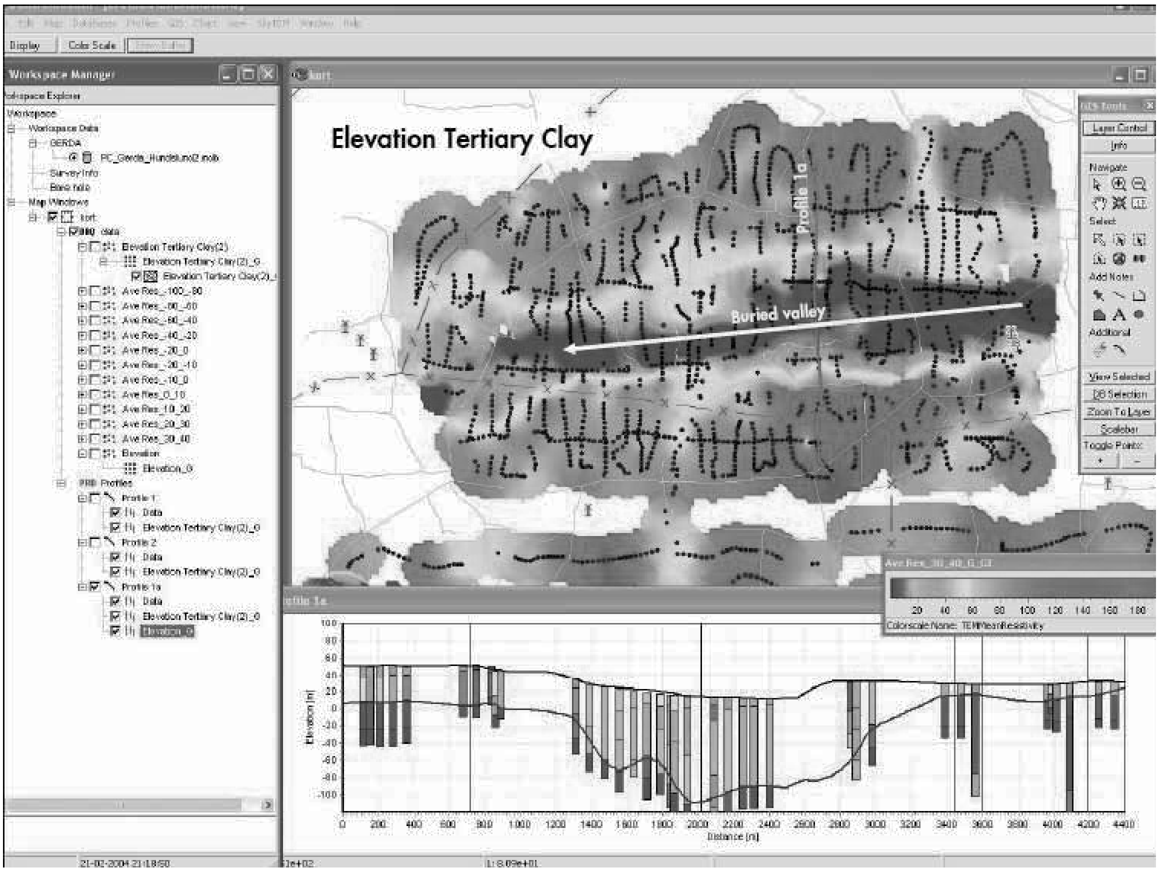


Figure 6.5 **An example of processed SkyTEM data presented in the ‘Workbench’ package.**

SkyTEM Specifications

Transmitter
Loop size: 283 m^2, 1 or 4 turns, vertical axis
Wave form: square pulse
Variable repetition frequency of 20-500 Hz
Low moment: 1 turn with 35 A (9905 Am^2) and a turn off-time of 4 µsec
High moment: 4 turns with 96 A (108,672 Am^2) and a turn-off time of 35 µsec

Receiver
Digital controlled analog gates
Gate centre times from 10 µsec to 10 msec – 10 gates per decade
Each single transient decay signal is stored
Both the vertical Z-component as well as the horizontal X-component are measured.

Online
Selected data are online transmitted to a laptop in the follow car as well as the mobile office.

The data can also be transmitted (GPRS) to a server connected to the internet. This makes it possible to follow the survey online from anywhere in the world.

Aeroquest - Aerotem

Aeroquest have designed airborne FDEM and TDEM systems but have optimized their designs for the mineral exploration and un-exploded ordinance detection market. Their Aerotem system is displayed in Figure 6.6. The system is fully rigid and this improves the effectiveness of the bucking coil, which is used to minimize primary field at the receiver coil.

Figure 6.6 Aerotem helicopter-borne rigid transient electromagnetic system.

Geotech - VTEM

Geotech Airborne has produced a time domain VTEM system in which a 30 m wide loop is suspended from a helicopter (see Figure 6.7).

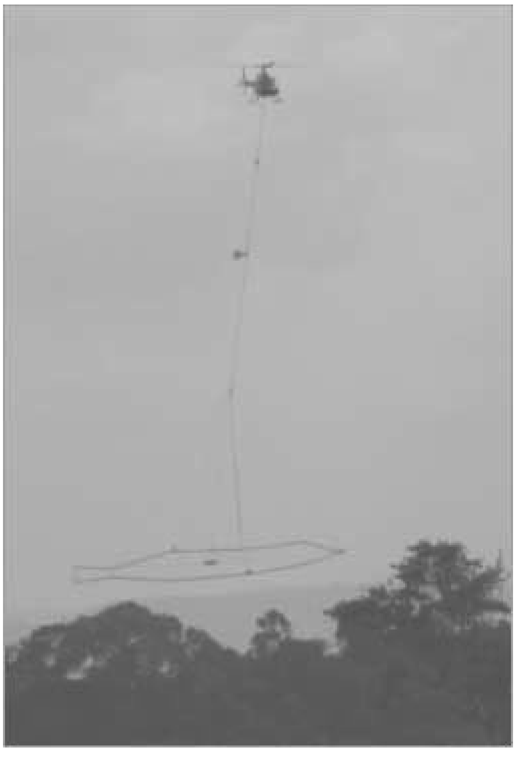


Figure 6.7 Geotech VTEM system

VTEM specifications (from their web site) are as follows – note that turn off time is not specified - this is critical for shallow aquifer definition and that NIA (number of turns x current x transmitter loop area) is assumed by the author to be in units of amps x metres^2: N is assumed to be equal to 1. VTEM uses a bucking coil like Aeroquest.

VTEM specifications

Transmitter:	
Transmitter coil	Vertical axis
Pulse:	Trapezoid
Pulse width	1 – 10 msec (selectable)
Base frequency	25 – 200 Hz (selectable)
Peak dipole moment	up to 500,000 NIA
Max Loop area	500 square metres
Max current	250 amps
Receiver:	
RX coils	Single Vertical axis
Sample rate	up to 200 kHz (selectable)
Interval recorded;	Total signal or up to 800 channels
Band width	up to 20 kHz
Spherical noise rejection	Digital, 3 levels
Industrial noise rejection	Digital, 50/60 Hz
Data recording	PCMCIA Flash Card
EM System	Noise at 30 Hz: ± 0.01 pico volts per amp metre squared ± 1.3 nanoteslas
Mechanical:	
Maximum airspeed	120 km per hour
Flying height	30 metres AGL
Temperature	- 40 °C to + 45 °C
Power requirement;	50 amps at 28 volts DC
Shipping length	2.5 metres
Weight	350 kg
Installation/Assembly time	4 hours

GPX Hoistem

GPX in Western Australia, have developed the lightweight high moment Hoistem system (Figure 6.8). It has some similarities in design to the Aeroquest VTEM system.

Figure 6.8 GPX Hoistem

Specifications of Hoistem Mk 2

Geometry
Helicopter to transmitter: 30 m
Receiver: 3 m below the centre of the plane of the transmitter loop
Transmitter terrain clearance: 30 metres

Transmitter

Waveform –	Square Wave
Pulse on Time -	5 millisecs
Pulse off Time -	15 millisecs
Pulse Current -	320 amps
Switch on Ramp -	1 millisec
Switch off Ramp -	40 microsecs
Tx Loop Area -	340 square metres
Tx NIA –	108,800
Tx Frequency-	25 Hz

Receiver

A-D Circuitry -	20 bit
Sample Time -	0 - 14 millisecs
Sampling -	124 linear channels
Sample Time-	0-14 milliseconds after switch-off

Receiver Coil

Effective NA -	3382 square metres
Bandwidth –	45,000 Hz

7. GEOELECTRIC SYSTEMS (DC RESISTIVITY AND INDUCED POLARIZATION)

Basics

Geoelectric methods use electrical current transmitted into the ground (or water) via two or more electrodes. This means that they are confined to applications where good ground or water contact can be made. Voltage differences are measured between multiple electrodes with various spacings between the electrodes.

Electrical conductivity is measured but is generally referred to through its inverse – resistivity. Apparent resistivity (ρ) values are calculated from the equation :

ρ = K x volts/amps where K is a geometric factor calculated for the various transmitter and current electrode spacings.

Geoelectric imaging is usually conducted with low frequency partial duty cycle square waves. The resistivity (or EC) data may be displayed as pseudo–sections which show the approximate variation of apparent resistivity (or EC) as a function of depth. Pseudo-sections can be inverted (see glossary) to create resistivity-depth sections.

For further detail on geoelectric surveying see Telford et al. (1990), Milsom (2003) or Reynolds (1997). The technique is schematically represented in Figure 7.1.

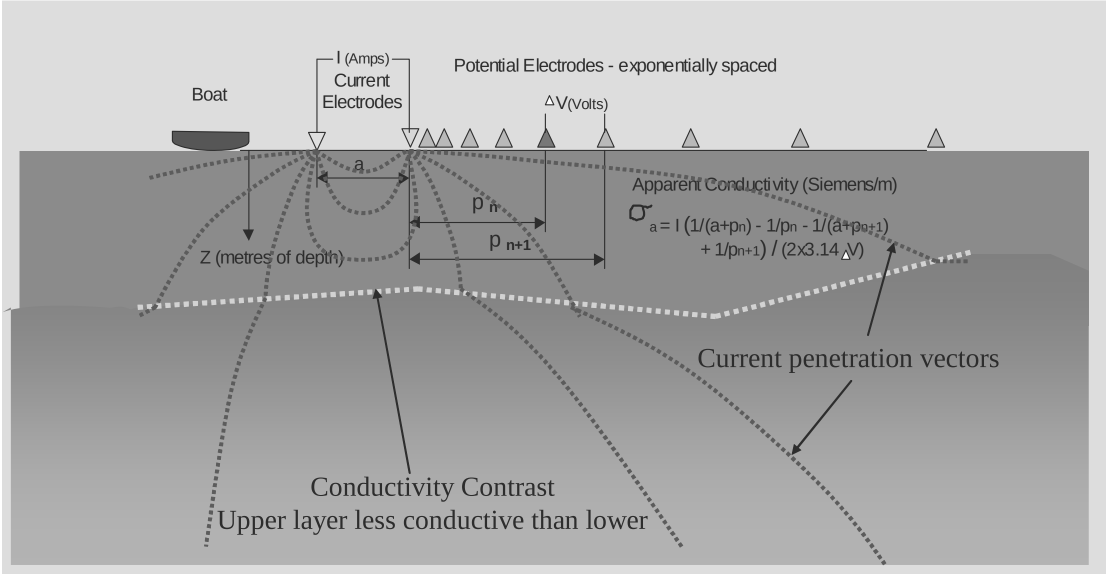


Figure 7.1 Geoelectric ('DC Resistivity') surveying on water using a towed cable. On land the same type of apparatus is used but electrodes must make good contact with the ground. Electric fields generated by the transmitter electrodes are distorted across conductivity contrast boundaries such as river beds.

Geoelectric system details

The following resistivity systems were reviewed :

- Aarhus University Hydrogeophysics Group PACES
- ABEM Terrameter and Lund Imaging system. Terraohm Instruments AB RIP 924 Mk2
- AGI Super Sting series
- DMT RESECS
- Geometrics OhmMapper
- Iris Instruments Corim
- Iris Instruments Syscal Pro
- Oyo Handy-Arm
- Radic Research SIP256
- Universite Pierre et Marie Curie - MUCEP and RATEAU
- Veris Technologies Mobile Sensor Platform
- Water Prospecting MPS
- Zonge GDP32-2

Geoelectric devices have an advantage over EM devices in that they use simple electric fields rather than complicated electromagnetic phenomena. This means that they can produce much less ambiguous data in some situations. With less complication and ambiguity, a second property, induced polarization (IP), is often measurable. IP reflects the proportion of saturated clay particle boundaries in soil.

Geoelectric systems require good electrical contact with the ground or water. This is fine on water but difficult to achieve on land without use of electrodes hammered into the ground. Some devices use capacitive coupling to overcome this problem while others use the weight of heavy electrodes, ploughing devices and innovative electronics.

PACES - Aarhus University

Aarhus University Hydrogeophysics Group have developed a resistivity system that they call ‘Pulled array continuous electric sounding – PACES’. A 300 kg resistivity array is towed behind a tractor of design similar to the Australian ‘Dingo’ excavator (Figures 7.2 and 7.3). The array is so heavy that it makes sufficient ground contact to operate continuously, with production efficiency, on the moist Danish soil. It images in detail down to about 30 m. The device has been used to image for tens of thousands of kilometres over various aquifers of interest in Denmark. PACES uses special controlled impedance electronics and selective stacking to cope with poor ground contact. Use of this or a similar device in Australia would be more difficult because our climate usually results in drier topsoil. We would probably need to plough the cable deeper. Trials by the author have suggested that it is possible. It is the author’s opinion that the recent invention of the Geometrics OhmMapper multi-dipole system is, however, likely to make the PACES system uncompetitive. PACES main advantages are that it can image deeper than the OhmMapper.

Figure 7.2 The PACES device being towed along near Aarhus, Denmark. The 300 kg 90 m long resistivity cable is being towed behind a tracked vehicle similar to the Australian 'Dingo' mini-earthmover. The system images to a depth of about 30 m provided that the ground is moist.

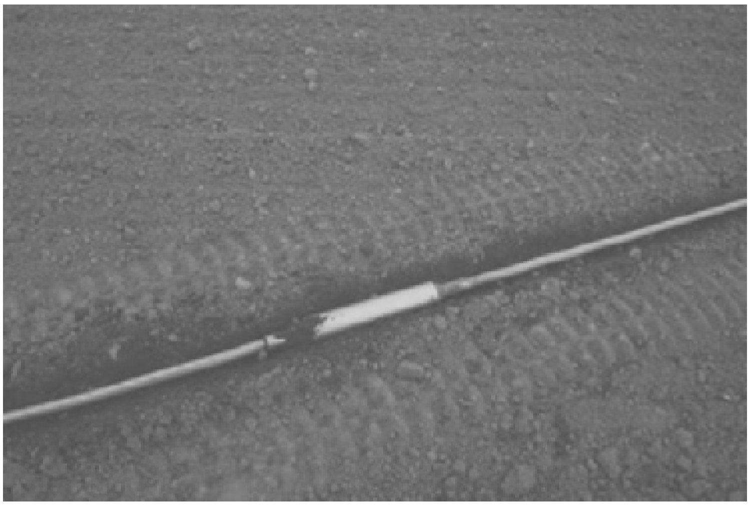


Figure 7.3 A PACES system electrode making contact with moist soil in a groove ploughed by the towing tractor.

ABEM Terrameter and Lund Imaging System and the Terraohm Instruments AB RIP924.

ABEM marketed what was probably the first automated resistivity mapping system and have upgraded the system progressively over the years[6]. Electrodes are laid out and sequentially utilized by an automated switchbox. The Lund Imaging System (Figures 7.4, 7.5 and 7.6) was developed by Torleif Dahlin of Lund University and has been commercialized by ABEM. The system has 4 isolated receiver channels and is compact. ABEM argue that 4 channels are enough to enable the instrument to collect data as fast as cables can be connected to electrodes when used with the automated switchbox. Competing receivers have 1, 8, 10 or more channels. Common receivers competing in the marketplace do not have isolated inputs and therefore can struggle to make use of simultaneously monitored widely differing signal strengths.

For aquifer imaging, it can be used in production mode only if a few transects are needed to resolve an aquifer ready for siting a bore. Timms and Acworth (Timms et al., 2002 and Charlesworth, 2005), have used it for spatially detailed soil moisture imaging in the Liverpool Plains, NSW, but due to survey speed, it is not appropriate for production soil surveying such as is typically conducted with the Geonics EM31 and EM38. Acworth is continuing to develop a means of using this instrument for efficient bulk soil moisture sampling in cracking soils.

Figure 7.4 The ABEM Lund Resistivity Imaging System

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[6] Disclosure: The author has purchased Terraohm Instruments AB equipment.

Figure 7.5 The ABEM SAS 4000 Terrameter and Lund Imaging System with electrodes laid out in a miniature array for demonstration purposes.

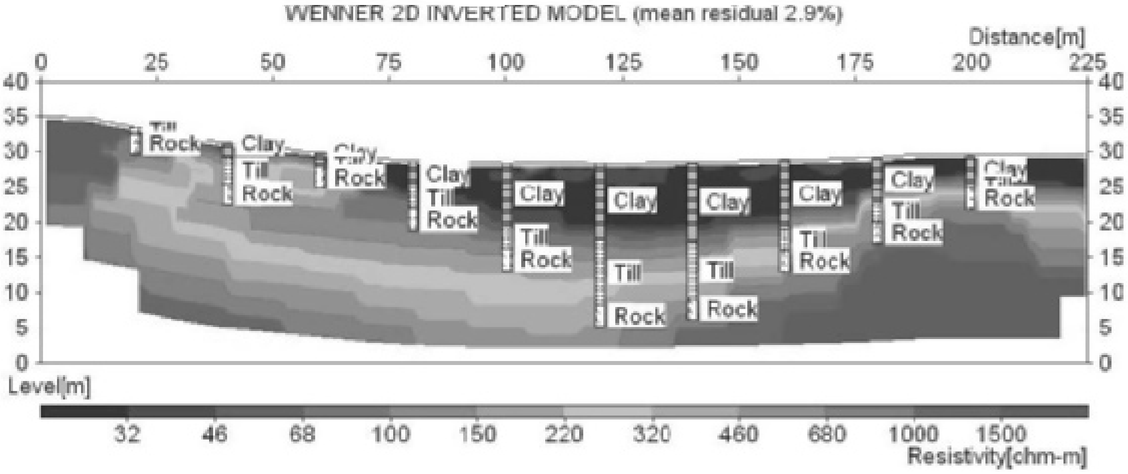

Figure 7.6 Multi-depth EC data, collected with a ABEM SAS4000, accompanied by borehole ground truthing.

Combination of the TerraOhm RIP 924 Mk2 (Figure 7.7) and an ABEM transmitter with a compact computer running MS Windows XP results in a compact continuous geoelectric imaging system for use in waterborne mode with a floating or submerged cable or in cultivated ground with a towed, ripped in cable or hammered in stakes. This device, which was initially developed for marine cable routing surveys, has fully isolated inputs that permit large voltages to be measured from some electrodes without compromising measurement of small voltages received from other electrodes.[7] This instrument collects electrical conductivity data and collects induced polarization (a property related to clay content) data continuously in 8 channels with

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[7] Further information is available from torleif.dahlin@tg.lth.se .

24 bit resolution.

Figure 7.7 The RIP924 from Terraohm Instruments AB

Advanced Geosciences Incorporated – Super Sting

AGI (www.AGIUSA.com) have produced instrumentation (Figure 7.8) very similar to that of ABEM. They produce 1 and 8 channel instruments and an instrument for waterborne surveying (Figure 7.9). They also produce automated electrode switching systems and multi-core arrays. They have gained much of the USA market. Currently their system is limited to 5 volts input which makes it difficult to use with optimized waterborne arrays but they plan to increase this limit to 15 volts like the Iris Syscal Pro.

Figure 7.8 The AGI Super Sting R8 IP Earth Resistivity/IP Meter.

Figure 7.9 The AGI Marine Resistivity Imaging System

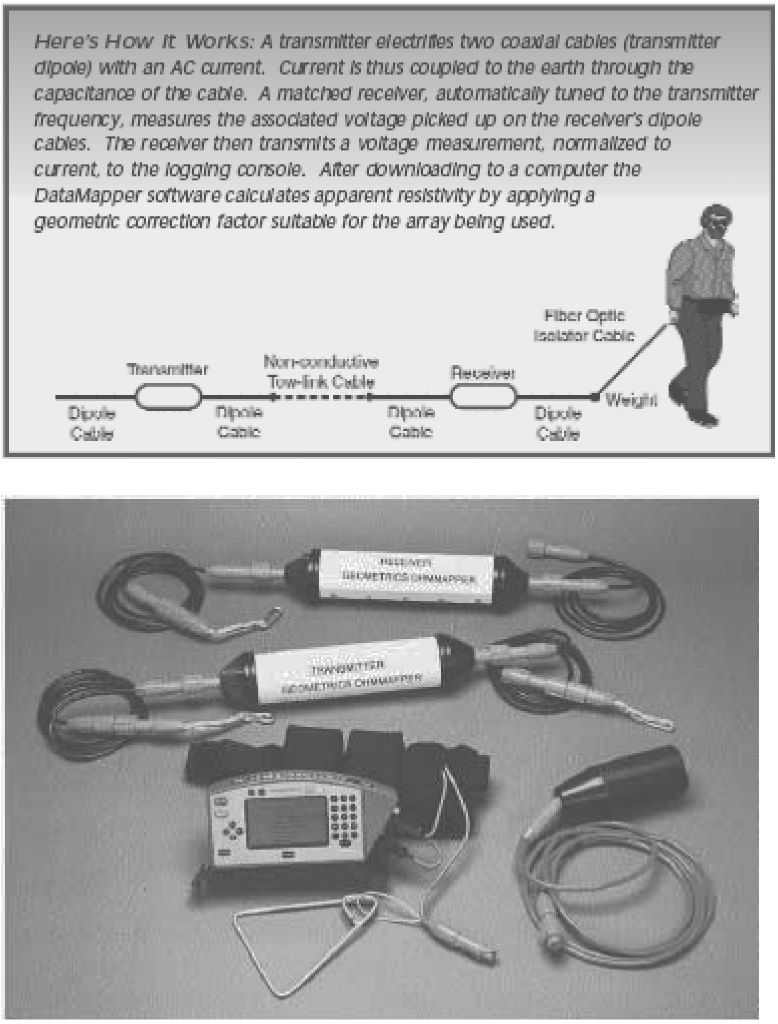
AGI have created extensive software resources for their instruments. They have also created telemetry support to permit their equipment to continuously monitor changes occurring in aquifer salinity in the vicinity of resistivity arrays permanently set up in boreholes.

Deutsche Montan Technologies - RESECS

Deutshe Montan Technologie GmbH (DMT) have produced a resistivity system which can handle up to 960 electrodes using addressable electronic packages on top of each electrode. The system is good for focussed high value imaging such as for archaeology but its features are not needed for soil imaging. Being a ground system that requires stakes to be hammered into the ground, it is not efficient for soil surveying.

Geometrics OhmMapper

The new Geometrics OhmMapper (Figures 7.10, 7.11 and 7.12) is a capacitively-coupled resistivity meter that measures the electrical properties of rock and soil without cumbersome galvanic electrodes used in traditional resistivity surveys. A simple coaxial-cable array with transmitter and receiver sections is pulled along the ground either by a single person or attached to a small all-terrain vehicle. Thus, data collection is many times faster than systems using conventional DC resistivity.



Here's How It Works: A transmitter electrifies two coaxial cables (transmitter dipole) with an AC current. Current is thus coupled to the earth through the capacitance of the cable. A matched receiver, automatically tuned to the transmitter frequency, measures the associated voltage picked up on the receiver's dipole cables. The receiver then transmits a voltage measurement, normalized to current, to the logging console. After downloading to a computer the DataMapper software calculates apparent resistivity by applying a geometric correction factor suitable for the array being used.

Figure 7.10 The OhmMapper with 2 transmitter and 2 receiver electrodes. A full system has 6 receiver electrodes (from www.geometrics.com).

The first introduction of this device to Australia did not make much impact but the instrument has since been greatly enhanced. A single dipole version of this device has been trialled in Australia by Monash University but it failed to gain a market because it collected basically the same data as Geonics EM31 instruments, already popular in Australia, but at a higher cost. The device now can be operated with 5 receiver dipoles which allow it to sample 5 different depths simultaneously. It easily samples to a depth of 20 metres at most locations. It can be towed efficiently behind a quad bike using a safety coupling and disposable sleeves that cover protrusions on the electrode array that drag along the ground. The electrode array needs to be about 5 times as long as the focus of the depth of investigation of the instrument so there is a limit to how sharply the device can be dragged around corners without the assistance of somebody lifting and dragging the array. This means that, when used to survey paddocks in a grid pattern, every second or third line would be surveyed first and then the other lines would be infilled on a second pass.

Figure 7.11 A capacitively coupled resistivity meter towed behind an all-terrain vehicle in Nebraska. The capacitively coupled resistivity meter (the cable and white tubes) consists of a coaxial-cable array with transmitter and receiver sections. (Source – USGS OGW Branch of Geophysics website)

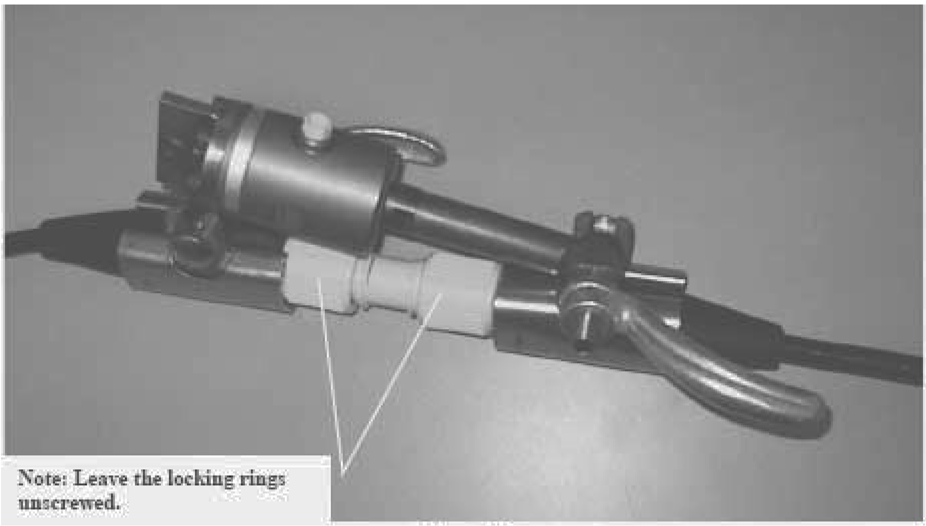


Figure 7.12 The limited strain coupler used to save the OhmMapper cables in case they get caught when being towed behind a quad bike.

Iris Instruments - Corim

The Corim is a capacitively coupled resistivity device for detailed mapping of the root zone. Data produced (Figure 7.14) and a photo of the instrument (Figure 7.13) provided here indicate its capabilities. Coupling to the ground when the instrument is towed across uneven ploughed ground may result in noisy data. The linear electrodes of the Geometrics OhmMapper may have greater coupling capability than the small plate electrodes of this device. Intending buyers should therefore discuss this limitation with both suppliers before purchase. This device is designed to image the root zone in much more detail than the OhmMapper.

Figure 7.13 The Iris Instruments Corim.

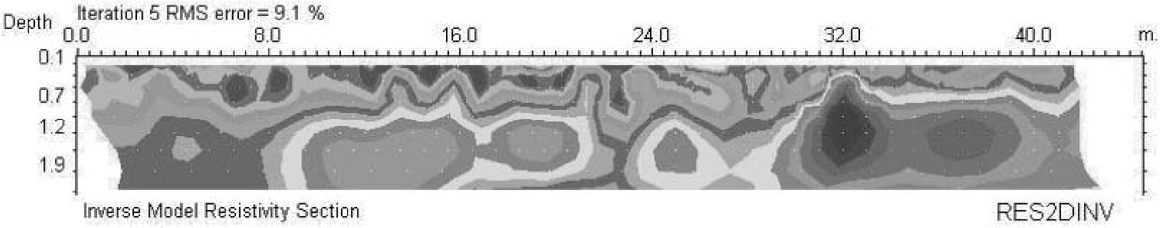


Figure 7.14 A sample of processed Corim data showing detailed variation in EC of a soil profile.

Iris Instruments - Syscal Pro

This instrument can measure 10 channels of resistivity data from waterborne or ground arrays (using an automated switchbox and multicore roll-along cable). It has a +/-15 volt range with reference to its second electrode which limits its ability to measure data from arrays with very large differences in input voltages. It does however have 1000 volt input protection. The transmitter, controller and some memory are all boxed with the receiver in a very compact way (see Figure 7.15). For waterborne surveys it should be used with a computer and GPS/Sounder. Software sold separately allows the operator to see imagery as it arrives and log it with GPS and sonar data. The author collected waterborne data on two occasions with a Syscal Pro but used internal storage rather than purchasing a computer and software for external logging as shown in the Figure 7.16. Without the external computer, it was very difficult to use the Syscal Pro to collect waterborne data due to lack of facility to check data as they were collected – nevertheless, a lot of data was successfully collected and the compactness of the instrument was greatly appreciated. In waterborne mode the instrument cannot collect induced polarization data.

Figure 7.15 The Iris Instruments Syscal Pro resistivity imaging device.

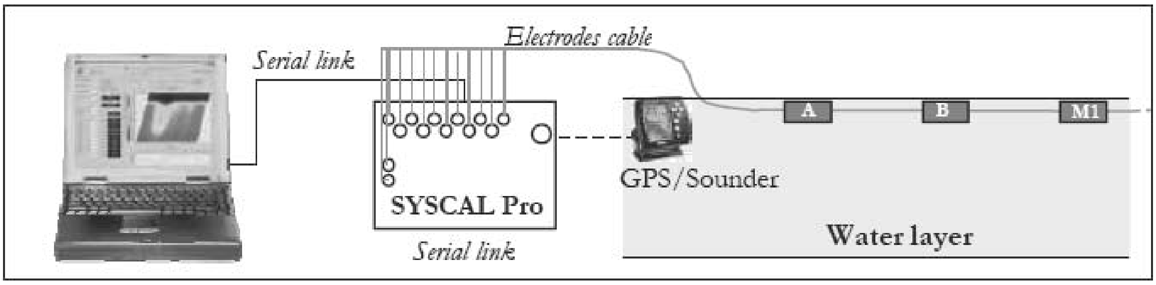


Figure 7.16 The Iris Instruments Syscal Pro and a Garmin GPS/Sounder 188 setup with a computer running Sysmar software for waterborne resistivity imaging.

Oyo - Handy-Arm

A Japanese company – Oyo – has recently entered the resistivity equipment manufacture market. They have produced a basic roll-along cable style of instrument for ground use called Handy-Arm.

Radic Research - SIP256

Radic Research have very recently released a high performance resistivity imaging system (Figure 7.17) specifically designed for spectral induced polarization imaging that can be used as a hydraulic permeability indicator in some types of geology. On each dipole, it has a box that digitizes signal for noise reduction.

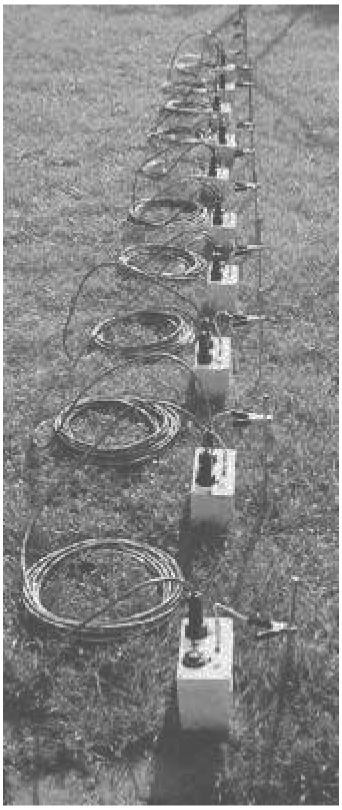


Figure 7.17 Radic Research SIP-256

Universite Pierre et Marie Curie – MUCEP and RATEAU

Resistivity arrays that use wheels with prongs that penetrate the soil (Figure 7.18) and capacitive electrodes inside the tyres of wheels (Figure 7.19) have been created by the Department of Applied Geophysics and the Centre for Geophysics Research at the Pierre and Marie Curie University in Paris. A shallow penetrating quadripole resistivity array was designed for an operator to tow while walking and a vol-de-canards resistivity array was designed for towing behind a tractor or car. Observation of the photos below will explain the device configurations. The devices sample at <0.01 sec in order to selectively reject bad quality data. The devices have been called RATEAU (Résistivimètre autotracté à enregistrement automatique) and MUCEP (Multi-pole Continuous Electrical Profiling) (Panissod et al., 1997).

Figure 7.18 A capacitive MUCEP

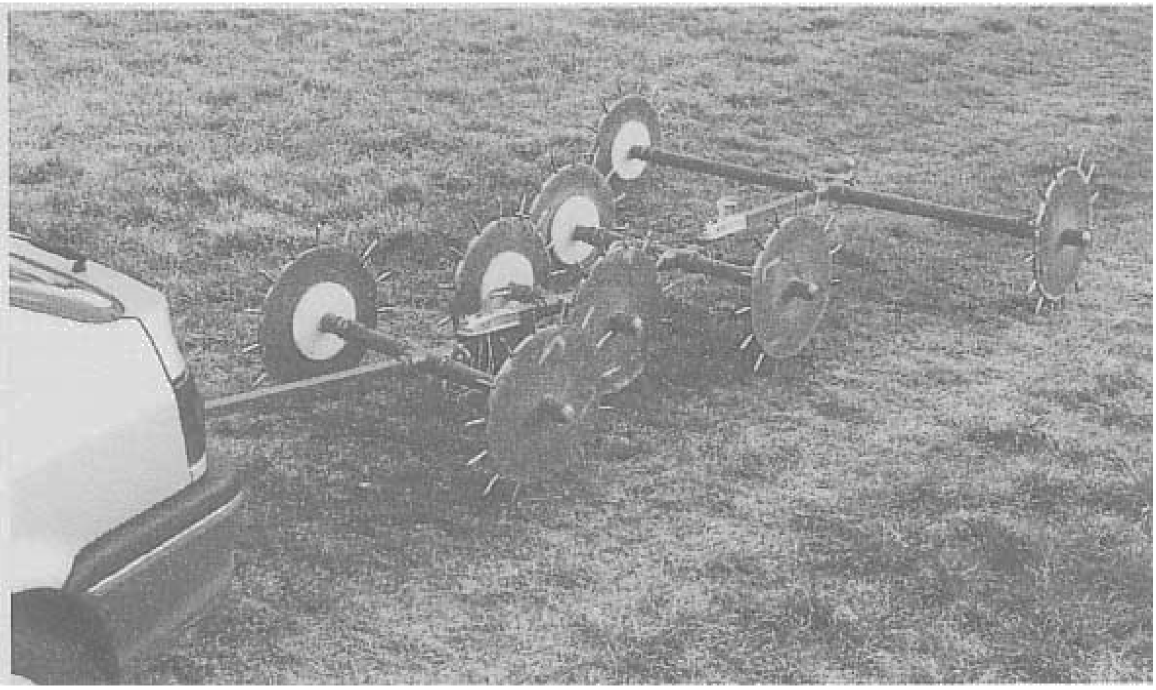


Figure 7.19 A spiked wheel MUCEP

Veris Technologies

Veris Technologies have produced a resistivity array mounted perpendicularly behind a tractor or 4WD and made up of coulter disks (Figure 7.20). It senses two depth intervals: 0 - 0.3 m and 0 -1 m deep. It also senses pH at 0.1 m depth every 12 seconds using a hydraulically controlled sampler, ion sensing electrodes and a water reservoir that cleans the electrodes and sampler. In recently cultivated, dry or cloddy soil the device may not maintain good ground contact resulting in inferior measurements to EM devices such as the Geonics EM38DD. This instrument has been intensively marketed for precision soils management and is much discussed in the United States Salinity Laboratory research documents (Rhoades et al., 1999).

Figure 7.20 The Veris mobile sensor platform with electrodes sensing EC at 0.0-0.3m and 0.0 to 1.0m and pH at 0.1m depth every 12 seconds.

Water Prospecting MPS

A company based in Orange, NSW, run by Greg Blight, advertise a technique called Multi-phase saturation. Their website (www.waterprospecting.com) gives no leads that may explain their technology but it is inferred that it is a geoelectric technique. They advertise that it is good for identifying water bearing zones. They lay out a 450 m multi-core cable with electrodes every 15 m. The scant explanation sounds somewhat like complex resistivity – a refined method of measuring induced polarization effect. Without further explanation, the author has some caution regarding ‘MPS’ but believes that it is a useful and reasonably efficient water prospecting technique.

Zonge – GDP 32

Zonge have produced a multipurpose geophysical data processor, the GDP32, that can be used for all types of resistivity surveying. It is used with a battery powered transmitter and voltage booster for this purpose. The system can be used for any type of waterborne or ground resistivity survey, as well as most types of electromagnetic survey and magnetotellurics. It is therefore more expensive and cumbersome than equipment dedicated to resistivity surveying. Individual inputs can be attenuated in order to measure voltages up to 40 volts without compromising measurement of other lower voltages received on other electrodes. The author has used Zonge equipment for many surveys without any major problems. Both EC and induced polarization (a property related to clay content) data were successfully collected on 8 dipoles using this instrument by the author.

The GDP-32 can collect induced polarization and spectral induced polarization data (complex resistivity) in frequency domain rather than time domain. This enables it to image hydraulic permeability in some types of geology. See Zonge – NanoTEM for equipment photo (Figures 4.7 and 4.8).

8. BOREHOLE GEOPHYSICS

Hydro-geophysical imaging is rarely much use on its own. It normally needs to be calibrated with borehole or other data before it can be used to manage aquifers. Lithological logs and water samples are very important, but, in most cases, geophysical logging is required to investigate deep boreholes. Many hydrological properties are only measurable before a drilling rig disturbs aquifers so some geophysical techniques are designed to measure during drilling or penetrating. Other techniques are designed to work once holes have been cased.

For most irrigation related borehole logging, a basic logging suite including a winch, logger, gamma tool, geoelectric tool and caliper tool is used. For PVC cased holes, an induction (EM) tool must be used to measure EC. The Gamma tool differentiates clays from sands while the EC tool measures salinity and clay content. The caliper tool finds blowouts in the boreholes that disturb the EC and gamma data and suggests areas of friable geology.

Often sonic and neutron tools are added to determine porosity and effective porosity. Gamma-Gamma density probes may measure rock density which helps to identify some sorts of aquifers.

Various water sampling tools are available for water sampling and temperature determination up and down boreholes. There is a problem with these instruments because water often flows up and down boreholes from one aquifer to another, particularly when disturbed by movement of the sampling tools. What they sample in the boreholes is therefore not representative of adjacent geology at each depth sampled.

To visualize the rock and casing of boreholes, acoustic televiewers and optical televiewers such as those produced by Advanced Logic Technology may be used. Such viewers identify fracture zone locations and orientations. Such zones typically are aquifers.

Various tools and techniques are also available for determining where water enters and leaves boreholes. These tools are important for investigating aquifer cross contamination occurrences such as are common in Great Artesian Basin bores. Reliable tools/techniques for such logging include heat pulse flow meters, EM flow meters and the hydrophysical logging technique. Other tools exist such as the impellor flow meter (not recommended, due to a lack of sensitivity) and the scanning colloidal borescope flow meter.

Downhole logging is a very advanced science due to its use in petroleum exploration and there is much that is possible; much more information can be gained through geophysical logging than can be obtained even with geological logging of drillhole core, which cannot all be described in this document. Only a few devices focussed on groundwater exploration will be discussed here.

Basic downhole Logging Equipment Packages

A small basic winch, logger, gamma tool, geoelectric EC tool and caliper tool typically costs about US$25,000 as a package deal in the USA. Companies selling such equipment include GeoVista, Mount Sopris Instruments, Colog and Robertson Geologging.

Induction EC loggers

Induction EC loggers (e.g. Figure 8.1) are available from Auslog, Geonics, GeoVista, Robertson Geologging and Mount Sopris Instruments. They are useful for logging EC through PVC casing and have been very popular for groundwater investigation in Australia.

Figure 8.1 Geonics EM39 downhole electromagnetic induction logger.

Undisturbed aquifer logging techniques - augers

To identify features such as perched aquifer, logging needs to be conducted before disturbing an aquifer (Figure 8.3). This may be achieved using an auger, with logging tools inside it, or a penetrometer, again with logging tools inside it.

Aarhus University Hydrogeophysics group created an auger with a geoelectric array, Gamma sensor and water sampler incorporated into it which they call Ellog. They also have experimented with incorporating a hydraulic conductivity measuring tool into an auger – see Figure 8.2. (Sørensen et al, 2003). The tool uses a geoelectric analog in which source and sink electrodes are replaced with source and sink water sources on the auger.

Figure 8.2 An auger tool set up to determine hydraulic permeability in undisturbed aquifers by injecting and withdrawing water through small holes while drilling.

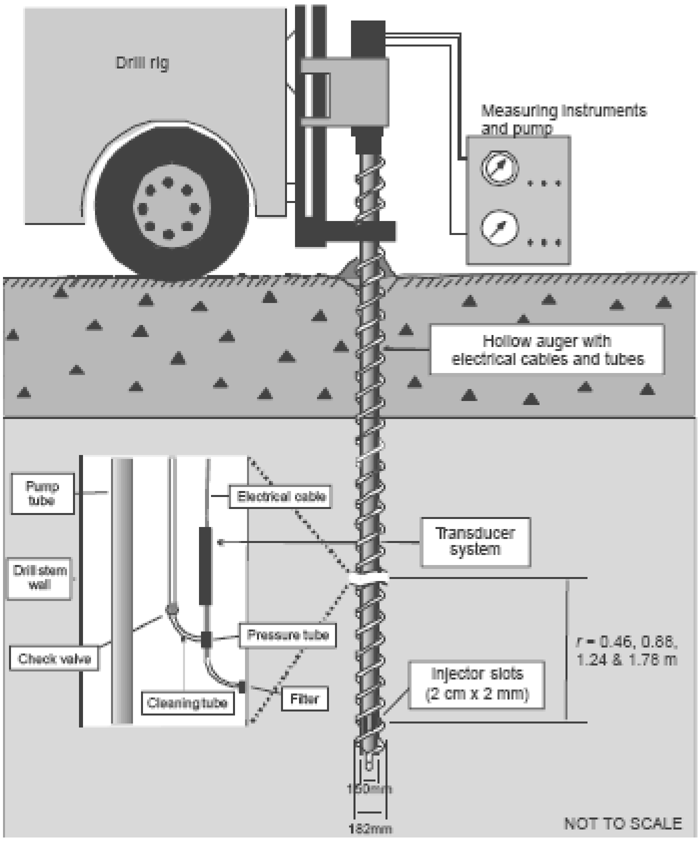


Figure 8.3 Measuring hydraulic conductivity in an undisturbed aquifer using an auger tool (Sørensen et al, 2003).

Undisturbed aquifer logging techniques – Penetrometers

Veris Technologies have produced a soil profile penetrometer for determining the variation of EC and soil stiffness with respect to depth through soil profiles (Figure 8.4).

Other companies have produced penetrometers with sensors that can detect EC and sediment stiffness to as deep as 30 m. Douglas Partners provide such a service in Australia. Geoprobe sell penetrometers with geoelectric arrays in their tips.

Figure 8.4 Veris Penetrometer with EC and pressure sensors.

Cross hole logging equipment

Cross hole logging gives detailed information on aquifers. However, costs confine its use to legal disputes over groundwater pollution by factories. It should not be considered for groundwater investigation on the scale required for irrigation unless it is part of an R&D program. An exception, perhaps, exists in research being done at the University of NSW water research laboratory where a miniature cross hole logging apparatus is being developed for soil scale studies looking at saturation heterogeneity in cracking clay soils (Acworth & Dasey, 2003; Acworth et al., 2005) . Because of its small scale, and resulting efficiency, this apparatus may soon be put into routine use studying soil moisture where moisture distribution heterogeneity precludes use of conventional, point source moisture sensors on their own.

9. OTHER GEOPHYSICAL TECHNIQUES

The following techniques, listed alphabetically, are briefly reviewed here:

- Electrokinetic seismic
- Gravity
- Ground Penetrating Radar
- Magnetics
- Magnetometric Resistivity
- Magnetotellurics (controlled and natural source)
- Nuclear Magnetic Resonance Sounding
- Radiometrics
- Remote sensing (satellite and airphoto imagery)
- Seismic
- Soil moisture and water suction meters
- VLF

Electrokinetic seismic

Electrokinetic seismic (EKS) is a method (see Figure 9.1) that is claimed to be able to image variation in hydraulic conductivity (or permeability) of sediments or rock containing water. Currently it is strictly a research topic because signal strengths needed for obtaining practical results are difficult to attain. Surveys use a seismic source to cause water molecules to generate charges, which permeate through sediment and create voltages at the surface that are picked up by a geoelectric array. To interpret EKS data, knowledge of the seismic velocities and electrical conductivities of the subsurface are required. [8]

Figure 9.1 Electrokinetic Imaging (from www.zetica.com)

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[8] Further information is available from Chris Waring, ANSTO, http://snow.stanford.edu/~morf/pride/octupole%20antenna/electro-seismic%20-osmotic%20/artpaperfrm.htm and http://www.zetica.com/methods/electrical/eks_outline.htm

Gravity

Gravity surveying simply involves the measurement of the gravitational field of the earth across a mapped area. After correcting for altitude, latitude and earth tides, the resulting data clearly indicates differences in rock densities. Soft uncompacted soil has much less density than hard rock so it is most useful for defining the shape of geological basins that hold groundwater used for irrigation. Faults that control groundwater movement can be identified (Figure 9.3). A national gravity dataset is available from Geoscience Australia (www.ga.gov.au). For identifying faults that confine groundwater flow, detailed gravity transects generally need to be conducted. A gravity meter such as the Scintrex CG-5 (Figure 9.2) is often used. Levelling of the instrument is required at each gravity station. Accurate horizontal positions and heights and required for each station. These data are often acquired by GPS techniques and are required to better than 5 cm accuracy. This corresponds to a change in Bouguer gravity of 0.01 mgals which is the typical resolution of modern gravity meters.

Figure 9.2 The Scintrex CG-5 Autograv gravity meter and Fugro Ground Geophysics gravity crews in operation (from Fugro Ground Geophysics website).

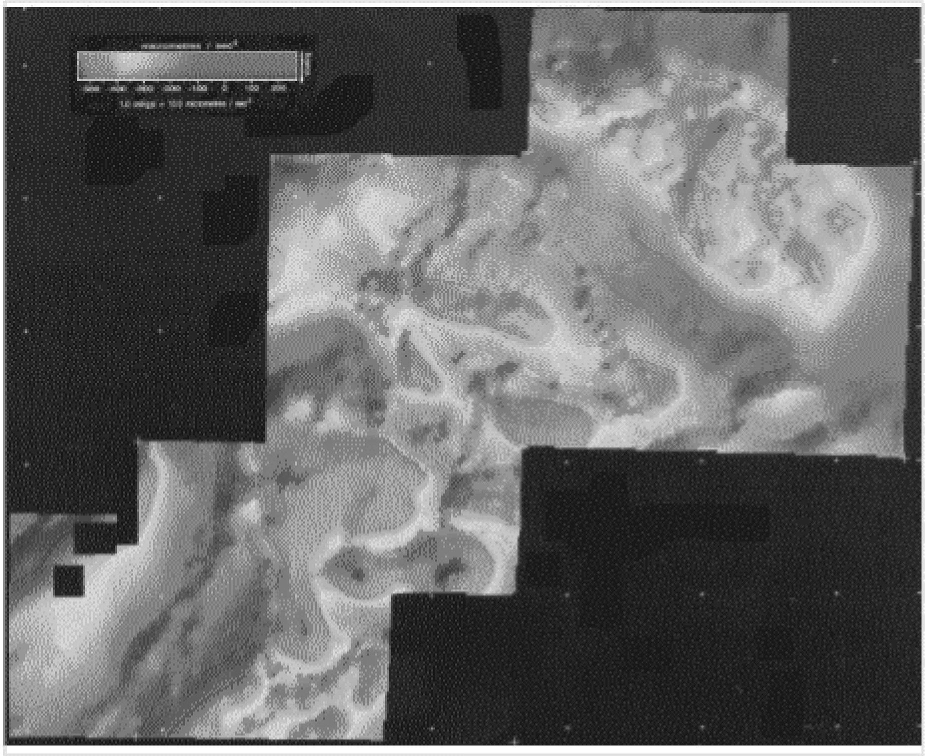


Figure 9.3 Bouguer Gravity under the Darling Basin (NSW) indicating potential groundwater confining geology (from www.FugroGround.com). The red tones show higher density (and therefore less porous) basement rocks of both the Mt. Wintlow High towards the west and the Mt. Jack High towards the north and the blue tones of the Early Palaeozoic sediments of the Darling Basin that are more likely to contain water.

Using gravity to map groundwater level changes

Some gravity meters are referred to as Micro-gravity meters due to their ability to detect very fine changes in gravity. Such meters are capable of measuring changes in groundwater level without the need for a bore at every measurement point. They are being used on some aquifer storage and recovery projects to periodically create detailed maps of the changes to the water table created by aquifer storage and recovery bore operation. The maps are statistically calibrated using water levels in a set of control bores.

Ground Penetrating Radar

GPR is a technique that measures reflections off boundaries of variable dielectric permittivity (related to water content) and EC.

Ground penetrating radar (GPR) is useful for identifying most sharp features in the near subsurface. A small electromagnetic pulse is transmitted and reflections of the pulse are received over time (see examples in Figures 9.7, 9.8 and 9.9). As the process is repeated while the device is being moved along the ground, a scan of reflections is developed.

In agriculture GPR is used to locate agricultural tile drain locations (Figure 9.4) and other pipes, soil stratigraphy and water table depth. It may also be used for water storage volume calculation (bathymetry) and subsurface stratigraphy relevant to seepage pathway identification (Figure 9.5).

Potential users should be warned that GPR signal is sharply attenuated in high EC ground such as saline clayey soil. Attenuation rates are known and disappointment can be avoided by confirming that a survey site is of sufficiently low EC to permit detection of features at the depth of interest. The effect of soil salinity on GPR data are clearly shown in Figure 9.6 – a traverse across a coastal subsurface salt water interface.

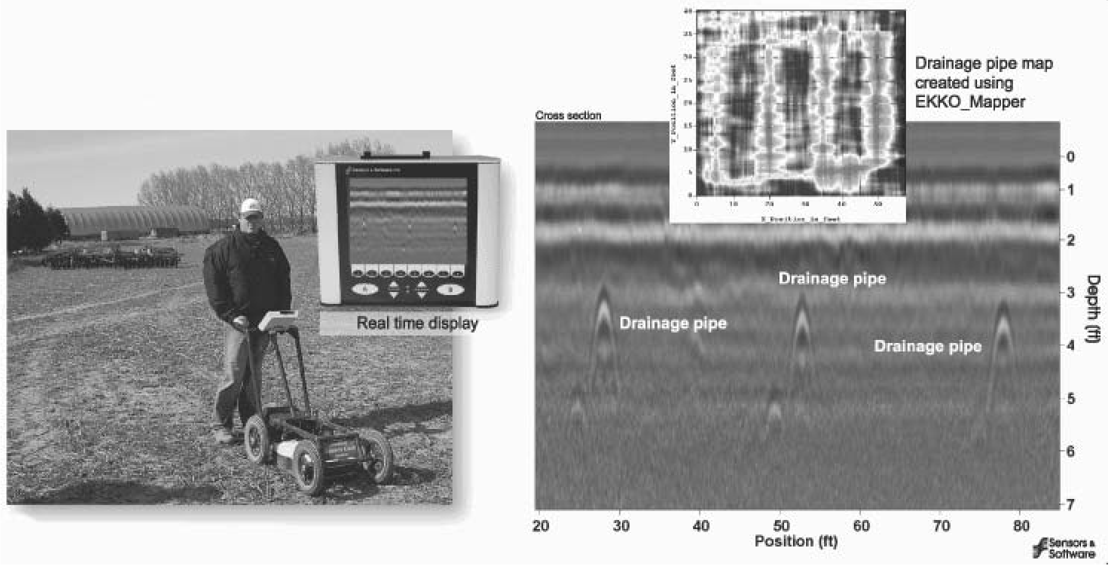


Figure 9.4 Sensors and Software Noggin ground penetrating radar system being used to locate agricultural tile drains.

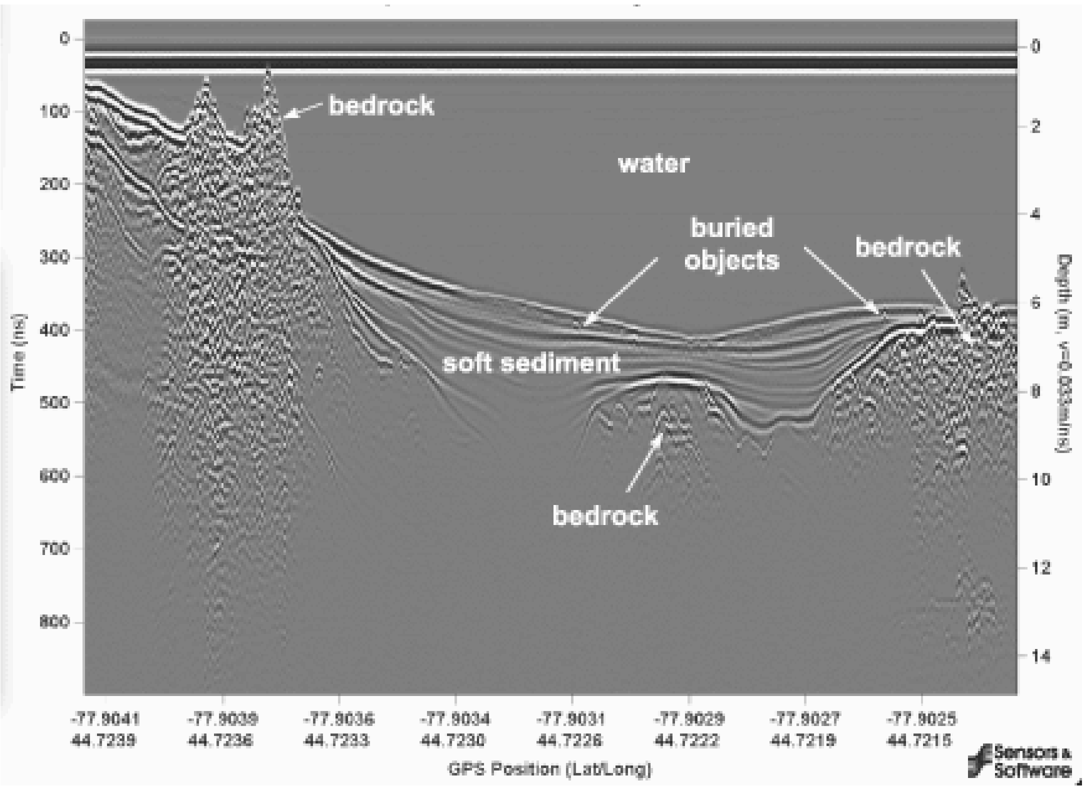


Figure 9.5 Watercourse bathymetry and sub-bottom stratigraphy revealed by a Sensors and Software ground penetrating radar system.

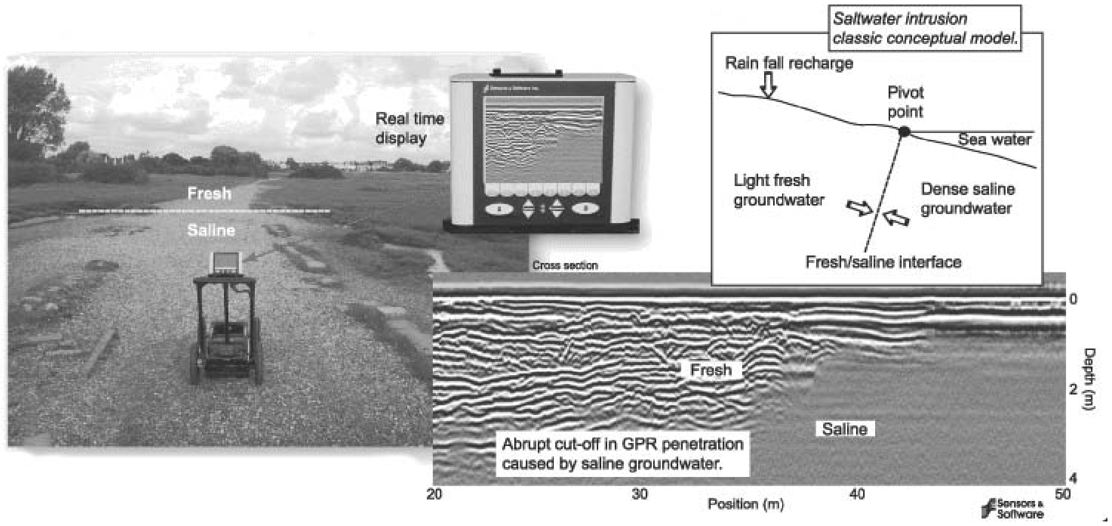


Figure 9.6 Sensors and Software Pulse Echo Pro detecting a freshwater / saline water interface through attenuation of signal.

Radar equipment is available from Sensors & Software Inc. (www.sensoft.ca), Mala Instruments (www.malags.com), Geophysical Survey Systems Inc. (http://www.geophysical.com/applications.htm#farming) and COS Company (http://www.cos.co.jp/en/b2e.html). Radar systems from Mala cost US$32000 to US$43000 (June 2005). Much research on soil moisture content measurement is being conducted using the Sensors and Software Inc. instruments and is mentioned in the section of this document on soil moisture sensors.

Figure 9.7 GSSI ground penetrating radar being used to identify soil structure variation

Figure 9.8 Mala Geoscience ground penetrating radar equipment

Figure 9.9 The COS Senci-On β2 ground penetrating radar instrument claimed to be able to indicate water leakage from pipes.

Magnetics

Total magnetic intensity (TMI) sensors are occasionally used for water exploration in upland areas where water occurs in rock fractures. They may also define palaeochannels in areas where there is a strong contrast between iron mineral content in the channels and surrounding sediment (see Figures 9.10 and 9.11). TMI sensors have no ability to directly correlate to water presence or salinity but only to iron minerals such as hematite and magnetite. Australia is relatively well covered by airborne magnetic surveys for which data are publicly available. Where increased resolution is desired, such as for siting a bore within a narrow water filled fracture zone, a ground based survey is warranted. Ground based instruments now being manufactured tend to be very well designed with GPS integration and moving map displays. Instruments manufactured by Geometrics, LRS Scintrex, and GEM are displayed in Figures 9.12, 9.13, 9.14 and 9.15.

Magnetic data acquisition is well understood by many mineral exploration geophysicists who could be requested to advise on their use in groundwater exploration.

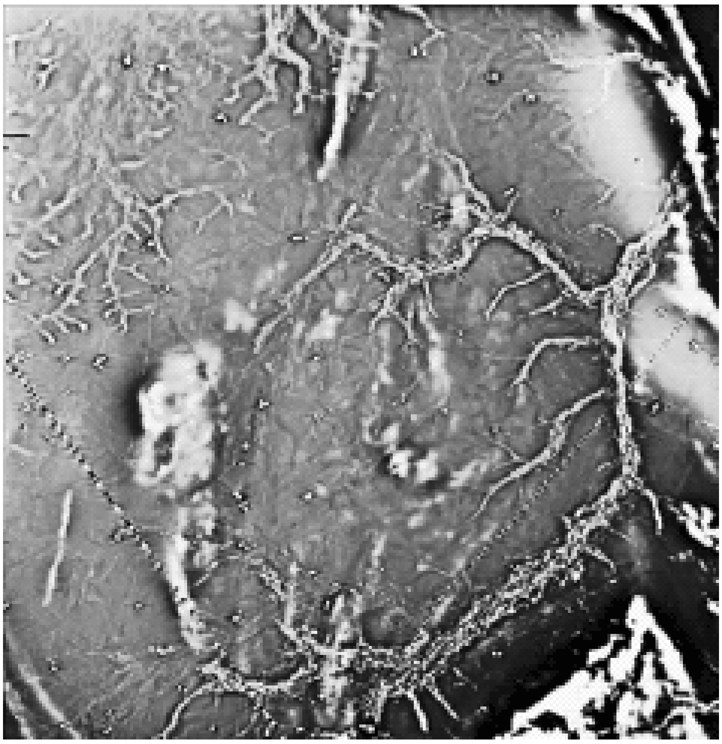


Figure 9.10 Palaeochannels identified by magnetics near West Wyalong (Brodie, 2002).

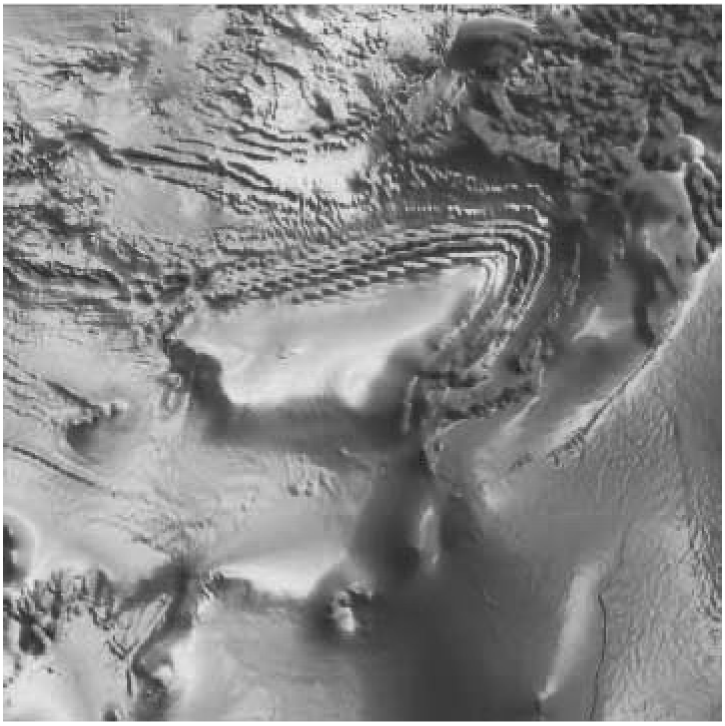


Figure 9.11 Basement rock features that may confine groundwater flow as identified by magnetics (Brodie, 2002).

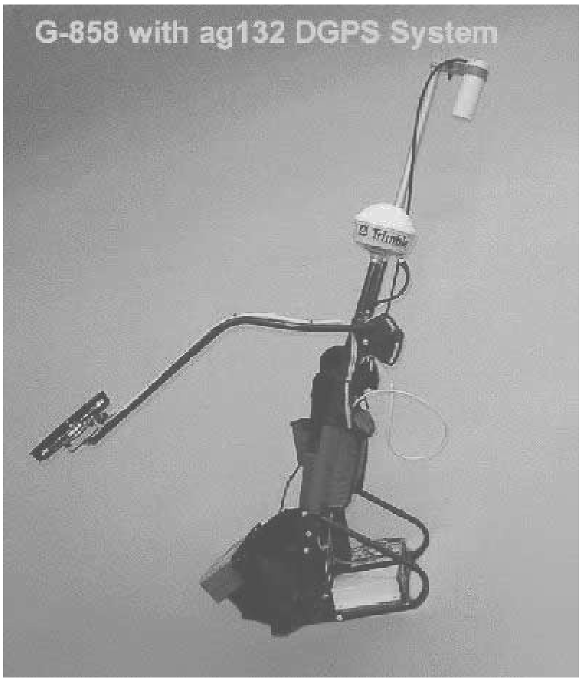


Figure 9.12 A backpack mounted Geometrics magnetometer with Trimble GPS

Figure 9.13 Geometrics G858 cesium magnetometer

Figure 9.14 Scintrex SM-5 Navmag

Figure 9.15 GEM GSM-19 Overhauser Magnetometer.

Magnetometric resistivity (Willowstick Aquatrack)

Magnetometric resistivity combines geoelectric and electromagnetic techniques to trace deep, relatively electrically conductive targets. It is used by a company called Willowstick (www.Willowstick.com) and they advertise an ability to map sub-surface water using their Aquatrack© technology. Willowstick have patented the use of magnetometric resistivity with electrodes placed down water bores. Electrodes are placed into boreholes or springs so that AC current transmitted into aquifers flows along the aquifers and dissipates then is drawn to an opposite polarity electrode in another borehole or on the ground surface. The current produces a changing magnetic field which is detected by magnetic field change detectors roving over the ground surface. The technique has never been used in Australia for water exploration, no doubt, because we have a predominance of saline aquifers. Current will preferentially flow through saline aquifers which means that the tool will map them in preference to the low salinity aquifers that are sought after.

The mechanism of Aquatrack is summarized by Willowstick as follows and is presented in Figure 9.16. “AquaTrack uses a low voltage, low amperage, audio frequency electrical current to energize the groundwater. Electrodes are placed strategically in wells, springs or surface water to inject electricity into the groundwater of interest. Because the groundwater is a conductor, the electrical current follows the groundwater between the electrodes. As the electrical current flows through the groundwater, the current creates a magnetic field characteristic of the injected electrical current. This unique magnetic field can be identified and surveyed from the ground surface using a tuned, sensitive magnetic receiver.”

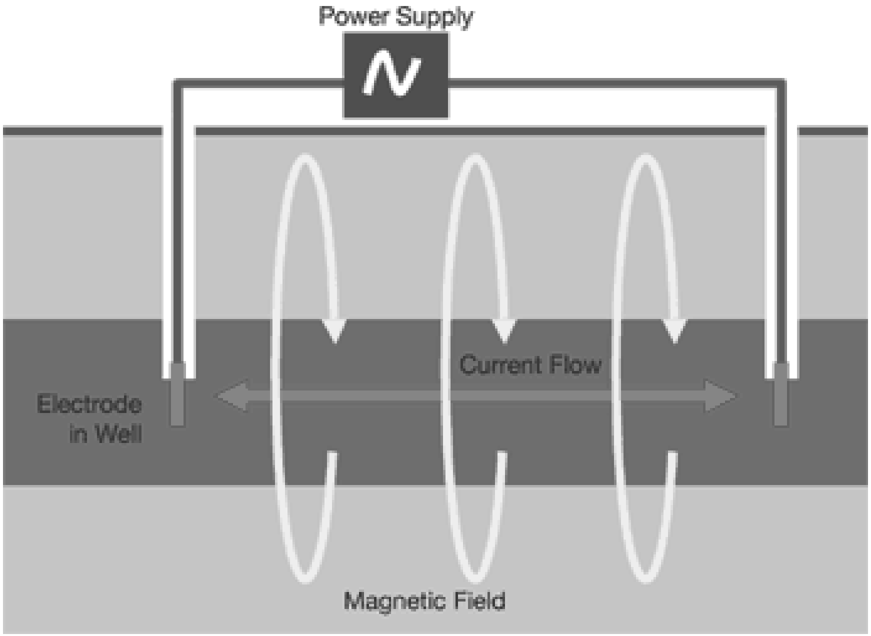


Figure 9.16 Willowstick's Aquatrack technology which can trace the path of groundwater from interception points such as wells but only in resistive host rock (from http://www.willowstick.com/technology.html).

Magnetotellurics (natural and controlled source)

Magnetotellurics is another electrical conductivity imaging technique typically used for deep exploration. It uses either natural sources (distant lightning etc) or controlled sources (large generators transmitting current into large loops or long grounded wires). Natural source magnetotelluric equipment is marketed by Geometrics, Zonge and others. Zonge pioneered the use of controlled source magnetotellurics (CSAMT, CSAET, CSMT etc). These techniques are particularly useful for detecting vertical resistive barriers and for deep imaging. They are used for deep groundwater investigation in hard rock areas. At most sites, transient electromagnetic methods can provide similar imagery at similar or less cost than CSAMT. CSAMT surveys require very large transmitters and therefore very large generators because survey can only be conducted at a significant distance from the transmitter, while electromagnetic surveys typically transmit and receive at the same location.

Nuclear Magnetic Resonance Sounding

Nuclear Magnetic Resonance (NRM) sounding (or Proton Magnetic Resonance sounding) is a direct method of detecting aquifer properties at different depths. It determines water content and estimates permeability. It works in the same way as medical MRI machines by exciting protons in water. However it must use the weak and variable magnetic field of the earth rather than the strong refined fields generated by the large magnets of medical MRI machines. The signal is attenuated by conductive saline groundwater in the same way that transient EM signal is attenuated so it should not be used to investigate deep aquifers under saline cover. It has been used in Australia to define highly valued arid area mine groundwater supplies. At this stage, it seems that the low cost of groundwater in irrigation areas does not warrant use of this technique for irrigation related projects.

An Iris Instruments Numis System (Figure 9.17) designed to penetrate 150 m costs 134 000 Euros (May 2005) including 5 days training at a buyer selected site.

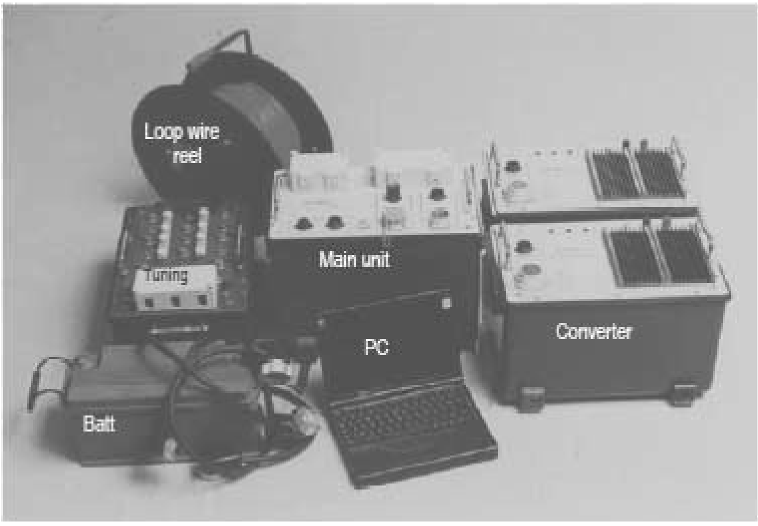


Figure 9.17 Iris Instruments Numis nuclear magnetic resonance sounding system

Radiometrics / Scintillometers / Gamma Ray Spectrometers

Gamma radiation occurs naturally due to the decay of Potassium, Uranium and Thorium and their decay products. Soils may sometimes be distinguished from their different radiometric signatures. With suitably calibrated spectrometers and careful survey procedures, geochemical concentrations may be obtained from gamma spectrometric data.

Exploranium (www.SAIC.com), Scintrex and GF Instruments produce scintillometers and spectrometers. These devices are useful for imaging the clay proportion of topsoil by detecting potassium counts. Handheld devices such as the one shown (Figure 9.18) need about 15 seconds to take a meaningful measurement. Longer times (several minutes) are required to obtain accurate geochemical measurements using handheld gamma spectrometers. Large crystal packs (15 to 30 litres) may be quad bike mounted for broad scale continuous acquisition. Aeromagnetic surveys usually acquire gamma spectrometry data simultaneously with the magnetic data. Detectors used in airborne surveys may be of up to 64 litres in volume.

Figure 9.18 GF Instruments 512 scintillometer also available in a borehole version.

Airborne radiometric data are available from Geoscience Australia and State Geological Surveys.

Seismic

Seismic surveys are used extensively for oil exploration but the author has not found any surveys in which seismic data have been used without R&D funding in hydrogeological surveys. On many occasions, however, seismic data obtained for petroleum exploration are very useful for deep bore siting and groundwater modelling. Much understanding of the extents of our deep aquifers has come from such data.

Seismic methods for shallow explorations are available and are used in R&D mode for groundwater exploration. Refraction techniques have been investigated by the

USGS Office of Groundwater Branch of Geophysics
(http://water.usgs.gov/ogw/bgas).

Recently surface wave seismic surveys have become a popular R&D topic. These surveys also concentrate on shallow hydro-geological applications (see Figure 9.19).

Figure 9.19 Conduct of a seismic survey in Nebraska (from USGS, OGW, Branch of Geophysics web site).

Soil moisture and water suction sensors

Most soil moisture measurement is now conducted using sensors that detect dielectric permittivity variation as does ground penetrating radar.

Static (non moving) soil moisture and water suction sensors are well known to the irrigation and drainage communities and a long list of such devices is hosted at http://www.microirrigationforum.com/new/sensors/ (see also Charlesworth, 2005). Neutron probes, now rarely used, measure soil moisture using radioactive phenomena. Now devices that use capacitive effects at high frequencies to measure soil moisture are most popular. The response is affected by dielectric permittivity and/or EC depending on the frequency. Time domain reflectometry devices use two wires or similar parallel conductors inserted into soil to measure dielectric permittivity and, in turn, soil moisture. Gypsum block sensors have existed for a long time – electrical conductivity is measured across the gypsum block to measure soil water suction. Other soil water content devices measure suction and include tensiometers and WATERMARK (granulated matrix) sensors (http://www.irrometer.com/agcat.htm).

Static sensors will not be considered in detail in this review but moving soil moisture content sensors used to map soil moisture in topsoil across paddock will. Those interested in static soil moisture sensors should see the extensive review by Charlesworth (2005).

Airborne thermal imagery can give an indication of topsoil water suction due to the effect of evapo-transpiration on soil temperature but such imagery is affected by numerous other factors and therefore is difficult, at best, to use.

Soil moisture content measurement using ground penetrating radar

Radar is promising to become a method with which soil moisture content will become measurable remotely using a vehicle passing across the land surface (See Figure 9.20). The dependence of radar on soil moisture content is via the property, dielectric permittivity, which is anomalously high for water at radar frequencies. This dependence is the same as utilized by point source moisture meters that utilize time domain reflectrometry (TDR).

Soil moisture content can be measured by radar, however, presently the techniques involved are probably for researchers only. Soil moisture content can be measured using reflected wave velocity, ground wave velocity, transmitted wave velocity (between boreholes) and surface reflection coefficients. Those with an interest in such methods are referred to Huissman et al. (2003) and the ground penetrating radar section of this document.

Figure 9.20 An elevated 500-MHz ground penetrating radar (GPR) system being used to measure soil moisture content using surface reflection amplitude (from Huissman et al., 2003).

Remote sensing - aerial photography and satellite imagery

Aerial photography has been used for tens of years to identify geomorphological features that control groundwater flow. It is still very useful. Various satellite imagery products now also are available but rarely show anything that good aerial photography, properly observed, cannot show. The differences are usually in ortho-rectification, uniformity and feature enhancement rather than image quality. Accurate digital elevation model generation is now possible using remote sensing techniques including LIDAR. Remote sensing is a large, very important topic but will not be discussed further here as this document focuses on investigating beneath the earth surface while most remote sensing technology looks only at the surface of the ground. The interested reader is referred to Drury (2001).

VLF

ABEM (Figure 9.21), LRS Scintrex (Figure 9.22), Iris Instruments (Figure 9.25) and Geonics (Figure 9.23) produce devices for VLF surveying. VLF (very low frequency – typically in the range 15 to 20 kHz) exploration uses signals transmitted for submarine communication to determine vertical or steeply inclined variations in EC in the earth. It can be used for identifying fracture zones in highly resistive rocks that may be suitable as aquifers for bore siting. Its ability to detect features depends on their orientation relative to the direction to the source of the VLF signal.

A Wadi VLF detector (Figure 9.21) costs SEK 63000 from ABEM Instruments AB (Sweden).
An EM16/16R costs US$11850 from Geonics (Canada) (Figures 9.23 and 9.24). Geonics. A Tx27 VLF transmitter is available from Geonics (US$8400) for locally transmitting VLF signal where government supplied signals are weak or directed in an inappropriate direction to detect local geological features and government regulations permit.

VLF has not been used much for groundwater investigation in Australia largely due to the electrically conductive nature of our terrain but maybe also due to the ambiguity of interpretation of VLF data.

Figure 9.21 ABEM Wadi VLF receiver

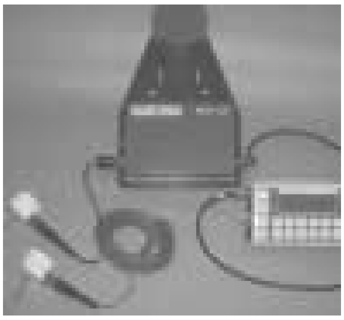


Figure 9.22 LRS Scintrex VLF receiver attachment for their Navmag magnetic receiver.

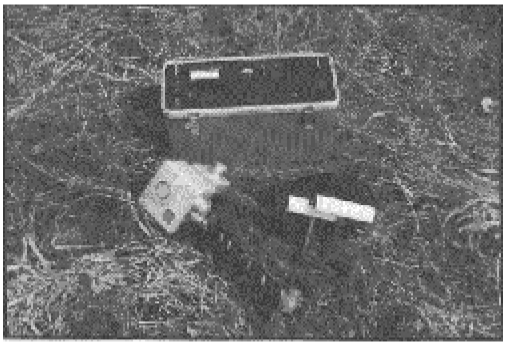


Figure 9.23 Geonics EM16/16R and the Tx27

Gisco provide VLF interpretation and presentation software.

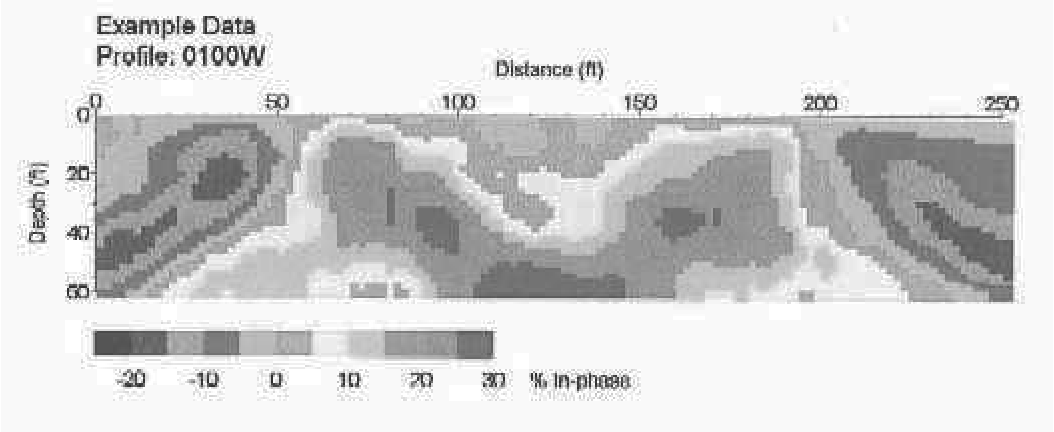


Figure 9.24 GiscoGeo RAMAG VLF software output.

Figure 9.25 Iris Instrument T-VLF

10. SOFTWARE

Software for processing and presentation of geophysical data is just as important as the instruments that collect the data. Various packages offer different refinements that speed up, automate and/or enhance resolution of data. Different visualization solutions also are available. Some of the software operates in real time or near real time during data collection.

Providers include the following:

Real time mapping - Geomar Software

Geomar Software Incorporated offers the Trackmaker series of software for navigation and data logging using the tough Allegro field pocket computer and Geonics instruments. For use with the EM31 or EM38, the software costs US$750. For use with the proposed EM31-multi coil spacing instrument it costs US$2500. An Allegro costs approximately US$3000.

Real time mapping - Geophex

Geophex offer PDA software for navigation and real time EC mapping (EC map generation as you survey) for use with the GEM2. It runs on Microsoft Pocket PC devices. As an operator drives or walks along, EM data comes up as points on the screen coloured to represent their conductivity value. At any time the operator may stop and execute gridding to transform the existing coloured points into a background gridded image.

Real time imaging - TerraOhm Instruments AB

TerraOhm offer real time imaging software for use with the RIP 924 waterborne acquisition device. They have facilitated simultaneous logging of extra devices such as pressure and water property sensors. They also offer the Lund Imaging System software for ground surveys using the same device with a switchbox.

Real time navigation and general purpose geophysical logging – Trimble

Much of the advantage of real time software is in the facilitation of easy, GPS-based navigation. Trimble are one company who specialize in this art, particularly concerning agricultural applications. Their instruments have facilities that make it very easy to practically evenly cover paddocks containing obstacles. Because some of their software is designed to flexibly receive and report data from geophysical survey instruments along with GPS data, it is used in preference to instrument specific real time mapping software. Such software includes the EZMap and TerraSync/Pathfinder Office packages. Some useful navigation features are also resident in firmware provided in their actual GPS devices.

Real time navigation – Others

Other suppliers of real time navigation software are numerous and many of the packages available are useful for geophysical surveyors. Of particular note are products ArcPad (marketed by ESRI) and the much cheaper Fugawi and Ozi-Explorer packages that, although being less than one tenth of the price of ESRI and Trimble packages, still do all that many geophysical surveyors require.

Real time imaging – Iris Instruments

Iris instruments offer real time imaging software (Geomar) for use with the Syscal Pro waterborne acquisition option. This software logs the geoelectric data, GPS data and sonar depth data and plots it in real time on a computer running Microsoft Windows XP.

Visualization software - Golden Software

Golden software offer ‘Surfer’ which is an affordable gridding and mapping package.

Visualization and archiving software - ESRI

ESRI offer ArcView. The package used by most agencies in Australia to work on EM31 imagery. It offers excellent archiving and data organization support for about A$4400 but the gridding algorithm only comes with an extension that costs about $7000.00. Using some scripting, Surfer 8 can be used to perform gridding.

Visualization software – other

Other gridding and imaging packages exist. GStat is free but requires C++ programming skills to use. Manifold is affordable as is Kilimanjaro (Idrisi) which is based on GStat. Geosoft Oasis Montaj is very capable, offers masses of features and has good macro recording support. The Australian company – ENCOM – make products for complex 3D imaging.

Multi-depth EC processing and visualization - Aarhus University Hydrogeophysics Group

The Aarhus University Hydrogeophysics Group writes custom software for all their instruments as well as web sites and databases for distributing their data. Their TEM processing software possibly is the most efficient and thorough on the market – there are too many features in their software to mention here. They also have written many of the most effective tools for continuous geoelectric survey processing.

Multi-depth EC geoelectric processing - AGI

AGI offer planning and inversion software for use with their instruments. It is called EarthImager 2D & 3D.

Multi-depth geoelectric EC processing - Loke

Loke offers Res2dInv and Res3DInv (see www.geoelectrical.com) packages for 2D inversion (see glossary) of data from geoelectric devices. Geometrics, ABEM and Iris Instruments device data generally are processed using Res2DInv.

Multi-depth EC processing - Interpex

Interpex offer inversion (see glossary) software with good interactivity and some automation. Their principle package is called IX1D. It can invert FEM, geoelectric and TEM data from numerous instruments. It can greatly enhance the vertical resolution of EC data. An example is given below (Figure 10.1) in which almost meaningless GEM - 2 data was transformed into useable information with some smart user applied constraints and IX1D.

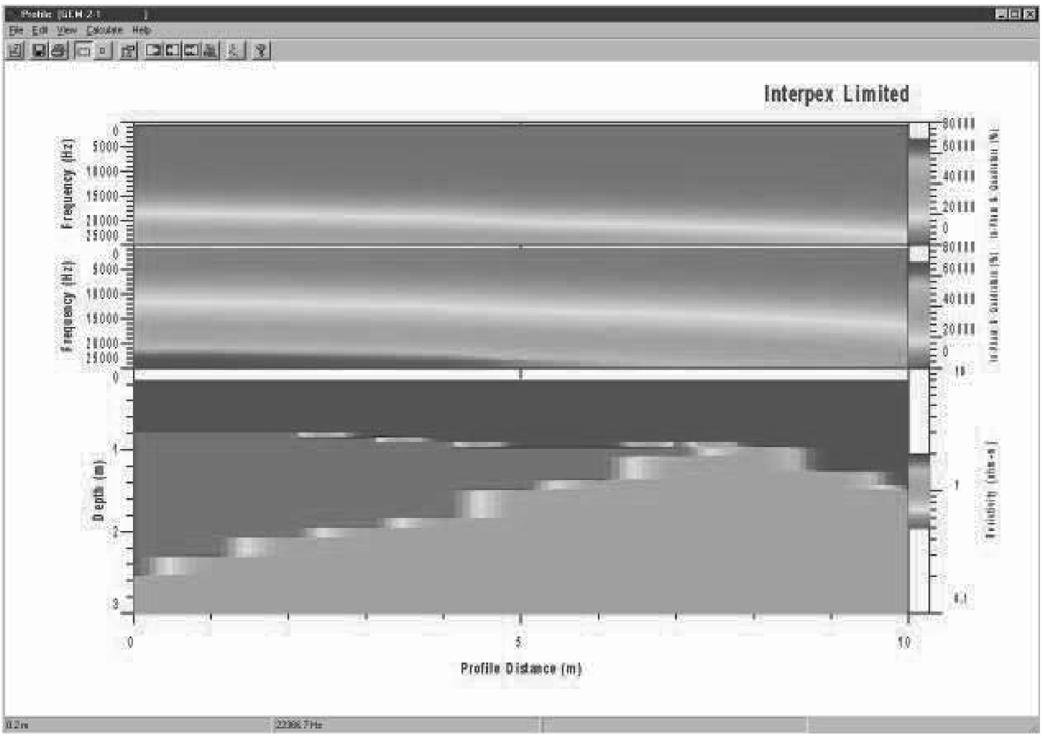


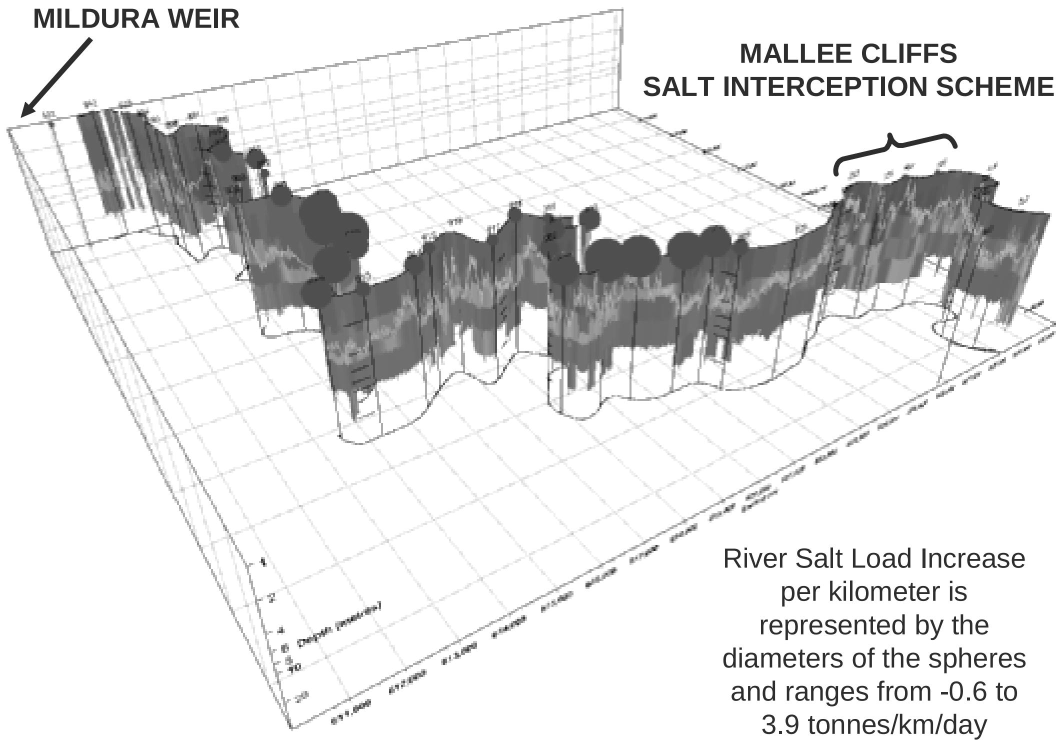
Figure 10.1 IX1D GEM-2 data interpreted with 3 layers; layered resistivities are fixed and only thicknesses are allowed to vary.

Multi-depth EC processing and visualization – Emigma V7.5

PetRos EiKon Inc. offer a package for processing and 3D visualization of data from many FEM, TEM, geoelectric and magnetic devices. The 3D visualization requires that data are collected across an entire grid.

3D imaging of EC data - Groundwater Imaging

The author of this document offers HydroGeoImager for inversion of waterborne or other continuously acquired geoelectric data. The software also offers visualization of that data and EM data in three dimensions using EC ribbons, as shown below (Figure 10.2), or as sets of depth slices. HydroGeoImager’s EC ribbon imaging facility permits almost instant 3D presentation of datasets collected along irregular tracks, logged using GPS.



MILDURA WEIR

MALLEE CLIFFS
SALT INTERCEPTION SCHEME

River Salt Load Increase per kilometer is represented by the diameters of the spheres and ranges from -0.6 to 3.9 tonnes/km/day

Figure 10.2 An example of 3D presentation of EC data collected beneath a river presented by the HydroGeoImager package.

11. CASE STUDIES 1 & 2 - APPLICATION OF GEOPHYSICAL METHODS TO IMPROVE KNOWLEDGE OF GROUNDWATER FLOW AND LEAKAGE FROM WATER SUPPLY INFRASTRUCTURE IN THE ORD AND BURDEKIN IRRIGATION AREAS

J. Clarke, K. Lawrie, A. Fitzpatrick, H. Apps, W. Lowis, M. Hatch, A. Price, P. Wilkes and D. Dore.

Overview

Existing hydrogeological models of aquifer systems in many areas do not explain in detail sufficient for land managers the patterns of groundwater flow between aquifers, surface waters, and irrigation and drainage networks. Better imaging and conceptualisation of subsurface hydrogeological parameters are a key part of improving knowledge of natural and man-made groundwater flow patterns. The Cooperative Research Centre for Landscape, Environments and Mineral Exploration (CRC LEME) has undertaken a wide range of studies using ground, in-river, down-hole, and airborne geophysics in conjunction with the best possible information of sedimentary architecture, surface materials, and landscape evolution to better map these flow patterns and their controlling factors. Two areas that typify such studies by the CRC have been those of the Ord and Burdekin irrigation areas (Clarke et al. 2006, Lawrie et al. 2006) as separate case studies.

Case study 1 – The Ord Irrigation area

Context

The Ord River Irrigation Area (ORIA) is a large-scale development of irrigation agriculture in northern Western Australia (Figure 1). The area consists of 14,000 ha of irrigated land (Stage 1), with a proposal to develop a further 20,000 ha (Stage 2). Key land and water resource management issues identified by the Ord Irrigation Cooperative (OIC) include the need for more efficient utilisation of irrigation water, as well as improved management of groundwaters, while minimizing the environmental impacts from processes such as the salinisation of soils and sub-soils, and the export of salt to the Ord River. Additional baseline data are also required to assist with planning for the proposed Stage 2 irrigation development. The Ord is recognised as a priority catchment within the National Action Plan for Salinity and Water Quality.

A number of studies have examined the hydrogeology and salinity of the region (O'Boy et al. 2001; Salama and Pollock, 2003; Pollock et al., 2003, Barr et al., 2003; Smith et al. 2005, 2006; Lawrie et al., 2006). Most recent studies have concluded that existing hydrogeological models of aquifer systems in the ORIA inadequately explain observed groundwater flows between individual aquifers, and between the aquifers and the deeply incised river system and drainage works (Smith et al., 2005). Post-1965 development has seen a substantial rise in groundwaters to within a few metres of the surface in much of the district (Salama et al., 2001). While there has been a hiatus and even a slight decline in groundwater trends in the last 4 years (Smith et al., 2006), generally shallow groundwater tables have led to increased evapo-transpiration in the sub-surface, and salt accumulation (and sodicity) in soil profiles (Ali and Salama, 2003). Overall, salinity poses a potential hazard to crop productivity, the increased mobilization of solutes in the soil profile by irrigation waters, and increasing salt load in the river (Pollock et al., 2003).

New insights into the lateral and vertical connectivity of the aquifer systems are required to assist with groundwater management. Similarly, new insights into the three-dimensional architecture of soils, sub-soil clay units, and sand and gravel aquifers are required to better understand the extent of surface-groundwater interactions, and to identify preferential recharge and infrastructure leakage in the landscape. This information is essential for improving the management of surface water, groundwater, salinity, and broader environmental management.

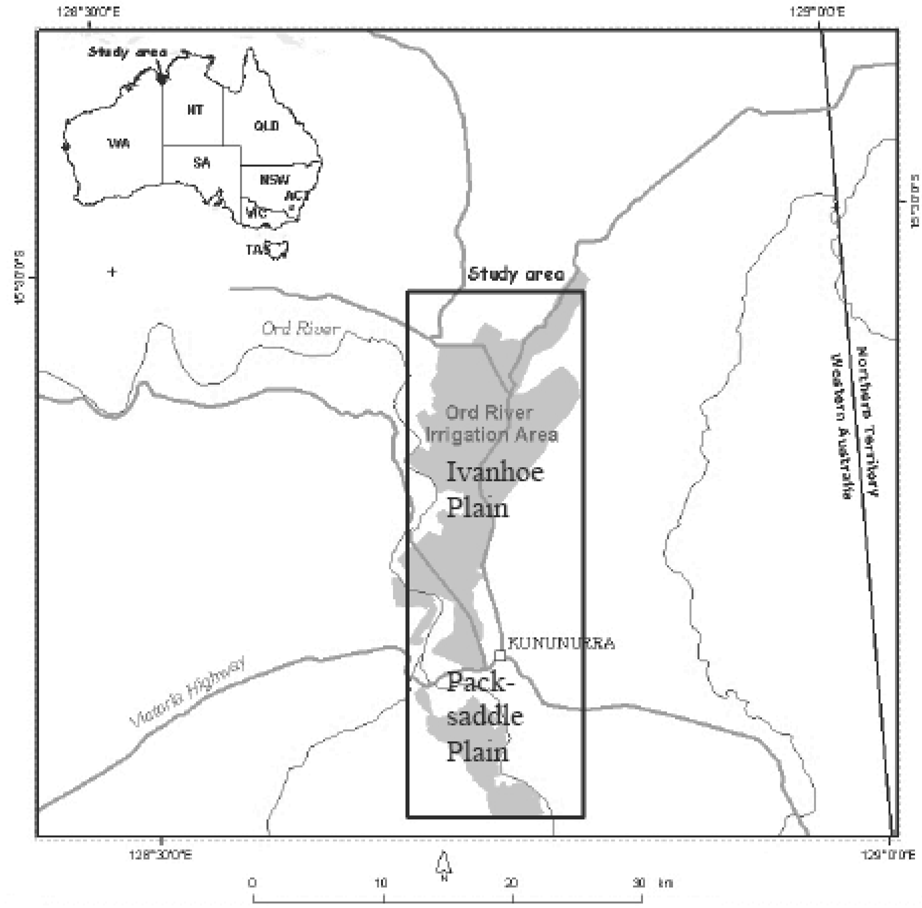


Figure 1. Ord River Irrigation Area, Stage 1

In late 2005 the Cooperative Centre for Landscape Environments and Mineral Exploration (CRC LEME) was commissioned by OIC to carry out a pilot study to assess existing hydrogeological data and knowledge gaps, and to assess the suitability of using ground and airborne electromagnetic (AEM) techniques to delineate aquifer systems, to map water quality variations, and identify zones of preferential recharge including infrastructure leakage. A reassessment of aquifer stratigraphy and connectivity was also undertaken. This paper presents some of the findings of this study.

Study results

As part of the pilot study, a re-assessment of aquifer stratigraphy and connectivity was undertaken, building on some excellent previous studies (eg O'Boy et al., 2001). The floodplain of the Ord River is a relict feature. This is shown by the incision of the channel down to bedrock (Figure 2a-d) and the dissection of the floodplain by gullies feeding into the present river. Flooding of the plain by overbank flow from the Ord River has not occurred during the period of European occupation, water build up during major rainfall events has been from tributaries and ponded rain.

O'Boy et al. (2001) constructed a hydrogeological framework for both stage 1 and 2 of the ORIA. In the sub-surface the total alluvial succession is 30-35 metres thick, of which up to half is composed of gravels, with sand a minor component. Of the remainder half is silty sand to sandy silt, and the other half clay-rich brown and black soils.

Three main stratigraphic units define the sub-surface aquifer systems. In general there are coarser-grained sand and gravel layers at the base, fining upwards to clay-rich soil layers. These results show that, despite the abrupt change in hydraulic conditions as the palaeo-Ord River emerged from its bedrock channel to the south and flowed out onto the valley now occupied by the Ord floodplain, the river did not deposit a recognisable fan or even a northward fining sediment fill, but rather maintained the capability for high energy flow and gravel transport along the length of the valley. This has important implications for local and regional scale modelling of the aquifer systems.

As part of this study, cross-sections derived previously from mineral exploration drillholes and groundwater boreholes (O'Boy et al., 2001), were redrawn using an approach more consistent with contemporary ideas on the depositional processes and architecture of river-lain sediments (Figure 2a-d). The spacing of borehole information is close enough to give a relatively good control on the subsurface architecture of the sedimentary units, although interpretation is reliant on descriptions of varying detail and quality. From these cross-sections it is evident that fluvial architecture is highly variable down the length of the Ord floodplain. Payenberg and Reilly (2003) and Makaske (2001) have demonstrated that the thickness to width ratios of sand and gravel bodies in the subsurface can be used to differentiate the type of channel that formed them. Braided, meandering and fixed channel systems are typically >300, 100, and 10 times wider than they are thick, respectively (see also review by Gibling, 2006). On this basis, all but one of 10 cross-sections re-examined for this study show the basal gravels with thickness to width ratios consistent with deposition in meandering gravel-bed channels. The exception is section F (Figure 2d), where the basal gravels are narrow; consistent with fixed gravel-bed channels (see Nanson and Young, 1981). Such changes in channel architecture along a river are not uncommon, and can be seen in the lower reaches of the Ord today (Coleman and Wright, 1978). This reinterpretation of fluvial architecture has important implications for how connections between sand and gravel aquifers are interpreted.

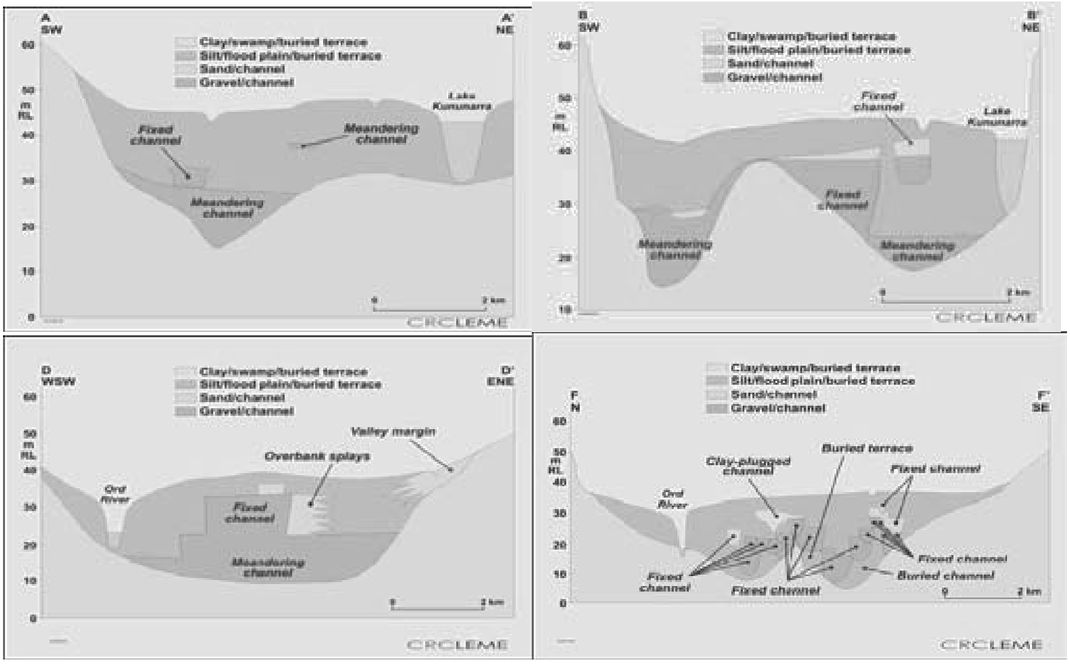


Figure 2. Figure 2a-d (Sections A, B, D and F respectively). Interpreted geological cross-sections of the Ord River valley-fill. Sections A and B are in the southern part of the area (through Packsaddle Plain), while sections D and F are through Ivanhoe Plain.

Also evident in the cross-sections is the complexity in the bedrock surface beneath the Ord floodplain. Structural analysis of adjacent rises and outcrops on small hills within the floodplain suggest that much of this complexity is due to past tectonic activity. It appears that some of the small rises in the floodplain may be connected in the sub-surface as fault-bounded blocks. This complexity in subsurface relief has considerable implications for the compartmentalization of aquifers, and the direction of groundwater flow in the gravel aquifers in the base of the alluvial sediment in the northwest of the Stage 1 area in particular.

Fig. 3a

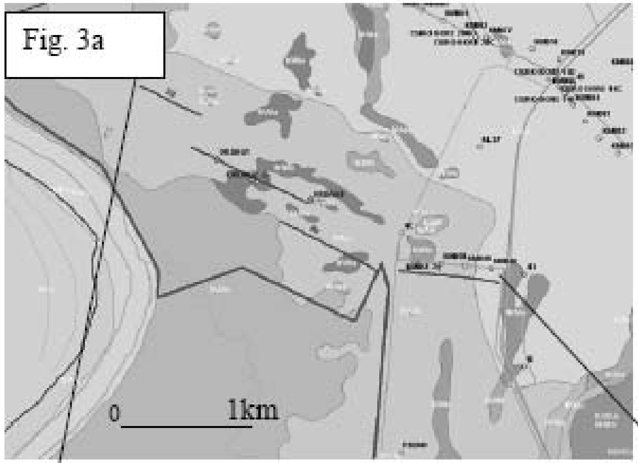


Figure 3a and 3b show the location of off-set nanoTEM transects in northern Ivanhoe Plain, draped over the regional soil map. Figure 3c is the nanoTEM conductivity data displayed in cross-section. More conductive layers are in reds, resistive layers in blue. Conductive clay-rich soils and sub-soils, are underlain by a layer of silty sands, with few discrete sand palaeo-channels (blue) evident.

Figure 3b

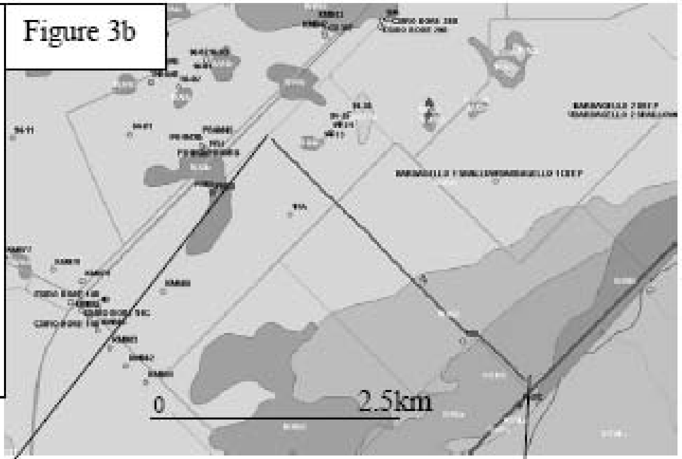
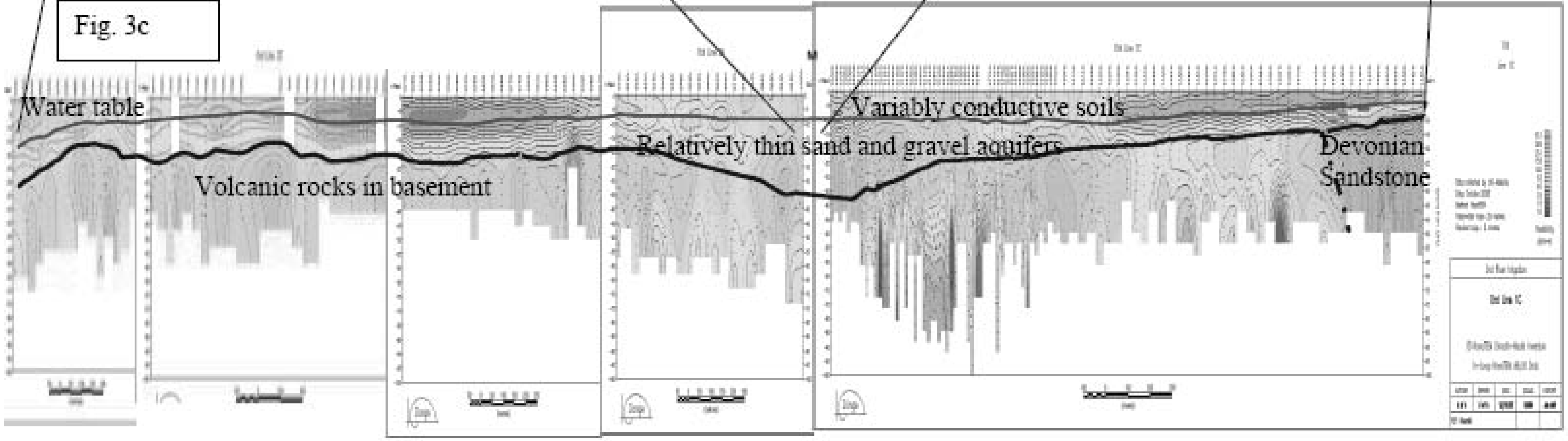


Fig. 3c



Case Studies 1 & 2 – Groundwater flow

Fig. 4a

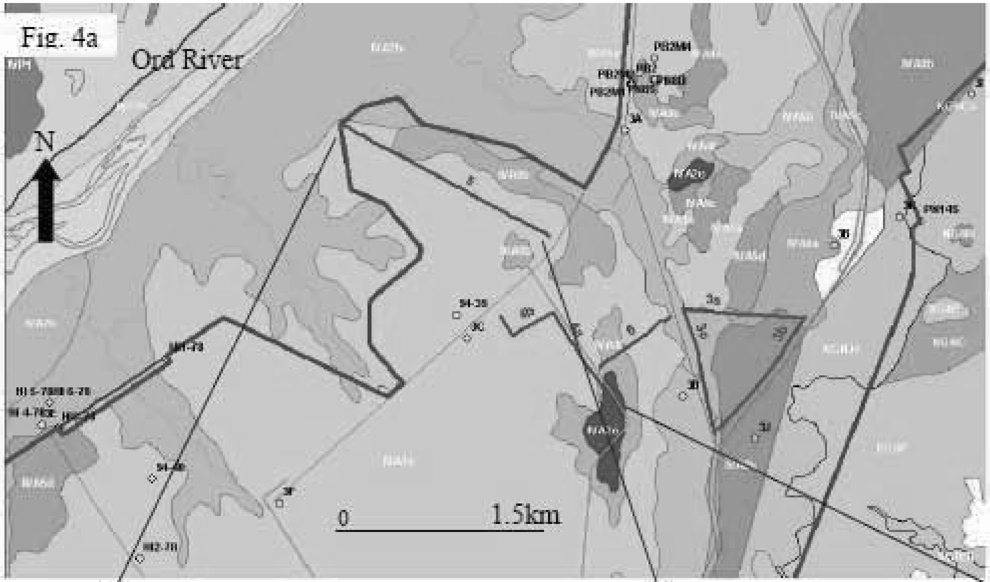
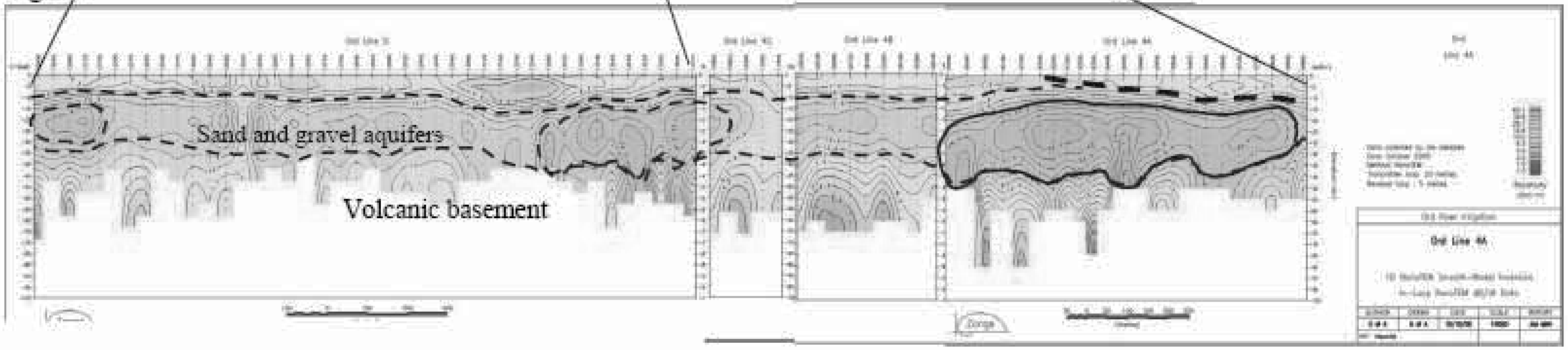


Figure 4a shows the location of nanoTEM transects (purple lines), in Central Ivanhoe Plain, plotted on top of the regional soils map. The boundaries of the ORIA Stage 1 are marked in red.

Figure 4b is the nanoTEM conductivity data displayed as a cross-section. More conductive layers are in reds, resistive layers in blue. Three layers are evident: a top layer of variably conductive clay-rich soils and sub-soils, underlain by a layer where discrete sand and gravel-filled channels (blue) lie within silty-sandy layer. These are underlain by volcanic basement.

Fig. 4b



In addition to a reanalysis of the sediments, a number of ground electromagnetic (EM) geophysics transects were acquired in the ORIA Stage 1 area. These data were used to assess the ability of ground and AEM techniques for delineating aquifer systems, map water quality variations, and recharge and infrastructure leakage. A NanoTEM instrument, using a 20 m square loop array provided conductivity data to depths of 40 - 50 m beneath the surface. Data were acquired in three staggered traverses, with total traverse length of approximately 13 km. Traverses were chosen to provide cross-sections across the central and northern portions of the Ivanhoe Plain, and as close to irrigation infrastructure as possible to assess leakage. A more regional program of borehole geophysical logging was also undertaken.

Examples from two traverses are shown in Figures 3 and 4. Major differences between the two sections are evident, with more discrete sand and gravel palaeo-channel aquifers in the central Ivanhoe Plain sections (Figure 4) compared with the section further to the north in Figure 3.

These data suggest a lack of longitudinal continuity in individual sand and gravel aquifer bodies in the central northern Ivanhoe Plain. This is common in aquifer units immediately overlying bedrock and is consistent with hydrogeological data (Smith, pers. comm., 2006). Furthermore, the variation occurs at a scale that is smaller than typical borehole spacing. Simply “dot-joining” of lithological units encountered in drilling may result in incorrect correlations being made.

In these conductivity sections, most of the mapped variability at depth is explained by texture contrasts (eg between gravels and clays) rather than water quality variability. While there is insufficient contrast in water quality, and therefore insufficient electrical contrast between surface and groundwaters for EM techniques to map water quality variations and channel leakage directly, EM techniques, such as NanoTEM, map materials very well in this area, and recharge and channel leakage can be predicted based on the juxtaposition of sand and gravel aquifers with irrigation infrastructure. In contrast, EM31 and EM 38 shallow geophysical surveys and associated studies of soil salinity profiles revealed a high degree of variability in soil and shallow sub-soil conductivities across the floodplain (Richards, 2002). These results reinforce the need for ground validation of survey results, particularly in the top 5 m in the Ord floodplain.

Case study 2 – the Lower Burdekin

Context

The Burdekin Irrigation District in North Queensland (Figure 5) is the oldest irrigation area in Australia. Natural flows along the river have been heavily modified by dams and barrages and there has been extensive groundwater extraction. This has resulted in intrusion of marine waters into sub-surface aquifers, despite extensive use of artificial recharge. Management of salt water intrusion in the coastal zone and integrated management of surface and groundwaters throughout the District have previously been hindered by a lack of a 3D understanding of aquifers and aquitards, and a poor understanding of the dynamics of groundwater movement and surface-groundwater interaction.

Previous studies have defined the Burdekin Delta as a wave or mixed wave-tide delta, and more recently as tide-dominated. However, these studies concentrated on the Holocene coastal fringe of the system. The geometry and proportion of sand and gravel bodies implied by these models have provided important constraints for hydrogeological modelling of sub-surface aquifer systems. This paper summarises new insights into the 3D geometry of the aquifers that have come from studies of the sub-surface sediments and the results of ground and in-stream EM surveys which have been used to map water quality variations, and hence map infrastructure leakage and recharge of aquifer systems in some areas.

Surface geomorphology

The scale and distribution of geomorphic features on the surface can often provide a guide to likely distribution, scale and connectivity of aquifers, at least in the shallow sub-surface. The recent acquisition of airborne laser scanning data has resulted in a new, high resolution digital elevation model (DEM) over the Burdekin Delta that reveals many subtleties in the landscape that were not available to earlier researchers. This dataset has revealed a complex geomorphology in the Delta that was previously only partially mapped. Depositional features include first, second, and third order lobes and channels. First order lobes (Figure 6) are 3-8 km wide and 12-20 km long, 2nd order 3 km long and 1 km wide, and 3rd order 1 km long and <1 km wide. First order channels are ~500 m wide, 2nd order 100 m wide, and 3rd order less than this. Only the main incised channel is active, the others are relict features. The depositional lobes and the incised channel together comprise the “upper delta plain” of Fielding et al. (2005). The only part of the Burdekin Delta complex that is currently active is the “lower delta plain” of Fielding et al. (2005).

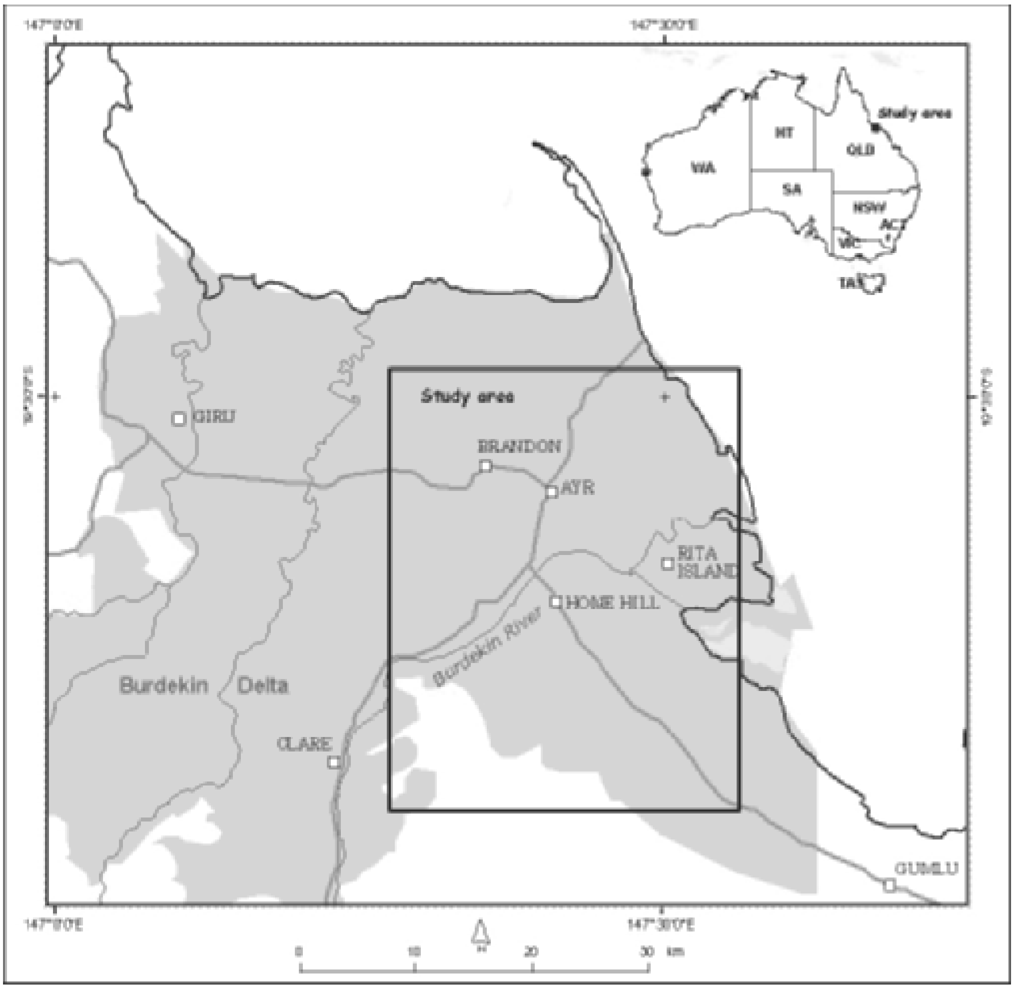


Figure 5. Location of the Lower Burdekin Delta.

The Burdekin as a fan delta complex - hydrogeological implications

Previous workers classified the Burdekin as a wave (Galloway 1975), wave and tide (Coleman and Wright 1975), or tide-dominated (Ryan et al. 2003) system, because they mainly studied the coastal zone rather that the whole delta. However, when seen in its overall context, there are three reasons why the lower Burdekin has the characteristics of a fan delta (Nemec 1990, Nemec and Steel 1988). These include:

The sediments are poorly sorted and both texturally and compositional immature.
Sedimentation is dominated by short-lived episodic high volume, bed-load dominated flows.
The morphology of the delta, especially that of the upper delta plain, with its distributary depositional lobes and entrenched main channel, closely resembles that

found on many fans.

Recognition of a fan-delta origin and geometry for the Burdekin has major implications for modelling of groundwater flow in the irrigation region, whether for groundwater resource estimation, artificial recharge calculation, or managing salt water intrusion. Previous interpretations emphasised the presence or absence of interstitial mud and represented the succession as mud-dominant, with isolated channel sands. Fan-delta geometry implies the reverse, with isolated lenses or drapes of mud locally separating stacked bodies of gravelly sand. The greatest variability in hydraulic properties is likely to be down fan, with variations of approximately 14 orders of magnitude predicted in fan systems (Neton et al. 1992). This contrasts with conventional deltas where variability is greater cross the distributary system. The implications of this new model are to be explored in future studies.

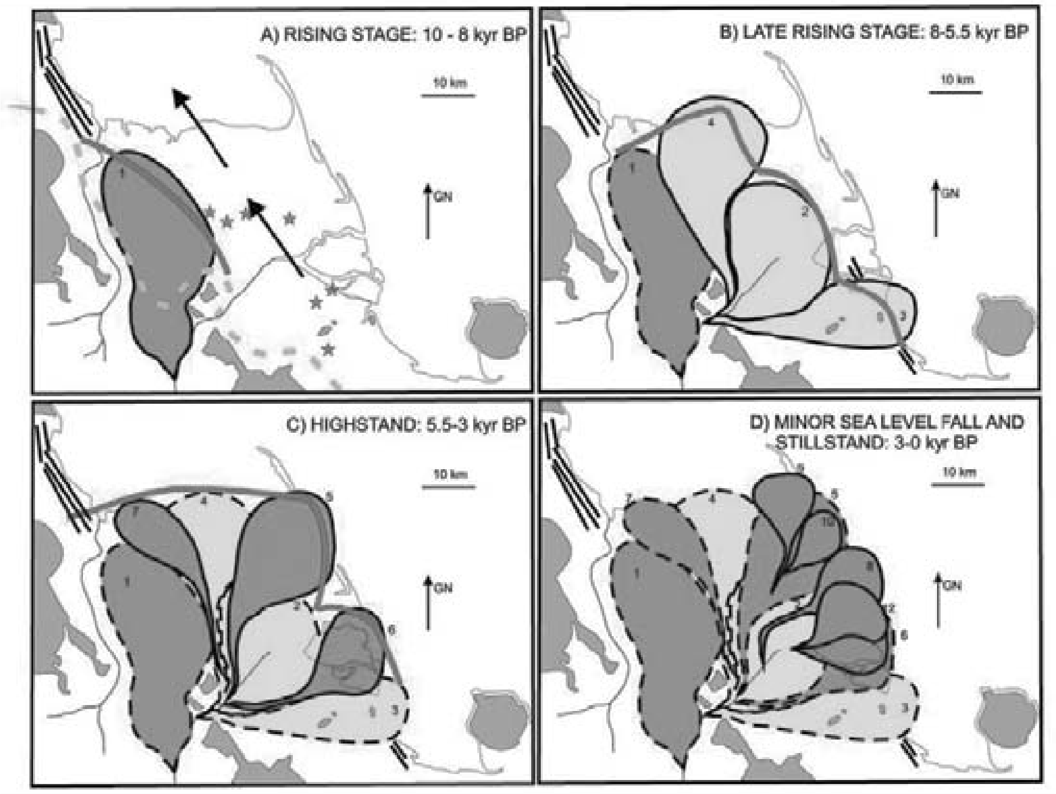
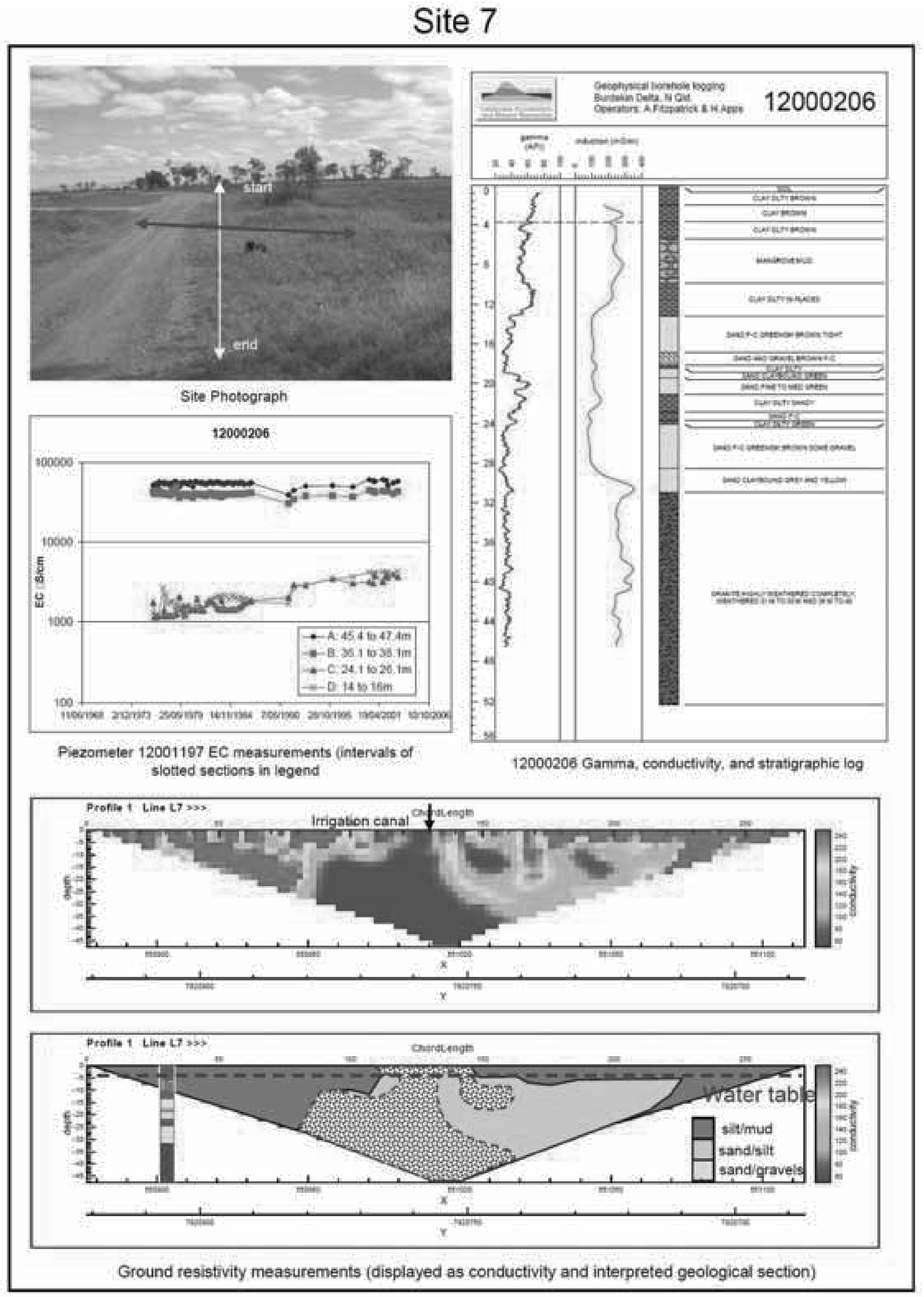


Figure 6. Evolution of the delta lobes over the last 10,000 years (from Fielding et al., 2006)

Geophysical surveys

Initial down-hole EM and gamma borehole logging (Fitzpatrick et al. 2004) showed that these methods greatly improved the understanding of aquifer characteristics. More recently, ground resistivity measurements were collected within the southern portion of the Burdekin Delta to investigate the spatial variability of groundwater quality, and assess whether it was possible to map surface-groundwater interactions (eg leakage from waterways). Several ground resistivity survey transects were acquired on land, and in canals and the Burdekin-river. These surveys mapped conductivity variations on the scale of several 10’s to 100’s of metres. These variations, when calibrated against boreholes, allowed discrimination of different sedimentary units such as clays and sands, and also waters of differing conductivities. Resistivity surveys allowed identification of freshwater leakage from irrigation infrastructure into relatively more saline groundwaters (Figure 7). In Figure 7, the resistivity data indicate the presence of the clay unit identified in the borehole log. A strong resistive anomaly occurs beneath the canal, and this correlates with an area of deliberate canal leakage that is being used to recharge the aquifer. The strong boundaries of the anomaly suggest the leakage occurs in a sand rich zone, bounded by silt rich units, especially on the left side of the resistivity transect. A near-surface conductor occurs on the right of the transect reflecting a well-developed clay unit.



Site Photograph

Piezometer 12001197 EC measurements (intervals of slotted sections in legend

12000206 Gamma, conductivity, and stratigraphic log

Ground resistivity measurements (displayed as conductivity and interpreted geological section)

Figure 7. Site 7 ground resistivity survey, EM conductivity log, groundwater EC and interpretation showing inferred architecture of sediments and canal leakage.

Conclusions

We believe these two case studies outlined in this paper show that integrating a range of geophysical methods (such as ground and borehole surveys) with a re-examination of soil and regolith data have demonstrated that specific EM techniques can successfully delineate sand and gravel aquifers, clay-rich layers, and the regolith-basement interface. Where there is sufficient contrast between the ground conductivity and that of the groundwater, whether naturally occurring or present through infrastructure leakage of deliberate recharge, EM methods can also map the subsurface distribution of different groundwater masses.

While acquisition of AEM data is recommended, scale, technology choice and survey design are critical. More generally, a key to the successful use of airborne geophysics for salinity and groundwater mapping and management is identification of the key management questions, integration of AEM data with appropriate hydrogeological data, and incorporation of interpretation products into hydrogeological models and broader NRM strategies. Catchment Managers will benefit from these data types, while some farm-scale benefits will also be derived.

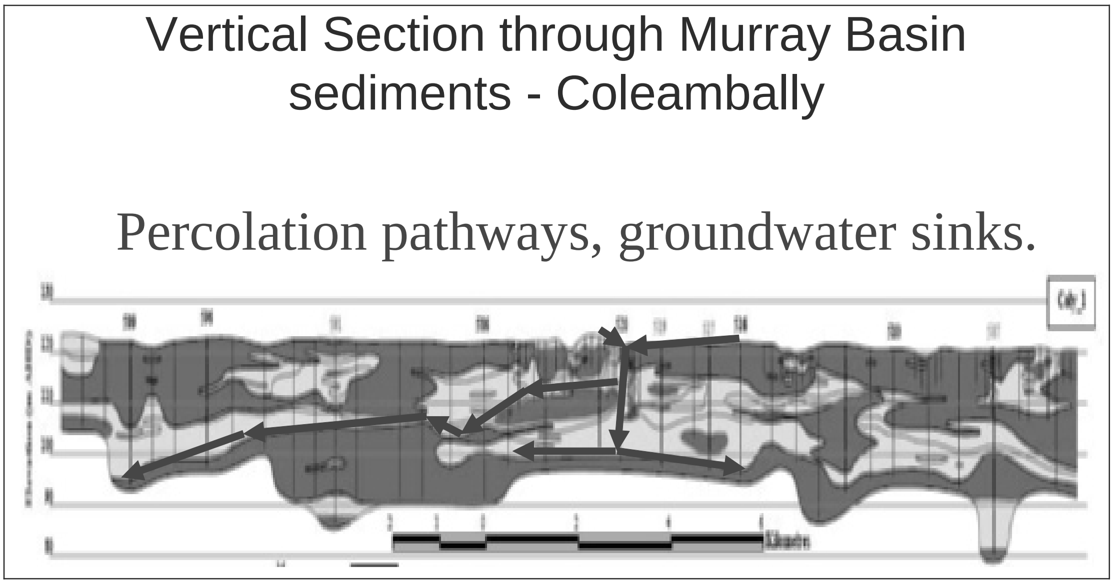
12. CASE STUDY 3 – SEEPAGE PATHWAY IMAGING

by David Allen

The author recently completed a PhD on Electrical conductivity imaging of aquifers beneath water courses, focussed in the Murray Darling Basin, Australia. This case study is an extract from that work.

The nature and significance of canal seepage

Seepage from irrigation canals in Australian Irrigation Areas has contributed to waterlogging and has been costly due to delivery inefficiency. While most Australian canals are old and have silted up and sealed well, there may still be very isolated seepage hot spots that can be fixed economically. Such sites normally combine a poor canal seal with a groundwater escape route such as a prior stream channel sand/gravel deposit which is well connected to deeper prior stream sand/gravel deposits. Such geological features have been investigated in detail under Coleambally Irrigation area and a vertical section through them is presented in Figure 12.1.



Vertical Section through Murray Basin sediments - Coleambally

Percolation pathways, groundwater sinks.

Figure 12.1 A documented example of the nature of percolation pathways in the upper Shepparton Formation such as exists under many of the Murray Darling Drainage Basin irrigation areas (Modified from Pucillo, 2005).

Percolation pathway geophysical imaging

Problematic sites can be identified geophysically by imaging EC because EC is dependent on sediment clay content, and, therefore, permeability. Where seepage has been prolific, fresh canal water has flushed salt from sediment beneath the canals which has further reduced EC. Under some canals, sandy sediment will be almost dry resulting in very high EC. Use of multi-depth EC imaging helps to distinguish the various causes for the EC anomalies. If a submersible geoelectric array is used, then higher resolution can be obtained at the canal bed. If a water depth sensor is used with the array, then anomalies in the data can be interpreted with increased confidence and clarity.

Identifying active and dormant seepage pathways

EC imagery may be good at spatially identifying historic seepage sites but it cannot determine at what rate seepage continues to occur. Seepage Penetration Observation Tubes (SPOTs) can estimate seepage rates at isolated sites chosen using EC imagery. They were developed in an attempt to economically evaluate Locally Observed Seepage Sites (LOSSes). The process has been summed up as 'SPOT the LOSS'. Accurate seepage quantification requires pondage tests, however, partly because a SPOT placed in a canal bed will not detect seepage in a canal bank or elsewhere in the bed. SPOTs can be installed at a small fraction of the cost of pondage tests and therefore provide a rough but cost effective estimate of seepage rates. Idaho seepage meters and other similar meters may be substituted for SPOTs but they introduce air bubble retention and other complications that tend to make measurements much less reliable. This unreliability becomes particularly troublesome when measuring extremely low seepage rates such as exist in most Australian canals. The extreme simplicity of SPOTs eliminates such causes of data unreliability.

Methodology

Specialized Geoelectric Array Design

Geoelectric arrays were selected as the most appropriate device for imaging EC beneath canals. Principles of operation of floating geoelectric arrays are presented in Chapter 7. Submerged arrays operate in the same way except that the electrodes are within the media they are investigating rather than on the surface of it.

Two Geoelectric arrays were used – one 40 m long submerged array capable of imaging to 7 m deep and one 144 m long floating array capable of imaging to 40 m deep. The floating array was used, with a boat, on long stretches of larger canals where there were few obstructions. Obstructions are costly when using a 144 m long array as the whole array needs to be lifted over each obstruction. On the other canals, a submerged geoelectric array was used with electrodes placed so that 7 effective depths ranging from 0.1 to 6 m below the canal bed could be imaged with adequate signal strength being present in each configuration. Effective depth is defined as the depth from above which 50% of signal received by an array configuration is contributed if the array is situated on the surface of a homogeneous half space. Software (HydroGeoImager – see Chapter 11) was especially designed for processing data from such arrays.

The floating array has been designed so that it slides past obstacles easily and has minimum drag that causes problems with cross track drift when cornering. The submerged array has been designed so that it can slide along the canal bottom and up over obstacles such as regulators and fences without getting caught frequently. Both arrays were kept maintained at all times so that their insulation, and conductor continuity integrity did not affect data being acquired.

Towing devices

Productive towing of geoelectric arrays along canals requires specialized towing devices. Channels are obstructed at irregular intervals by fences, checks and vegetation. Aquatic weed, that fouls outboard motors, fills much of channels. Vehicular bank access varies but many canals can be surveyed using a boom extending 4 to 6 m from the side of a 4WD. A lightweight, foldable boom that is able to be raised with a reach of 6 metres was used (Figure 12.2). The boom is made principally of PVC and aluminium tubing encasing wooden dowel fitted together in a 3D truss arrangement. A spring mechanism has been included for situations where the array becomes caught. When folded against the side of the vehicle, the boom and vehicle are of legal height and width for public road travel. For large canals and for canal segments where bank access is poor, a boat must be used. An airboat was found to be appropriate where problems with shallow water and weed existed. The boat can be coupled with a 2 m reach crane for lifting it over regulators and fences and for launching/retrieving it off steep high canal banks.

Figure 12.2 A foldable boom with a 6 metre reach, ability to straddle small trees and capable of towing geoelectric arrays using a spring attachment. The boom is raised/lowered using an electric winch on the roof.

Geoelectric transceiver specifications

Various geoelectric transceivers were utilized, including a Terraohm RIP924b with an ABEM SAS2000, Zonge GDP32 with a ZT30 transmitter (from Zonge, S.Aust.), and an Iris Instruments Syscal Pro (from Geoforce, WA.). The transceivers measured the signal coming from the 7 and 8 electrode combinations simultaneously and were able to stack data into stored records approximately every 10 seconds.

When using the Terraohm RIP924b, the operator was able to view the data being acquired as a graphical display on a handheld Panasonic Toughbook WiFi touchscreen.

Canal depth measurement

Canal depth is used in generation of electrical conductivity imagery and therefore was measured. A Greenspan PS700 pressure sensor was supplied for the surveying. A Garmin GPSMap188 sonar device with a blanking distance of around 1.1 metres was used simultaneously on the deeper canals. Depth sampling occurred at least once every 15 seconds.

Survey track logging

Survey vehicle track was logged at regular intervals of time or distance using various global positioning system receivers with and without differential correction. During times of poor GPS constellation orientation, the operator paused surveying.

Speed of coverage did not exceed 9 km / hour to reduce geoelectric noise caused by turbulence around the measuring electrodes. An attempt to maintain a speed of less than 5 km/hour was made.

Processing
Data from all the relevant devices was merged together using interpolation and extrapolation where necessary. Position data was written in WGS84 UTM(MGA94 equivalent at the accuracy of the DGPS that will be used). Data was created in tabular format in dBase files suitable for importing into ArcGIS and Google Earth products as specified in Allen (2005).

Position was corrected for geoelectric array midpoint and boom offsets taking into account the meandering survey path and GPS accuracy.

Data was filtered for under-current, under-voltage, over-voltage and excessive array curvature as appropriate.

Submerged array data was converted to layers of electrical conductivities centred on effective depths of each array configuration. The formula for submerged array apparent resistivity was used.

Floating array data underwent the iterative process of inversion whereby the response of numerous layered theoretical models was calculated and compared with each field sounding until a good match was achieved.

SPOTs

Seepage penetration observation tubes were inserted in the most prominent seepage pathways identified and monitored several times over a period of months. Some that were found to drain quickly had to be monitored over shorter periods. Alarmingly, some had to be monitored over a period of only hours. A SPOT installation is presented in Figure 12.3 and various SPOT interpretation scenarios are presented in Figure 12.4.

Figure 12.3 A SPOT. Note that the water level was originally at the level of the ‘hook’ on the wire in the tube and has fallen over a period of a few days while the canal level remained approximately constant.

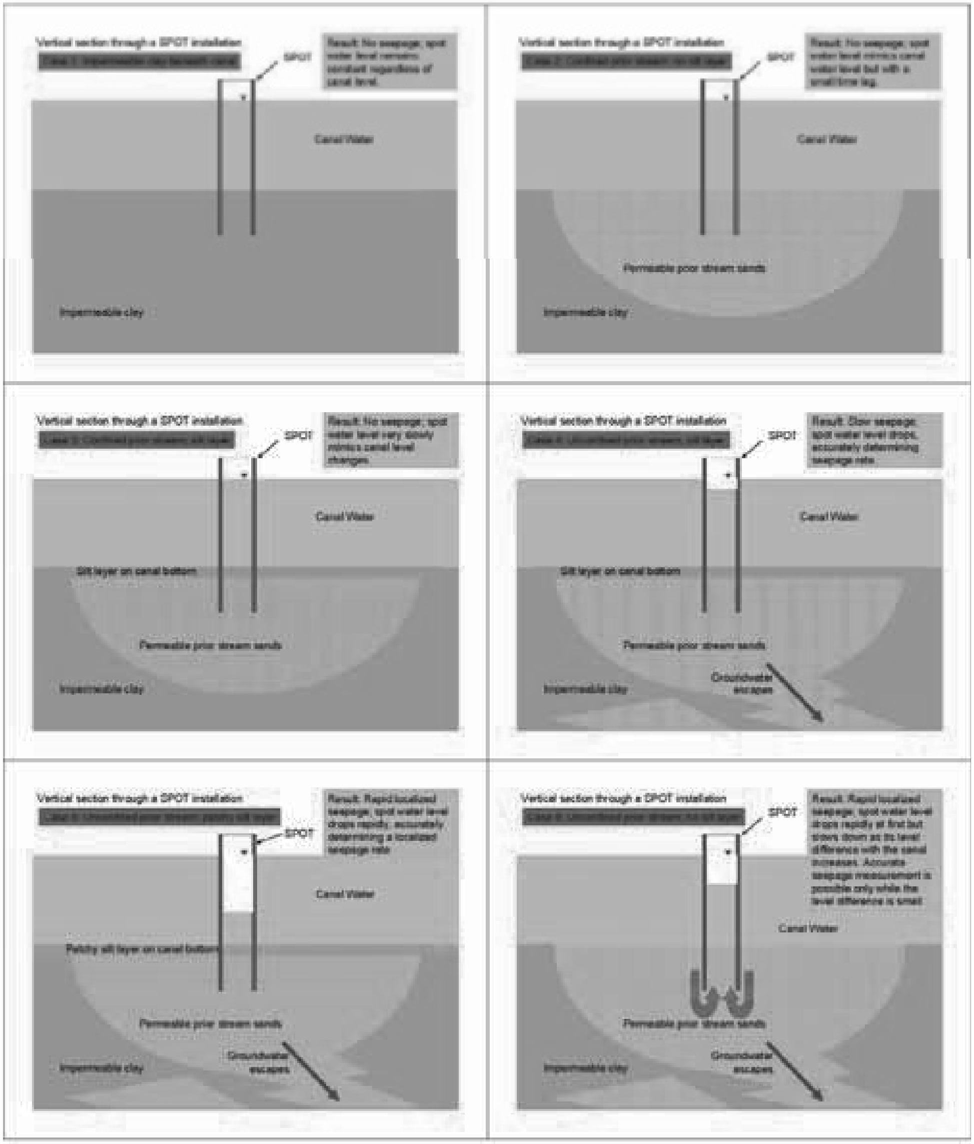


Figure 12.4 SPOT scenarios showing what is measured in each scenario. Note that the scenarios

that accurately measure seepage are most common in irrigation canals.

Results

Hundreds of kilometres of canals were effectively surveyed during the course of the PhD and most seepage sites found were dormant and isolated. A few however were active and Figure 12.5 presents one such site adjacent to the Murrumbidgee River at the Gogeldrie Weir (near Tom Bullen Storage between Hay and Narrandera). The figure shows how, at this site, there is no impediment to seepage evident at least 40 metres beneath the river and adjacent canals. On the left of the image, higher EC values indicate clays and saline perched water typically present under the adjacent irrigation areas.

Figure 12.6 is a zoomed in view of the vertical section obtained with a submerged array just near the offtake from the river. Seepage rates identified using SPOTs are superimposed. Figure 12.7 presents calculations that give an estimate of the amount of water lost from the seepage site identified. Pondage testing would be required to give a reliable estimate of seepage but this is difficult to arrange on a large major supply canal.

This canal has been deflected here in order to cross a prominent high permeability prior stream. Shallow groundwater pumping from prior streams such as this one in times of high water demand is logical.

Figure 12.5 EC imagery collected using a floating geoelectric array towed along the Coleambally Main Canal (funding provided by the Rice CRC).

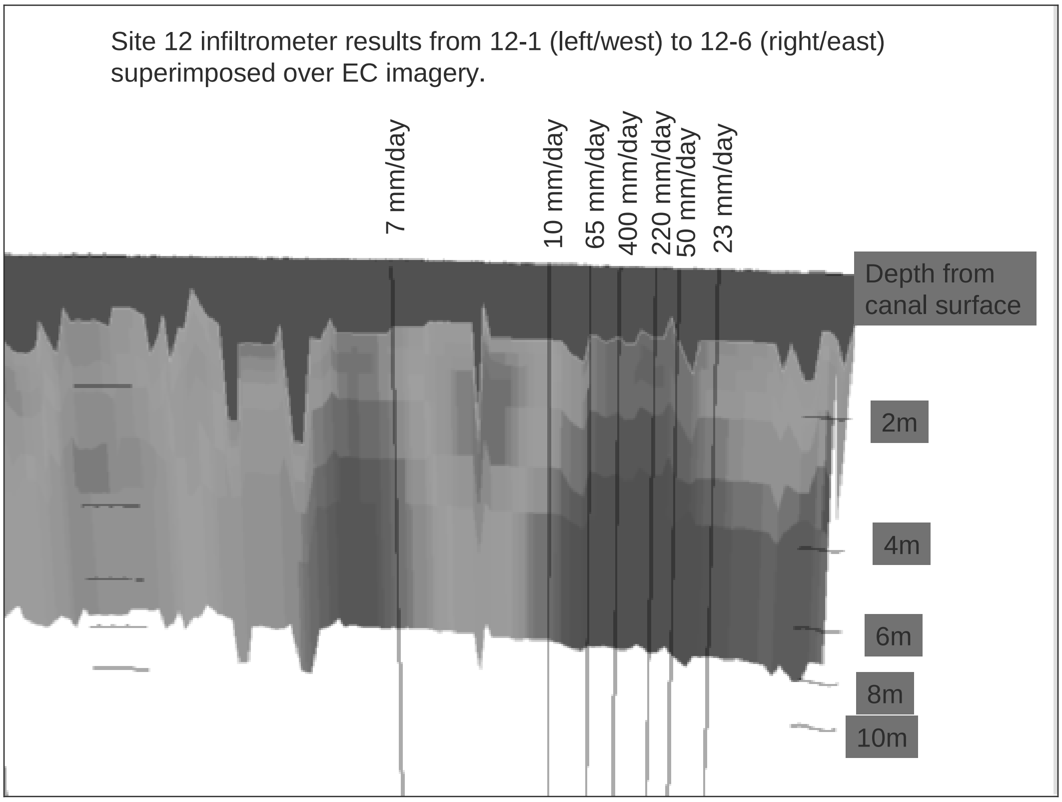


Figure 12.6 A zoomed in view of a seepage hot spot near the river offtake in the canal of figure 12.5 (funding provided by Coleambally Irrigation Cooperative Limited).

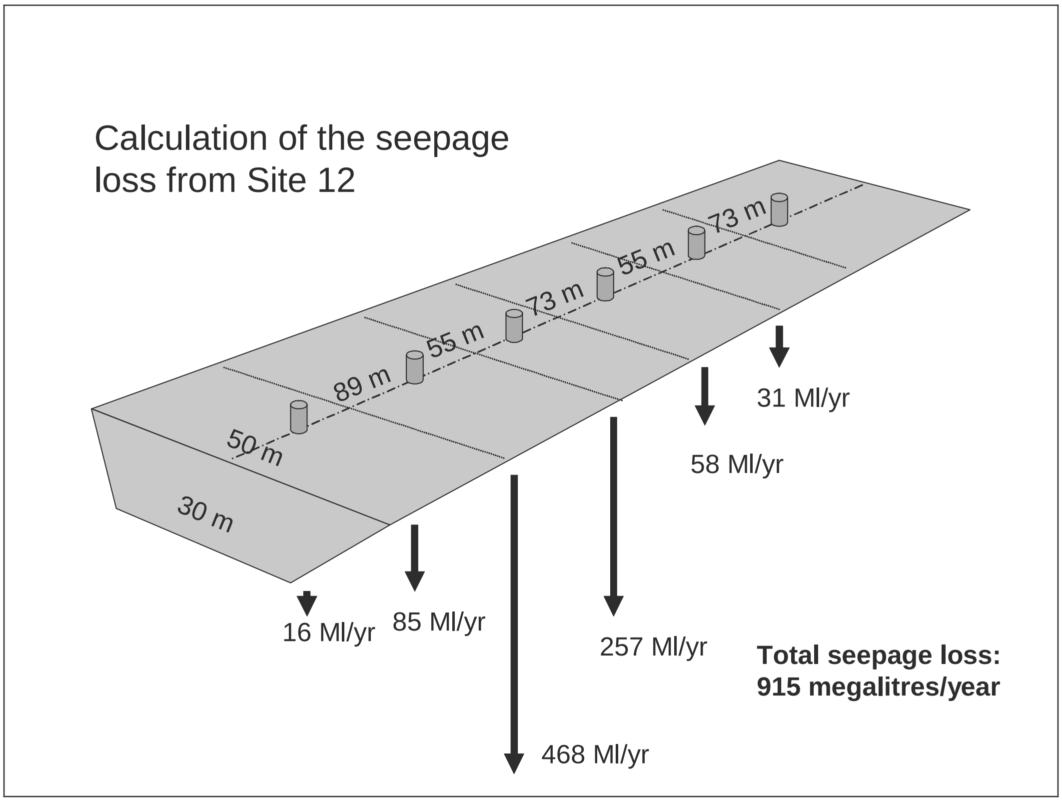


Figure 12.7 Calculation of seepage loss using unreliable SPOT seepage rates collected at the site shown in Figure 12.6. Expensive pondage testing would be needed to give reliable seepage loss estimates.

High seepage rates suggested by SPOTs were always found to correspond with low EC anomalies in imagery collected along the canals. SPOT behaviour was, however, erratic at such sites. SPOTs placed metres apart would respond very differently. Some SPOTs seeped rapidly then ceased to seep. This behaviour suggested that thin delicate silt layers on canal bottoms are playing a big part in abating seepage losses. Cores taken from canal beds always identified sands and gravels at sites where low EC was detected but at many sites the top of the sands was clogged with silt (Figure 12.8). Figure 12.9 presents a dormant seepage site.

Figure 12.8 Coarse Sand of a prior stream evident under the kink in the canal presented in Figure 12.5. Three x 700 mm samples with 100 mm of silt impregnation at the tops (Right) are displayed.

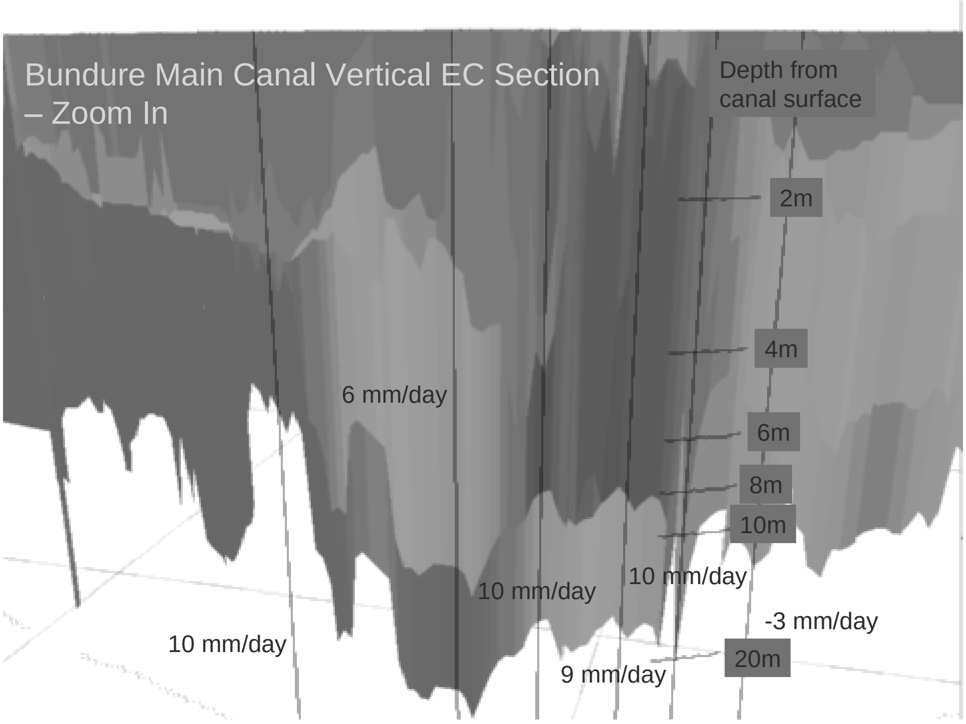


Figure 12.9 An example of a relatively dormant seepage site with SPOT results superimposed. A prior stream is clearly evident (blue area) in the 3D zoomed in view of EC data beneath the canal but canal siltation has almost completely prevented seepage at this site. The depth of the bottom of the image is erratic due to clipping of low SNR data.

Conclusion

Isolated seepage sites can clearly and efficiently be identified by electrical conductivity imaging but the imagery does not show if the sites are currently active or dormant. Multi-depth imagery is useful for removing ambiguity related to canal depth, width and water salinity. It is useful also for identifying the depth of percolation pathways and their interconnectivity with deeper aquifers. Submerged arrays can identify clay lining at some sites due to their ability to resolve clearly just beneath canal beds but generally cannot identify silt dropped from water flowing through the canals.

The detail provided by multi-depth geophysical imagery collected beneath water bodies is not only useful for focussing seepage remediation but may potentially be used for development of deep percolation pathways as part of managed aquifer recharge and recovery projects.

13. CASE STUDY 4 – SOIL MAPPING ASSISTED BY GEOPHYSICAL SURVEYS

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Abstract

Increased water costs and deregulation of the dairy industry will eventually force a change in land use in areas previously managed as irrigated pasture. The Harvey Irrigation Area south of Perth in Western Australia is an area undergoing these changes. Lying close to the Darling Fault scarp which separates the Perth Basin from the crystalline rocks of the Yilgarn Block the area has highly variable soils. In order to guide future land use detailed maps of soils are needed. A 2000 hectare section was mapped with ground gamma radiometric and electromagnetic conductivity instruments. The collected data have been analysed for detailed soil mapping. At least 10 separate classes can be separated from the geophysical data. The classes were field checked and shown to have observable differences in texture and texture contrast between horizons. The analysis of the geophysical data shows fine detailed patterns in the final maps that reflect the variability of such an environment. Such detail could not be achieved using conventional soil mapping techniques. Final products from this study include maps of texture differences, drainability of soils and soil textures. The data can now be used to guide future land use and for land management. The advantage of the classification of geophysical data is the ability to identify detailed distribution of agriculturally important soil characteristics. This provides land managers with the information about the agricultural capability of the land. It also allows issues such as poor drainage on land classes to be addressed by improved drainage or other forms of management.

Introduction

A good knowledge of the spatial distribution of soil types can improve efficient water delivery in irrigated agriculture. Many irrigation areas, developed on alluvial soils, have highly variable soils with major differences in drainage capability within individual management areas. Conventional soil mapping involving digging of pits and physical examination of soils can be tedious and labour consuming. Digital soil mapping techniques using geophysical measurements of differences within the top 1 metre of the ground offer a faster method of mapping differences in the physical characteristics of the soil. Once boundaries of units are defined then further refinement of a 'soil map' can be made by field sampling within each of the units identified. The technique combines a rapid measurement of physical differences of soils to create soil "classes" followed by field investigations to assign soil types to the classes.

In this study in the northern part of Harvey Irrigation Area in Western Australia (Street et al., in prep.), a combination of gamma radiometric, electromagnetic conductivity and digital terrain data were used to prepare a map of soil classes. The data were collected rapidly using instruments mounted on a quad bike linked to a GPS. The initial data analysis and preliminary soil mapping were done using a GIS system. Follow-up ground investigations assigned observable differences in soil type to each of the classes. Final maps included those showing the relative priority for drainage for the soils in the area.

Location

Waroona is located around 100 km south of Perth along the eastern edge of the Swan Coastal Plain (Figure 1). The area is irrigated from a network of earth-lined open irrigation channels that are gradually being replaced by a system of reticulated pipes. Maps of soil types are required to assist in efficient land use planning as agriculture changes from irrigated pasture for dairy to other enterprises.

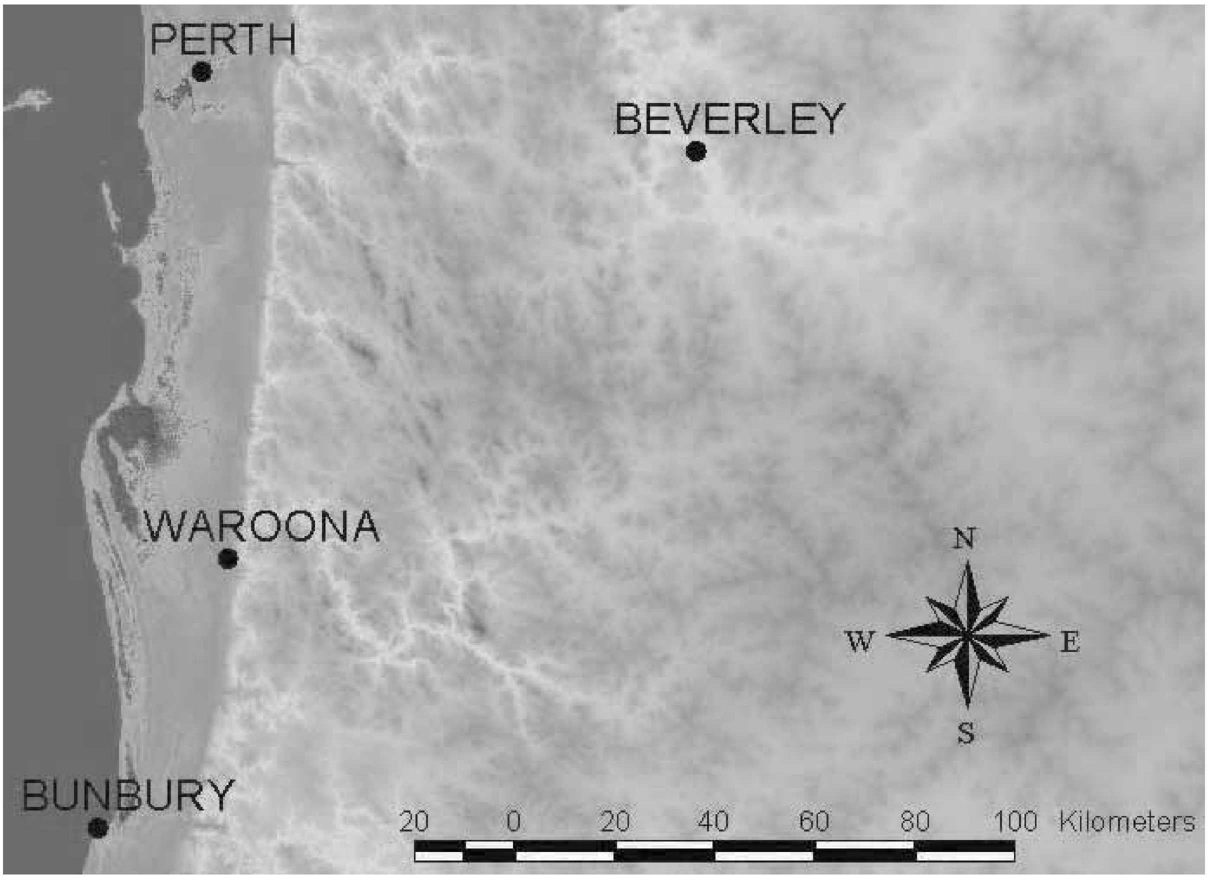

Figure 10. Waroona is located around 100 km south of Perth in southwest of Western Australia. Colours are derived from a Shuttle radar image and show the ocean (darker blue), flat areas of the Swan Coastal Plain (light blue to green) and upland areas of the Yilgarn Block east of the Darling Fault (yellow to red)

The soils in the area are mostly derived from erosion of the laterite profiles of the Yilgarn Carton and are dominated by younger colluvial soils in the east grading westwards into a mixture of alluvial deposits, lacustrine sediments and aeolian sands from deflated dunes. Farmers reported changes in the properties of these soils over tens of metres which had not been adequately described in existing soil mapping.

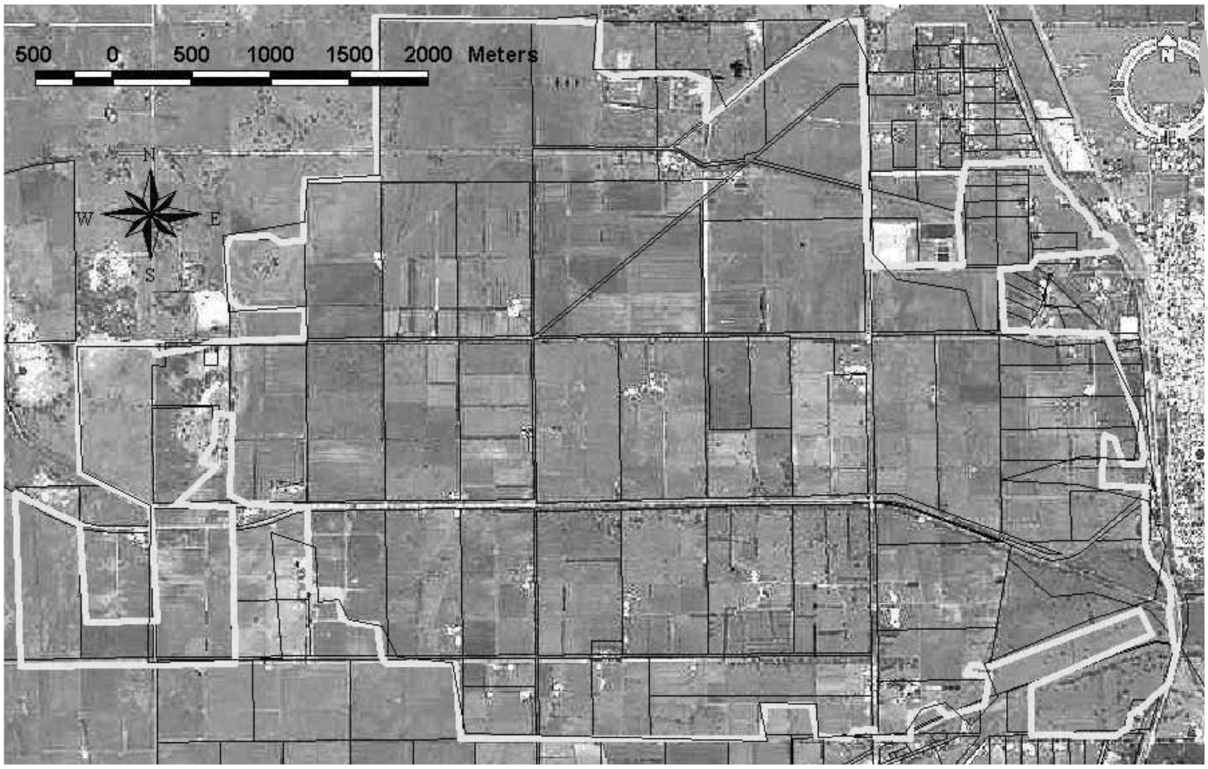

Figure 11 Aerial photograph mosaic, with cadastre plan overlaid showing outline of study area with Waroona to the east. Fenced areas range between 5 and 50 ha.

In the Waroona area the elevation ranges from around 14 to 32 m above sea level. The land slopes down to the west. A perspective image looking from the southwest is shown as Figure 3. The image shows a broad alluvial fan sloping extending westwards, with minor superimposed undulations. In the northwest is a small dune with a flatter area to the east, corresponding to the lacustrine/swamp deposits. The raised areas on the fan appear to be deflated, possibly older dunes.

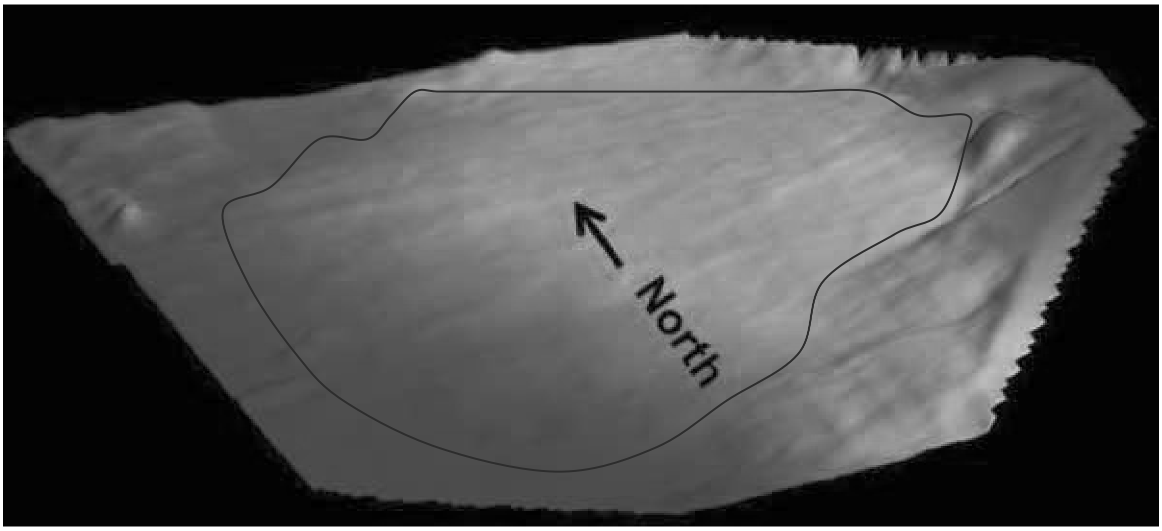

Figure 3. Perspective image of topography of study area. Elevation is around 14 m ASL in the southwest to 32 m in the east. Black line shows approximate outline of alluvial fan.

Geophysical Surveys

The area has been surveyed with both electromagnetic and radiometric instruments using a quad bike as a platform and GPS navigation. Line spacing was 25 m with readings at 5 m intervals.

Electromagnetic (EM) instruments measure the electrical conductivity of the ground to a depth governed by the separation of the transmitter and receiver coils and the frequency employed (McNeill, 1980a). Figure 4 shows the EM38 data for the study area. The EM38 was measured in vertical dipole mode measuring a hemisphical half space to around 0.75 m below the surface (McNeill, 1980b). Significant conductivity variations in the EM38 data are in the west and northwest of the study area in an area of heavier clay soils. Most of the area has very low conductivity and EM alone is not sufficient for distinguishing differences in soils.

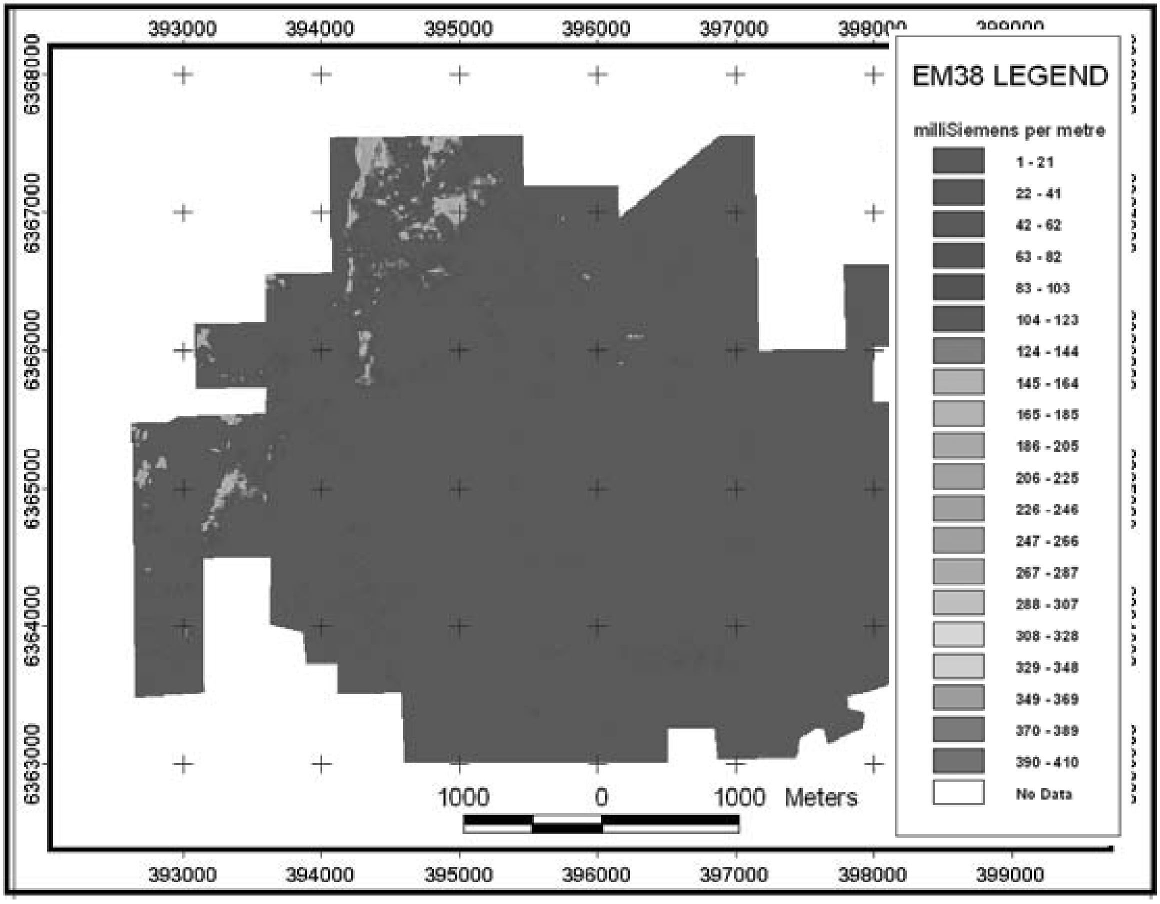

Figure 4. EM38 data across the study area showing outline of surveyed area.

Gamma-ray (radiometric) spectrometry measures natural gamma radiation, particularly from emissions due to decay of three elements - potassium (K), thorium (Th) and uranium (U). The gamma rays measured arise from within approximately the top 30 cm of the earth's surface. Radiometric surveys can provide information about the soil parent materials and other properties such as surface texture, weathering, leaching, soil depth and clay types (Bierwirth et al., 1996a). In contrast to other remote sensing techniques used for soils, radiometrics has some clear advantages. In particular dense vegetation will not significantly reduce the radiometric signal and radiometrics measures the top 30 cm and not just the surface.

High potassium is often related to potassium feldspars and mica, particularly from granite and granitic soils (Wilford et al., 1992). Potassium is mobile and is leached during the weathering process. During hydrolysis potassium is released and is used in the formation of illite or absorbed onto other clays (Bierwirth et al., 1996b). An increase in both thorium and potassium has been found to be related to an increase in silt content and recent deposition (Slater and De Plater 1997; Bierwirth et al., 1996a & b). Thorium also assists in discrimination between cracking clays (smectite or montmorillonite with low Th) and non-cracking clays (illite, kaolinite with high Th).

Thorium and uranium are present in the heavy minerals zircon, apatite, sphene and monazite (Wilford et al., 1992, Dickson and Scott, 1997). Thus, higher thorium and uranium signatures are often associated with the laterite iron accumulations due to concentration of heavy minerals left as a lag in the weathering process and also due to thorium and uranium concentrating in secondary iron oxide minerals. (Smith and Pridmore, 1989; Cook et al., 1996; Dauth, 1997). Uranium and thorium may also be transported with colloidal clays (Dickson and Scott, 1997).

A low total count indicates the presence of quartz sands (Cook et al., 1996) which have a very low concentration of radioactive isotopes. A thin layer of water will completely attenuate gamma radiation and water bodies will appear dark on radiometric ternary images but vegetation usually has only minor effects except in forest conditions where it can reduce the signal by up to 10% (Kogan et al., 1969). A ternary image of the radiometric data is shown as Figure 5. In this image dark areas of sand are obvious to the west adjacent to a blue/green area corresponding to heavy clays. The centre of the area has higher potassium associated with loamy soil. Effects of soil disturbance for agriculture can be seen through the middle of the area where darker squares are areas where sand has been deposited and the ground levelled for irrigated agriculture.

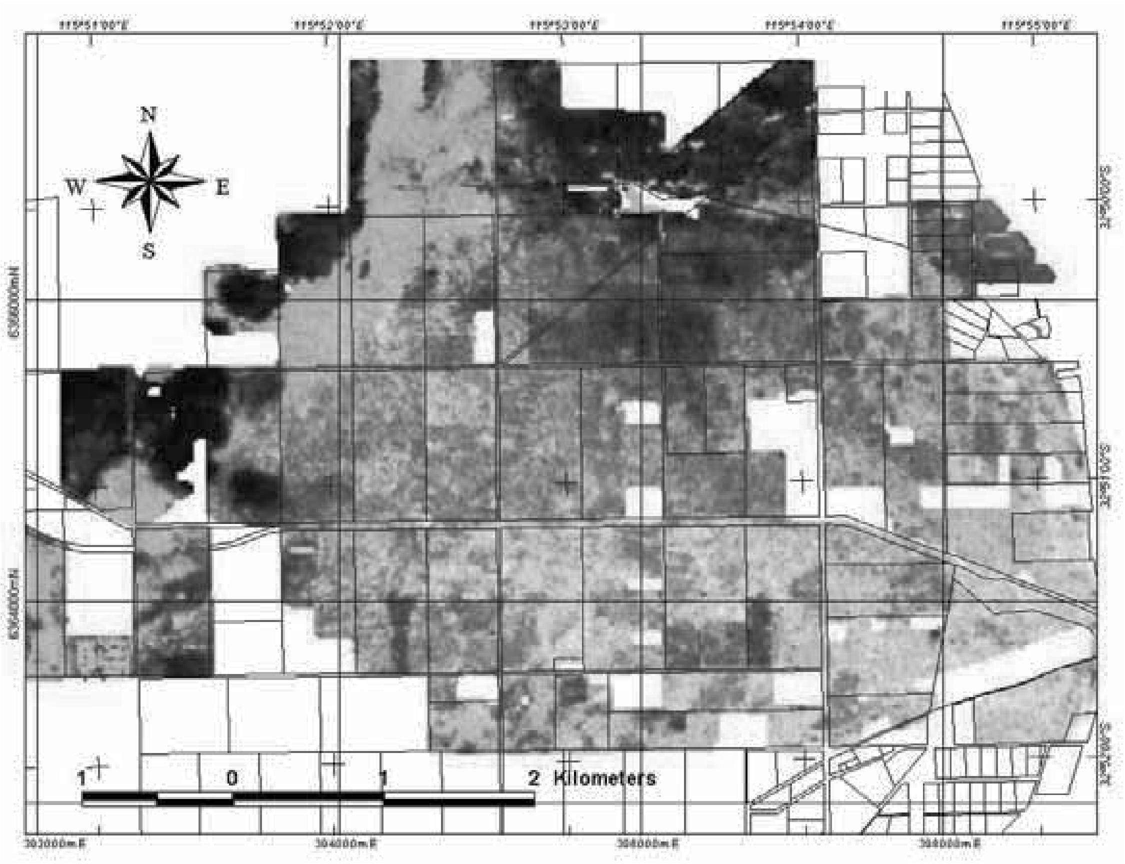

Figure 5. Ternary radiometric image of the Waroona Study Area. Colours are assigned to each radioactive isotope so that Potassium = red; Uranium = blue and Thorium = green.

Field investigations and Interpretation Methodology

The radiometric data was classified using an unsupervised classification process. Classification is a process of dividing the dataset into classes with similar characteristics. Clarke et al. (1998) showed how this approach could be used on airborne geophysical data to map variations in soil permeability. Anderson-Mayes (2000) stresses the fundamental difference between classification used in remote sensing and that used in geophysics. Whereas with remote sensing the approach can be an interpretation procedure, with geophysics classification provides a method of interrogating the spatial information content of the geophysics that may or may not result in named informational classes.

Initial classification resulted in 23 classes. The classification divided the data into natural clusters, reflecting soils with similar potassium, thorium, uranium, total count and EM conductivity responses. Field sites were chosen to ensure a significant number of sites in each class. All the sites were selected using GIS software and located using a GPS receiver. At each site soil descriptions including texture, colour and clay content were recorded. The descriptions recorded for each horizon are an average of A-Horizon = top 15 cm; B 15 to 30 cm and C 30 to 45 cm. In general there was an increase in clay content with depth and over most of the alluvial fan the soils were duplex with a thin 20 cm covering of sand over clay. The soil in the area in the northwest, by comparison, was found to be composed of deep sand. The fieldwork indicated that some classes were not easily distinguishable in the field and it was more appropriate to assign them to larger groups.

Grouping of the initial 23 classes (Figure 6) down to ten classes produced coherent spatial units and comparison with the original data indicated that significant information was not lost. A texture description could then be applied to each horizon in the 10 classes based on the field observations. The result was three grids of soil textural properties (Table 1) for horizons A, B and C. These grids may be reduced further into main soil associations by grouping similar textural classes.

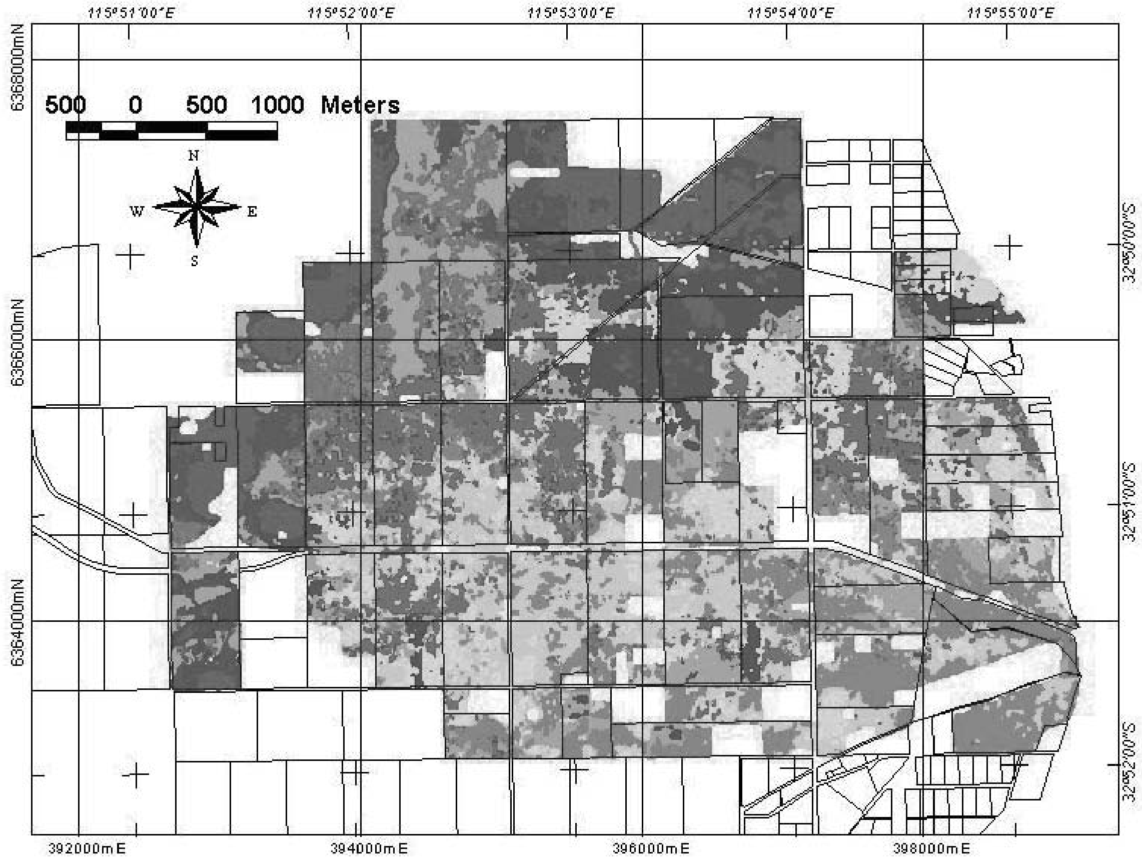

Figure 6. Map of 10 soil classes after field checking.

TEXTURE	NUMBER
Heavy Clay	1
Clay	2
Light Clay	3
Very Light (Friable) Clay	4
Clay Loam	5
Sandy Clay Loam	6
Loam	7
Sandy Loam	8
Loamy Sand	9
Sand	10

Table 1 Assignment of numbers to soil textures used in this study.

Classes and Soil Physical Characteristics

The physical characteristics of soils control the water holding capacity and drainage behaviour of soils. Thus in irrigated areas the depth of the least permeable layer is a major influence on drainage as it controls the volume of soil available for water storage. In this study area, clay was intersected in most auger holes at less than 40 cm and the thin sandy-loam soil over clay results in frequent waterlogging. In addition, the high variability of soils results in parts of paddocks that are easily waterlogged and other sections that drain quickly.

The classification of radiometric and EM38 data in this study identified ten soil classes (Figure 6) which field survey showed were significantly different in physical characteristics. These classes can be ranked in order of characteristics which determine the rate and volume of water that should be delivered by irrigation. The physical characteristics are the average texture of each horizon; average texture of all three horizons and electrical conductivity of the top 1 metre.

The averaged texture code map was then regrouped into three soil classes as shown in Figure 7 using the codes <5 = light to heavy clays; 5 to <7 = loams and clay loam and >7 = sandy loams and sands. This allowed the production of a map of three classes ready for use in land management decisions by farmers. In particular, farmers changing from a flood irrigated pasture to spray irrigated horticulture can now use the map to decide on design of irrigation spay layouts and rates and duration of water delivery.

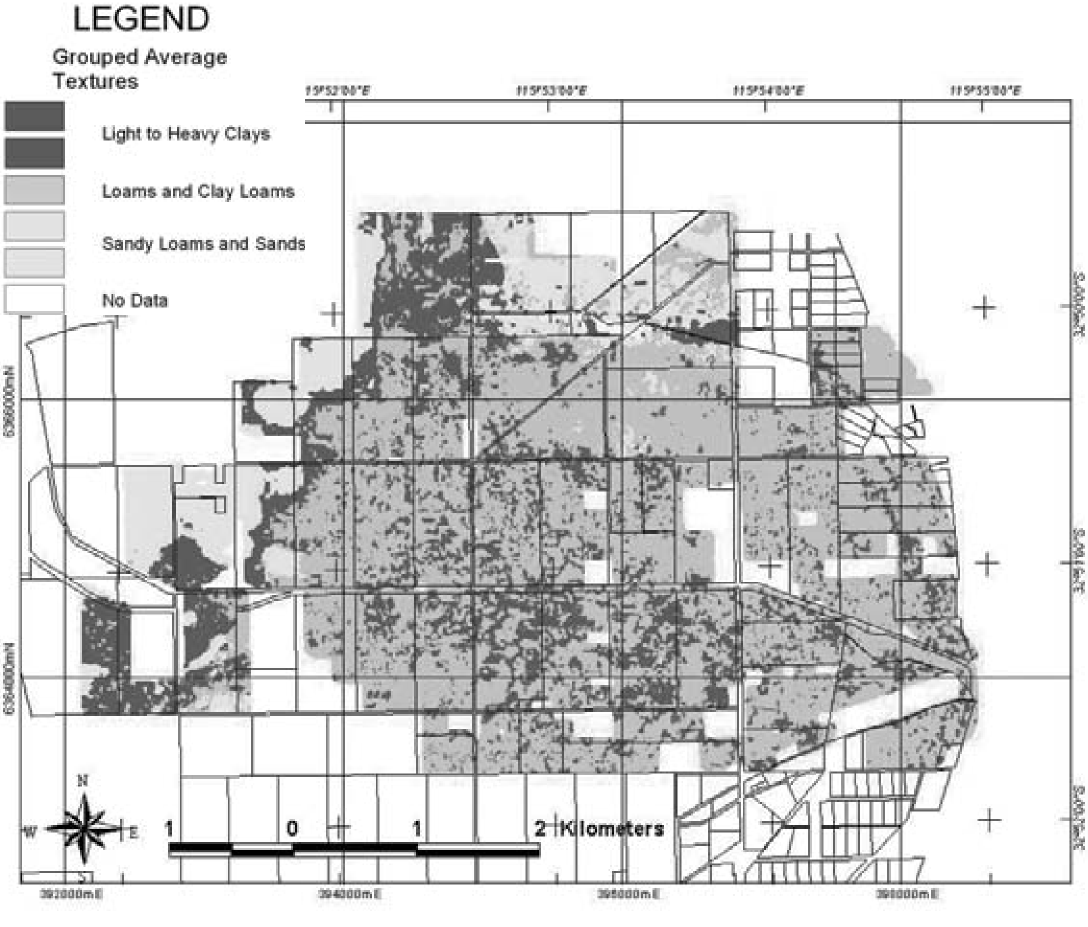

Figure 7. Map of grouped average texture codes from Figure 6 showing "heavy", "medium" and "light" soil classes.

Conclusion

An area of around 2000 hectares west of Waroona in the Harvey Irrigation Area has been studied to produce detailed maps of soil characteristics that are useful for agricultural management.

The source material of the soils was predominantly deeply leached saprolite and sands low in nutrients. On the positive side for agriculture the source material results in predominately clay-loam soils with good water holding capacity. In addition, the presence of ferruginous laterite material helps to bind phosphorus within the soil.

The approach used in the study was the incorporation and computer analysis of geophysical data comprised of ground gamma radiometric and electromagnetic surveys. The majority of gamma rays measured by radiometric equipment originate from minerals in the top 30-50 cm of the soil profile, and thus are used to map differences in soil character. The electromagnetic equipment employed was an EM38 which measures in the top 1 m of the soil.

The geophysical data were classified and the results field checked. Up to 23 classes can be separated, which was too many to be easily differentiated in the field. A 10 class division was selected for field checking and this was found to reflect patterns that are related to observable soil differences.

Maps of textures for soil horizons A, B and C were produced as well as maps of textural differences between horizons. Drainability of the soils was estimated using the textural differences between horizons, and the areas of higher conductivity were used to map poorly drained soils. Maps of drainage priority were produced.

Using field observations of texture and texture differences between horizons the ten classes were amalgamated to produce a map of average texture from heavy soils through to light which was then further grouped into three texture class groups that could be used by farmers in management decisions. The average texture maps can be overlain with the drainage priority maps to assess the suitability of land for irrigation and further agricultural development. In addition, a more sophisticated approach can be taken by using the computer interrogation ability of GIS technology. The most readily waterlogged soils will be those with a heavy texture in all three horizons and a relatively high EM38 reading.

The resulting soil texture maps strongly reflect the depositional environment on the alluvial fan, and the young age of the soils. Conditions for sediment transport in such an environment range from quiet stream flows with little sediment or local to widespread flooding with higher sediment loads. The depositional environment will result in highly variable soils with gradational boundaries both laterally and vertically. Combined with bioturbation and disturbance by agriculture, the A, B and C soil horizon depths are variable and observational soil data from individual soil sites may not be reliable for any distance from any particular site.

The information products developed from classification of geophysical data provide measurements of soil properties on an eight metre grid distributed both horizontally and vertically into three horizons. Such detail over a broad area cannot be obtained cost effectively by conventional soil survey techniques. There is potential to develop other information products from these data by improving the interrogation process and by including other spatially distributed data in the analysis. Such information products need to be defined by farmers' individual needs for specific types of information.

14. REFERENCES

Acworth, I., 2001, The electrical image method compared with resistivity sounding and electromagnetic profiling for investigation in areas of complex geology - A case study from groundwater investigation in a weathered crystalline rock environment. *Exploration Geophysics*, 32, 119-128.

Acworth, I., 1999, The investigation of dryland salinity using the electrical image method. *Australian Journal of Soil Research* 37.4, 623-636.

Acworth, R.I. and Dasey, G.R., 2003. Mapping of the hyporheic zone around a tidal creek using a combination of borehole logging, borehole electrical tomography and cross-creek electrical imaging, New South Wales, Australia. Hydrogeology Journal, 11: 368-377.

Acworth, R.I., Young, R.R. and Bernadi, A.L., 2005. Monitoring soil moisture status in a Black Vertosol on the Liverpool Plains, NSW, using a combination of neutron scattering and electrical image methods. Australian Journal of Soil Research, 43: 105-117.

Ali, R. and Salama, R. 2003. Groundwater quality in the Ord River irrigation area, its suitability for irrigation and prediction of salinity and sodicity hazards. CSIRO Land and Water Technical Report 07/03

Allen, D. A., and Merrick N.P. 2005, Towed geoelectric arrays for analysis of surface water groundwater interaction. Proceedings of the Symposium. on Applications of Geophysics to Engineering and Environmental Problems conference – April – Atlanta, USA, ISSN 1554-8015.

Allen, D. A., 2006, Electrical conductivity imaging of aquifers connected to watercourses – A thesis focussed in the Murray Darling Basin, Australia. PhD, University of Technology, Sydney. (under review)

Allen, D. A., and Merrick, N. P., 2003, A floating electrode array for continuous geoelectric imaging. Extended abstract – *proceedings of the Aust. Soc. of Exploration Geophysicists 16th Geophysical Conference and Exhibition.*

Allen, D. A., and Merrick, N. P., 2003, Identifying fresh and saline water using hydro-geophysical imagery of strata beneath watercourses. Paper and posters presented in the proceedings of the 9th Murray Darling Basin Groundwater Conference – Feb. - Bendigo.

Allen, D. A., and Merrick, N. P., 2005, Electrical Conductivity Imaging of Aquifers Connected to Watercourses. International Association of Hydrogeologists Australian and NZ conference, Auckland, (under review).

Allen, D.A., 2005, Towards creation of a national multi-depth electrical conductivity database. Australian Society of Exploration Geophysicists, Preview, August, Issue No. 117.

Anderson-Mayes, A.M. 2000. Enhancing interpretation of multivariate airborne geophysical data for dryland salinity studies. Unpub. PhD thesis. Dept of geographical sciences and planning, Univ of Queensland.

Arcone, S.A., 1981, Distortion of model subsurface radar pulses in complex dielectrics: Rad.Sci., v.16, p.855-864.

Auken, E., and Christiansen, A. V., 2004, Layered and laterally constrained 2D inversion of resistivity data. *Geophysics*, Vol. 69, No. 3, (May-June), 752-761.

Auken, E., Breiner, M., Nebel, L., Pellerin, L., Thomsen, P., and Sørensen, K. I., 2001, EMMA - Electromagnetic modelling and analysis. *EEGS Birmingham Proceedings*. Birmingham, U.K.:EEGS. 114-115, 2001. JED.

Auken, E., Nebel, L., Sørensen, K., Breiner, M., Pellerin, L., and Christensen, N., 2002, EMMA – A Geophysical Training and Educational Tool for Electromagnetic Modeling and Analysis. *Journal of Engineering and Environmental Geophysics*, Vol. 7, Issue 2, 57-68.

Barrett, B., Hatch, M., Heinson, G., and Telfer, A., 2003, Salinity monitoring of the Murray River using a towed TEM array: *Aust. Soc. of Explor. Geophysicists 16th Geophysical Conference and Exhibition.*

Bierwirth, P., Gessler, P. and McKane, D. 1996b. Empirical investigation of airborne gamma-ray images as an indicator of soil properties – Wagga Wagga, NSW. Australian Geological Survey Organisation, 8th Australasian Remote Sensing Conference Proceedings, Canberra.

Bierwirth, P., Hardy, S., Wilson, P., Philip, S., Smith, D., Heiner, I. and Grundy, M. 1996a. Radio Ga-Ga - Integrating gamma-radiometrics into landscape modelling of soils attributes; results of an ACLEP exchange. ACLEP newsletter, Vol 5/3.

Brodie, R., Green, A. and Munday, T., 2004, Constrained Inversion of Dighem Resolve Electromagnetic Data – Riverland, South Australia. CRC LEME Open File Report 175, September 2004. http://crcleme.org.au/Pubs/OPEN%20FILE%20REPORTS/OFR%20171-180/OFR175.pdf

Brodie, R.C. 2002, Airborne and ground magnetics. pp 33-45 In: Papp E, ed. Geophysical and remote sensing methods for regolith exploration. Canberra: CRC LEME, open-file report 144.

C Panissod, C., Dabas, M., Jolivet, A. and Tabbagh, A., 1997, A novel mobile multipole system (MUCEP) for shallow (0-3 m) geoelectrical investigation: the 'Vol-de-canards' array. Geophysical Prospecting 45 (06), 983–1002.

Charlesworth, P., 2005, Irrigation Insights No. 1, Second edition Soil water monitoring. 96 pp. http://www.lwa.gov.au/downloads/publications_pdf/PR050832.pdf (2.4Mb)

Clarke, C.J., Bell, R.W., Anderson-Mayes, A., Street, G.J., Beeston, G. and George, R.J. 1998. Using airborne geophysical data to map landscape scale variation in regolith permeability. In Proceedings of the First International Conference on Geospatial Information in Agriculture and Forestry, Florida, USA.

Clarke, J., Lawrie, K., Fitzpatrick, A., Apps, H. and Lowis, B. (2006). New insights into aquifer systems in the Burdekin Irrigation Area. ANCID 2006 "The North - Opportunities for the future - The catchment community working together." Darwin, N.T., Australian National Committee on Irrigation and Drainage

Coleman, J. M. and Wright, L. D. 1975. Modern river deltas: variability of processes and sand bodies. In Broussard, M. L. (ed.). Deltas, models for exploration. Houston Geological Society, pp. 99-150.

Cook, S.E., Corner, R.J., Groves, P.R. and Grelish, G.J. 1996. Use of Airborne Gamma radiometric data for soil mapping. Australian Journal of Soil Research 34: 183-194.

Dauth, C. 1997. Airborne magnetic, radiometric and satellite imagery for regolith mapping in the Yilgarn Craton of Western Australia. Exploration Geophysics, 28: 199-203.

Dickson, B.L. and Scott, K.M. 1997. Interpretation of aerial gamma-ray surveys - adding the geochemical factors. AGSO Journal of Australian Geology and Geophysics 17 (2): 187-200.

Drury, S.A., 2001, Image interpretation in Geology, 3rd edition, published by Chapman and Hall. 296 pp.

Fielding, C. R., Trueman, J. D., and Alexander, J. 2005. Sedimentology of the modern and Holocene Burdekin Delta of north Queensland, Australia – controlled by river output, not waves and tides. In Bhattacharya, J. and Giosan, L. (eds.). Deltas. Society of Economic Paleontologists and Mineralogists Special Publication.

Fielding, C. R., Trueman, J. D., and Alexander, J.2006. Holocene depositional history of the Burdekin-river delta of northeastern Australia: a model for a low-accommodation, highstand delta. Journal of Sedimentary Research 76, 411–428.

Fitzpatrick, A., Apps, H. Clarke, J. D. A., and Lawrie, K. 2004. Mapping salt water intrusion and understanding water-rock interactions in saline aquifers in the lower Burdekin Delta: phase 1 report. CRC LEME Restricted Report 204R.

Galloway, W. E. 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaicdepositional systems. In Broussard, M. L. (ed.). Deltas, models for exploration. Houston Geological Society, pp.87-98.

Geonics Limited (~1997) Application of "Dipole-Dipole" Electromagnetic Systems for Geological Depth Sounding. Technical Note TN-31, Geonics Limited, Ontario, Canada. http://www.geonics.com/pdfs/technicalnotes/tn31.pdf (303kB). Accessed 15/1/2007.

Gibling, M. R. 2006. Width and thickness of fluvial channel bodies and valley hills in the geological record: a literature compilation and classification. Journal of Sedimentary Research 76, 731-770.

Hallenburg, J. K., 1984, Geophysical logging for mineral and engineering applications. PennWell Books, Tulsa, Oklahoma.

Huissman, J. A., Hubbard, S. S., Redman, J..D., and Annan, A. P., 2003, Measuring Soil Water Content with Ground Penetrating Radar: A Review. Vadose Zone Journal Vol 2, 476-491.

Kogan, R.M., Nazarov, I.M. and Fridman, Sh. D. 1969. Gamma spectrometry of natural environments and formations. Theory of the method applications for geology and geophysics. Atomizdat, Moscow.

Lane, R., 2002, Ground and airborne electromagnetic methods, *in* Papp, E. (ed), 2002, *Geophysical and Remote Sensing Methods for Regolith Exploration,* http://crcleme.org.au/Pubs/OPEN%20FILE%20REPORTS/OFR%20144/OFR144.html

Lawrie, K., Clarke, J., Hatch, M., Price, A., Apps, H. and Wilkes, P. (2006). Improving hydrogeological models of aquifer systems in the Ord Irrigation Area: assessing the potential of geophysics and other geoscience methods. ANCID 2006 "The North - Opportunities for the future - The catchment community working together." Darwin, N.T., Australian National Committee on Irrigation and Drainage.

Loke, M. H., and Lane, J. W., 2004, Inversion of data from electrical imaging surveys in water-covered areas, Extended abstract (and paper submitted for publication in *Exploration Geophysics*), *Proceedings of the Australian Society of Exploration Geophysicists Conference* (August).

Makaske, B. 2001. Anastomosing rivers: a review of their classification, origin, and sedimentary products. Earth Science Reviews 53: 149-196.

McNeill, J.D. 1980, Electromagnetic terrain conductivity at low induction numbers, Technical Note TN-6, Geonics Limited, Ontario, Canada. http://www.geonics.com/pdfs/technicalnotes/tn6.pdf (4.8Mb)

McNeill, J.D. 1980a. Electrical conductivity of soils and rocks. Geonics Technical Note TN-5 (www.geonics.com).

McNeill, J.D. 1980b. Electromagnetic terrain conductivity measurements at low induction numbers: Geonics Technical Note TN-6 (www.geonics.com)

McNeill, J.D. 1996, Why doesn't Geonics Limited Build a Multi-Frequency EM31 or EM38? Technical Note TN-30, Geonics Limited, Ontario, Canada. http://www.geonics.com/pdfs/technicalnotes/tn30.pdf (35kB).

Milsom, J., 2003, Field Geophysics (3rd edition), John Wiley & Sons.

Nabighan, M.N., 1987, Electromagnetic methods in applied geophysics – Theory, Volume 1. Investigations in geophysics No. 3. Society of Exploration Geophysicists.

Nanson, G. C. and Young, R. W. 1981. Overbank deposition and floodplain formation on small coastal streams of NSW. Zeitschrift fur Geomorphologie 25, 332-347.

Nemec, W. 1990. Deltas – remarks on terminology and classification. In Colella, A. and Prior, D. B. (eds.). Coarse grained deltas International Association of Sedimentologists Special Publication 10. Blackwell Scientific Publications, Oxford, UK, pp. 3-12.

Nemec, W. and Steele, R. J. 1988. What is a fan delta and how do we recognize it? In Nemec, W. M. and Steel, R. J. (eds.). Fan deltas: sedimentology and tectonic settings. Blackie and Son, Glasgow & London, pp. 3-13.

Neton, M. J., Dorsch, J., Young, S. C., and Olson, C. D. 1992. Archiecture and directional scales of heterogeneity in alluvial fan aquifers. Journal of Sedimentary Research B64, 245-257.

O'Boy, C. A., Tickell, S., Yesertener, C., Comannder, D. P., Jolly, P., and Laws, A. T. 2001. Hydrogeology of the Ord River Irrigation Area. Water and Rivers Commission Hydrogeological Record Series HG 7

Papp, E.,(ed.) 2002, Geophysical and remote sensing methods for regolith exploration, CRC LEME Open File Report 144. http://crcleme.org.au/Pubs/OPEN%20FILE%20REPORTS/OFR%20144/OFR144.html

Parasnis, D.S., 1997, Principles of Applied Geophysics, 5th edition, 437pp. Chapman and Hall.

Payenberg, T. H. D. and Reilly, M. R. W. 2003. Core descriptions of ten conventional cores from the St George region, Queensland. CRC LEME Open File Report 166.

Pollock, D. W., Salama, R. B., and Viney, N. R. 2003. Water levels and water quality trends in the Ord River Irrigation Area (ORIA) for the period September 2001 – March 2003. CSIRO Land and Water Technical Report 40/03.

Pucillo, K., 2005, Quarternary palaeochannel evolution and groundwater movement in the Coleambally irrigation district of New South Wales, PhD Dissertation, University of Wollongong.

Reid, J. E., Pfaffling, A., and Vrbancich, J. 2006, Airborne electromagnetic footprints in 1D earths, *Geophysics*, 71(2), G63-G72.

Reynolds, J, M., 1997, An introduction to Applied and Environmental Geophysics, 806 pp. John Wiley & Sons.

Rhoades, J.D., Chanduvi, F. & Lesch, S., 1999, *Soil Salinity Assessment, Methods* *and interpretation of electrical conductivity measurements*, FAO (Food and Agriculture Organisation of the United Nations) Irrigation and Drainage Paper 57.

Richards, N., 2002. Assessment of the potential value of electromagnetic survey methods for soil permeability investigations, in the Ord River Irrigation Area. Draft Report, WA Dept. of Agriculture. 65p.

Ryan, D. A., Heap, A. D., Radke, L., and Heggie, D. T. 2003. Conceptual models of Australia’s estuaries and coastal waterways: applications for coastal resource management. Geoscience Australia Record 2003/09.

Salama, R. B. and Pollock, D. W. 2003. Preliminary appraisal of salinity development in the Packsaddle Creek area. CSIRO Land and Water, Technical Report 17/03

Shaw, C. 2001, Murray Irrigation Limited Commercial Application of the EM31 technology for rice soil suitability. Unpublished paper in ‘Electromagnetic Techniques for Agricultural Resource Management’ presented on 3-5 July at Yanco Agricultural College. NSW Agriculture, CSIRO Land and Water, Canberra.

Shaw, C., 2002, *Infiltration on common rice soils within MIL.* chriss@murrayirrigation.com.au

Sheriff, R. E., 1991, Encyclopedic Dictionary of Exploration Geophysics, 3rd edition. Society of Exploration Geophysicists.

Slater, K.R. and De Plater, K. 1997. The application of radiometric data for soil mapping, Nagambie 1:100,000 Map. Geological Survey of Queensland, Technical Record 1997/1, Department of Natural Resources and Environment, Queensland.

Slavich, P. J., and Petterson, G. H., 1993, Estimating the Electrical Conductivity of Saturated Paste Extracts from 1:5 Soil:Water Suspensions and Texture, *Aust. J. Soil Res.*, 31, 73-81.

Smith, A. J., Pollock, D. W., Salama, R. B., and Palmer, D. 2005. Ivanhoe Plain Aquifer Pumping Trial July 2003 - April 2005: Stage 1 Ord River Irrigation Area, Kununurra, Western Australia. CSIRO Land and Water Technical Report 24/05.

Smith, R.J. and Pridmore, D.F. 1989. Exploration in weathered terrains 1989 perspective. Exploration Geophysics 20: 411-434.

Sørensen, K. I. and Auken, E., 2004, SkyTEM, a new high-resolution helicopter transient electromagnetic system., *Exploration Geophysics* Vol 35, No. 3.

Sørensen, K. I., Pellerin, L., and Auken, E., 2003, An auger tool to estimate hydraulic conductivity using a resistivity analogy. *ASEG 16th Geophysical Conference and Exhibition, February, Adelaide. Extended Abstracts.*

Spies, B. R., and Woodgate, P., 2005 Salinity mapping methods in the Australian context. Department of Environment and Heritage; and Agriculture, Fisheries and Forestry. User guide: http://www.nrm.gov.au/publications/salinity-mapping/user-guide/ .

Street, G.J., Abbott, S. and Beckett, K. Digital Soil Mapping using Electromagnetic Conductivity and Gamma Radiometric Surveys. Near Surface Geophysics (in prep.)

Telford, W.M.,Goldart, L.P, Sheriff, R.E, 1990 Applied Geophysics, 2nd Edition. 770pp. Cambridge University Press.

Thomsen, R., Sondergaard, V. H., and Sorensen, K. I., 2004, Hydrogeological mapping as a basis for establishing site-specific groundwater protection zones in Denmark. *Hydrogeology Journal*, 12, 550-562.

Timms W. A., Acworth, R. I., and Young, R. R., 2002, Natural leakage pathways through smectite clay: a hydrogeological synthesis of data from the Hudson Agricultural trial site on the Liverpool Plains. *Water Research Laboratory Research Report No 209*, ISBN 85 824 0521, published in August 2002 on website *www.wrl.unsw.edu.au/research.*

Viezzoli, A., and Cull, J. P., 2005, Induced Polarization measurements applied to irrigation canals freshwater seepage detection, Submitted to *Near Surface 2005 –* Palermo, Italy, Sept.

Volmer, B., Hatch, M., Wilson, T. and Hill, T., 2004, River-borne NanoTEM survey for location of salt accession to the River Murray at Loxton, Extended Abstract, *Proceedings of the Australian Society of Exploration Geophysicists Conference* (August).

Wait, J.R., 1962. A note on the electromagnetic response of a stratified earth. Geophysics 27, 382-385.

Wilford, J.R., Pain, C.F. and Dohrenwend, J.C. 1992. Enhancement and integration of airborne gamma-ray spectrometric and Landsat imagery for regolith mapping - Cape York Peninsula. Exploration Geophysics, 23: 441-446.

Won, I.J. Apparent conductivity (or resistivity) revisited.
http://www.geophex.com/GEM-2/How%20it%20works/Apparent%20Conductivity.pdf Accessed January 2007.

APPENDIX 1 – MANUFACTURER CONTACT DETAILS

ASEG Australian Society of Exploration Geophysicists	www.aseg.org.au
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Aarhus University Hydro-geophysics Group	www.hgg.au.dk
ABEM Instruments AB	www.ABEM.com
Advanced Geosciences Incorporated	www.AGIUSA.com
Aeroquest	www.aeroquest.com
Alpha Geoscience	www.Alpha-geo.com
Apex Parametrics	Tapio Vaare, Canada, Phone +1 905 852 5875 (fax +1 905 852 9688)
Dept. of Geoph. Appliquee, Univ. Pierre et Marie Curie	cpanissod@ccr.jussieu.fr
Deutshe Montan Technologie GmbH	www.dmt-gmbh.net/G5_EG/doc/mm_doc_03.html
DUALEM	www.DUALEM.com
EMIT (Perth)	www.EMIT.iinet.com.au
Fugro	www.fugroairborne.com.au
Geonics Ltd.	www.Geonics.com
Geophex	www.Geophex.com
Geotech	www.Geotech.com
Exploranium	www.saic.com
GF Instruments	www.giscogeo.com or www.gfinstruments.cz

Geometrics	www.Geometrics.com
GPX (Perth)	www.gpx.com.au
GSSI (Geophysical Survey Systems Inc.)	www.geophysical.com
Iris Instruments	www.Iris-Instruments.com
L and R Instruments	www.L-and-R.com
OYO Corp. Phone +81-29-851-6621	www.oyo.co.jp
Radic Research	www.Radic-research.de
Red Dog Scientific	www.geoafrica.co.za/reddog/barlow/emsystem/htm
Scintrex	www.scintrexltd.com
Skytem	www.SkyTEM.com (in Australia www.Geoforce.com.au)
Terraohm Instruments AB	Torleif.Dahlin@tg.lth.se
Veris Technologies	www.veristech.com
Zonge	www.Zonge.com

APPENDIX 2 - EQUIPMENT TABLES (ELECTRICAL CONDUCTIVITY IMAGING DEVICES ONLY)

Note that prices are for April 2005 at country of origin before tax unless specified otherwise and are only approximate. Many options vary prices of most instruments. Devices within each category are listed in a combination of order of prevalence on the Australian market and perceived appropriateness to the Australian irrigation industry.

FREQUENCY DOMAIN ELECTROMAGNETIC DEVICES

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
EM38	US$9275 + $1500 for real time output	<10 km/hr	HCP or VCP	0-0.75 m VCP or 0-1.5 m HCP	Production Extensively used in Australia	Geonics
EM38DD	US$22200	<10 km/hr	HCP and VCP	0-1.5 m in 2 layers	Production Extensively used in Australia	Geonics
EM31-Mk2	US$22200 Contractors charge approx $1500 per day.	<10 km/hr	HCP or VCP	0-6 m HCP	Production Extensively used in Australia	Geonics
EM31-SH	US$21350	<10 km/hr	HCP or VCP	0-3 m HCP	Production	Geonics

Appendix 2

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
EM34-3	US$26850	With 3 spacings/depths, 1 sounding every 5 to 10 minutes. Towed mode up to 10 km/hour by special order.	3 x HCP or VCP, 10, 20 and 40 m separations	0-60 m in 3 fixed thickness layers, or 6 fixed thickness layers if both HCP and VCP are measured.0-40 m in 3 layers	Production Limited history of use in Australia	Geonics
EM34-3XL	US$29350	With 3 spacings/depths, 1 sounding every 5 to 10 minutes. Towed mode up to 10 km/hour by special order.	3 x HCP or VCP, 10, 20 and 40 m separations	0-60 m in 3 fixed thickness layers, or 6 fixed thickness layers if both HCP and VCP are measured.	Production	Geonics
EM31-3 Multi Rx Coil FDEM	<US$30000 predicted by April 2006	<10 km/hr	3 x HCP or 3 x VCP	0-6 m in 3 layers	Research ready. Production model proposed for April 2006.	Geonics
DUALEM2+4	Ask	<10km/hr	2 x HCP and 2 x perpendicular	0-6m in 4 layers	Production (new design)	DUALEM
DUALEM1s	Ask	<10km/hr	HCP and perpendicular	0-1.5m in 2 layers	Production	DUALEM
DUALEM2s	Ask	<10km/hr	HCP and perpendicular	0-3m in 2 layers	Production	DUALEM
DUALEM4s	Ask	<10km/hr	HCP and perpendicular	0-6m in 2 layers	Production	DUALEM

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
DUALEM2/4	Ask	<10km/hr	HCP and perpendicular	0-6m in 2 layers or 0-3m in 2 layers interchangeable	Production	DUALEM
DUALEM1+2 +4s	Ask	<10km/hr	3 x HCP and 2 x perpendicular	0-6m in 5 layers	Production (new design)	DUALEM
DT Barlow FDEM-8 System	US$6450 ex Johannesburg	One sounding each 15 seconds plus walking time.	HCP or VCP Operating at 8 frequencies to give, limited multi-depth information.	0-40m assumed Depth resolution of frequency sounding instruments is poor	Production	Red Dog Scientific
Max Min	Ask	With 3 spacings/depths, 1 sounding every 5 to 30 minutes	HCP normally	0-200m in as many layers as the user wishes to individually measure	Production for fracture zone definition	Apex Parametrics,
Promis EM	not yet in production	With 3 spacings/depths, 1 sounding every 5 to 30 minutes	10 to 400m coil separation 10 frequencies from 110Hz to 56320Hz	0-200m in as many layers as the user wishes to individually measure	Design/ Construction	Iris Instruments
GEM 2	US$19600	<10km/hr	HCP or VCP with multiple frequencies 3A.m^2	0-4m. Multiple frequencies do not significantly help resolve depths	Production	Geophex

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
GEM2H	>US$19600	<15km/hr – high moment receiver coils can allow faster survey if mounted with good suspension.	As for GEM2 but with large high moment receiver coils that allow one to collect high moment data.	As for GEM2	Production	Geophex
Profiler EMP-400	Released after April 2005	<15 km/hr	HCP or VCP with multiple frequencies and 1.219m separation. (smaller freq. range than GEM 2)	0-2 m	Production. Released in 2006.	Geophysical Survey Systems, Inc.
CM031	US$15390	<10 km/hr	3.74 m HCP or VCP	0-6 m	Production, robustness limitations	GF Instruments
CM032	US$14310	<10 km/hr	2 m HCP or VCP	0-3 m	Production, robustness limitations	
CM138	US$12690	<10 km/hr	1 m HCP or VCP	0-1.5 m	Production, robustness limitations	GF Instruments

Device	***Price***	***Coverage Rate***	***Configuration***	***Depths of Investigation***	***Development stage***	***Manufacturer***
MiniEM	US$6950 (Aug 2005) + case US$490 outside USA	<10 km/hr	Coil separation 2 m. 45 degree sloped Tx coil gives HCP + VCP 3 A.m^2	0-3 m in two layers	Analogue electronics complete; digital electronics still being designed at Dec 2006.	L and R Instruments

GEOELECTRIC (DC RESISTIVITY & IP) SYSTEMS

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
OhmMapper TR4	US$48880 including 5 receiver dipoles, a replacement parts kit and an ATV tow quick release device.	Up to 10 km/hour	Geoelectric bipole-bipole array with linear electrodes of 0.5 m, 1 m, 2 m, 4 m and multiples of 4 m long.	0 to 30 m except in highly conductive areas.	Production	Geometrics
TerraOhm RIP924 receiver and ABEM ET200 transmitter	€16706 or SEK153700 ES10-64 switchbox SEK90000 5m roll along cables SEK90000 Alternate transmitters may be substituted for the ET200	<=10 km/hr waterborne, approx 500m per hour using stakes and roll along cables on ground or much faster using a ripped in cable.	8 isolated channel continuous acquisition geoelectric system	8 layers as determined by geoelectric array configuration. Array is 5 times as long as depth of exploration.	Receiver Production but awaiting IP capability. Transmitter not ready – alternate Xantrex and ABEM transmitters are currently used.	Terraohm Instruments AB

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
Terrameter SAS4000 LUND imaging system	Terrameter SEK 125000 ES10-64 switchbox SEK 90000 5 m roll along cables SEK 90000	Dependent on time taken for field crew to hammer stakes into the ground.	Terrestrial geoelectric arrays – 5 m interval roll along cables are commonly used.	0 to 30 m typical in several layers/2D.	Production	ABEM Instruments AB
PACES (Pulled Array Continuous Electrical Sounding)	€550 per linear km including presentation, comprehensive reporting and interpretation	Walking speed. Advanced route planning advised.	A combination of Wenner and Pole dipole configurations in a 90 m long pulled geoelectric array.	0-30 m in several well resolved layers.	Production. 10’s of 1000’s of km covered.	Aahrus University Hydro-geophysics Group.
Corim	€17000 ex France	<10 km per hour	6 capacitive dipoles placed perpendicular to array axis (Vol-de-Canards).	0-2 m very well resolved.	Production but application appears to have only occurred in fields other than irrigated soils management.	Iris Instruments

Appendix 2

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
Syscal Pro Switch, Sysmar	Syscal Pro Switch system with automated switching and multi-take-out cables €46000 ex France Sysmar software and calbes approx €2000.	<10 km per hour in continuous waterborne mode. Terrestrial mode dependant on speed at which stakes can be hammered in and connected to cables.	Any geoelectric array may be connected but the device is designed for dipole-dipole arrays.	Dependant on electrode array design. 0 to 30m is typical. The instrument has ten input channels that permit many layers to be resolved if used appropriately.	Production	Iris Instruments
Super Sting R8, SuperSting Marine.	Unknown	<10 km per hour marine. Terrestrial rates determined by crew hammering in electrodes	Dipole Dipole arrays of various sizes are offered	0 to 30 m typical	Production	Advanced Geosciences Incorporated.

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
GDP32-2	Ask	With roll-along cable, depends on speed at which electrodes are hammered into the ground. Waterborne <10 km/hr.	Any geoelectric array may be used on water or land with the 8 channel receiver. May be used for Spectral IP measurement of hydraulic permeability of sandstones	0 to 30 m with multi-layer resolution is typical. Any depth is possible.	Production. The multi-function equipment is suitable for experimentation with new techniques.	Zonge
SIP-256	Unknown	Up to approx 500 m per hour estimated	Roll along cable instrument with digitizers on each dipole to reduce noise. Designed specifically for measurement of spectral induced polarization data useful for hydraulic permeability measurement.	0 to 30 m typical with multi-layer resolution	Production	Radic Research

Appendix 2

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
RESECS	Approx €36000 for a 48 electrode system.	Up to approx 500 m per hour	Geoelectric array for use with a switchbox and hammer in electrodes. Up to 960 electrodes can be controlled by the switchbox.	Dependent on electrode array design. 0 to 30 m is typical.	Production	Deutshe Montan Technologie GmbH
Handy-Arm	Unknown	Approx 500 m per hour	Roll along cables with hammer in electrodes. 90V 100mA	8 layers as determined by geoelectric array configuration. Array is 5 times as long as depth of exploration.	Production but documented in Japanese	OYO Corp.
MUCEP	Unknown	Walking speed.	Vol-de-Canards towed by motorized vehicle or Quadropole devices towed by a person Devices made of pronged wheels and/or capacitive wheels.	0 to 0.3 m quadripole and 0 to 0.7 m Vol-de-canards MUCEP with 3 layer resolution.	Research	Dept. de Geoph. Appliquee, Univ. Pierre et Marie Curie

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
Veris Multisensor platform	Ask	<10 km/hour – towed by 4wd or tractor	Wenner array of 6 plough disks approx 3m wide. pH is also sampled every 12 seconds.	0 to 0.6 m in two layers.	Production – intensively marketed for precision soils management.	Veris Technologies

TIME DOMAIN ELECTROMAGNETIC SYSTEMS

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
NanoTEM	Ask	<10 km/hour in towed mode.	TEM with turn off time as low as 2 us.	4-40 m with 8 m x 8 m loop. Deeper with larger loops. Multilayer interpretation is possible.	Production, for use in towed mode, a sensor platform needs to be designed and constructed (see the principle author regarding progress on platform).	Zonge Engineering and Research Organization.
TerraTEM	A$45000 with continuous imaging option. Roving vector receiver coil A$6500	<10 km/hour in towed mode.	TEM with turn off time as low as 2 us. External transmitter can supply up to 32 Amps.	4-40 m with 8 m x 8 m loop. Deeper with larger loops. Multilayer interpretation is possible.	Production, for use in towed mode, a sensor platform needs to be designed and constructed (see David@GroundwaterImaging.com for progress on platform).	Monash University; marketed by Alpha Geoscience

Device	***Price***	***Coverage Rate***	***Configuration***	***Depths of Investigation***	***Development stage***	***Manufacturer***
PATEM (Pulled Array TEM)	€750 per linear km (Denmark) including presentation, comprehensive reporting and interpretation.	Walking speed	TEM with turn off time as low as 2 us. Slingram config.	Approx. 10 to 150 m	Development but now replaced by SkyTEM in Denmark. Over 10000km surveyed.	Aarhus Universtiy HydroGeophysics Group.
PROTEM	PROTEM 47 full system ex Canada US$64150 Production cost €140 per sounding with comprehensive reporting and interpretation (Denmark)	<10 km/hour in towed TEM mode (special order). Or dependant on speed at which personnel lay out loops if used in standard moving loop mode.	TEM – continuous mode operation is only available by special order	4 to 800 metres typical depending on loop size and transmitter power	Production only for the mode of operation in which loops are laid on the ground manually. 45000 soundings achieved for groundwater in Denmark.	Geonics Limited (Canada).

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
SMARTem V Receiver (must be augmented by a transmitter and coil or electrode array).	A transmitter must be purchased separately	<10 km/hour in towed TEM mode. Other modes dependant on configuration. A small mobile platform for use of SMARTem for shallow imaging is called TinyTEM	This is a multipurpose instrument set up for TEM, CSAMT and geoelectric surveying.	Typically deep but configuration is up to the user. It can mimic operation of many other instruments.	Production however the instrument has principally been marketed to the mineral exploration industry.	EMIT (Perth) TinyTEM – see Geoforce

AIRBORNE ELECTROMAGNETIC DEVICES

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
SkyTEM	Ask	30 to >100 km per hour depending on desired resolution, helicopter and flying height.	Rigid loop TEM with Z and X component receiver loop in a position of null coupling with transmitter loop. Dual moment with 2 us turn off time on low moment. 34 us turn off time on high moment (100000 Am^2). Higher moments are planned for the future.	4 – 200 m but depends on EC distribution in the ground.	Production. Plus development ongoing.	SkyTEM in conjunction with Aarhus University
Fugro Tempest	Ask	Well over 100 km per hour	Flexible loop TEM mounted around aircraft. Receiver hanging about 60m below and behind aircraft.	10 to 200 m but depends on EC distribution in the ground.	Production with a history of use in Australia (enhancement of SaltTEM).	Fugro Airborne Surveys
Fugro Resolve	Ask	Up to 160 km per hour with a powerful helicopter.	Horizontal coplanar FDEM – one coil pair per frequency from 380 to 10100Hz.	Approximately 5 m down to 150 m but depends of geology and conductivity	Production	Fugro

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
HOISTem	Ask	Not known	Flexible loop TEM suspended below a helicopter.	10 to 200 m but depends on EC distribution in the ground.	Production	GPX, Western Australia
VTEM	Ask	30 to 120 km per hour depending on desired resolution	Flexible loop TEM. Rx and bucking loop in centre of Tx loop. Moments of up to 750000NIA but not simultan-eously with fast turn off times	10-200 m but depends on EC distribution and survey speed.	Production	Geotech
Hummingbird	Ask	Helicopter dependent	FDEM	Similar to Fugro Resolve but with less shallow resolution	Production	Geotech
Impulse	Ask	Helicopter dependent	FDEM	Similar to Fugro Resolve but with less shallow resolution.	Production	Aeroquest
AeroTEM	Ask	Helicopter dependent	Rigid loop TEM, Receiver and bucking loop in transmitter loop centre	Assumed to be similar to VTEM.	Production	Aeroquest

Device	*Price*	*Coverage Rate*	*Configuration*	*Depths of Investigation*	*Development stage*	*Manufacturer*
GEM 2A Broadband	Ask	Helicopter dependent	5 m long FDEM bird with common Tx and Rx coils	Less than Fugro Resolve	Production	Geophex

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