DEFINITION OF SOIL WATER DYNAMICS BY COMBINING HYDROMETRY AND GEOPHYSICS IN A HILLSLOPE TRANSECT IN THE KNP

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B.Sc (Hons)

Submitted in partial fulfilment of the
requirements for the degree of
MSc in Hydrology

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July 2006

DECLARATION

I hereby certify that the research reported in this dissertation is my own original and unaided work except where specific acknowledgements are made.

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ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation for the assistance given by the following people and institutes:

- **Prof. S.A. Lorentz**, Senior Research Fellow, School of Bioresources Engineering and Environmental Hydrology, University of Kwa-Zulu Natal, for his assistance and support while supervising this research;

- **The Foundation for Research and Development** for providing a post-graduate grant;

- **University of Kwa-Zulu-Natal**, for funding the 2 Dimensional Resistivity instrument from Sweden.

- **South African National Parks** for the ongoing support and monitoring for research in the Kruger National Park;

- **Mr J.J. Pretorius**, Senior Technician, School of Bioresources Engineering and Environmental Hydrology, University of Kwa-Zulu Natal, for his advice and invaluable assistance on numerous field trips and maintenance of the field equipment and operating the ERT instrument.

- **Mr S.R. Berry**, Fellow Research Student, **Mr E. Riddell**, Fellow Research Student, School of Bioresources Engineering and Environmental Hydrology, University of Kwa-Zulu Natal, for their advice and invaluable assistance on numerous field trips and maintenance of the field equipment and operating the ERT instrument.

- **Mr J.K. Ngeleka**, Laboratory Technician, School of Bioresources Engineering and Environmental Hydrology, University of Kwa-Zulu Natal, for the assistance in calibrating the TDR probes.

- **Mr R. Bester**, Consulting geologist, Dundee, South Africa, for all the help with earlier studies and introductions to the ERT instrumentation.

- **Mr G. Barkhuisen**, ABEM agent, Durban, South Africa, for all the assistance in making the correct cable set-ups and the invaluable assistance in getting the instrument running and helping with the protocol modelling after the problem encounted in the KNP.

- **Eva my Wife and my Parents,** for their continual support and encouragement.

ABSTRACT

The budgeting of water fluxes in the soil is an extremely complex problem, and is compounded by subsurface controls and environmental forces which modify the soil water dynamics. Of the controlling factors, the underlying geology and the soil media are vital components and are often misinterpreted. The geology and soil media components have been neglected mostly because of the difficulty in monitoring the dominant processes that are linked to the water balance in the subsurface. Until recently, hydrometry has been the dominant method of measuring and monitoring the subsurface water balance. Hydrometric measurements have included water content measurement by Time Domain Reflectometry (TDR), soil water potential measurements through tensiometry and groundwater water level monitoring. Hydrometry is still the preferred method of monitoring soil water dynamics, but measurements are generally localised and lateral accumulations and fluxes of water are difficult to interpret.

Using geophysical methods and instrumentation to define soil water dynamics could have numerous advantages over conventional hydrometric methods. Among the geophysical techniques dedicated to image the near surface, Electrical Resistivity Tomography (ERT) surveying has been increasingly used for environmental, engineering and geological purposes during the last decade. The aim of this study is to determine if ERT observations could yield the accuracy required to define vertical and lateral soil water dynamics.

The ERT instrumentation uses an electrical current that is inserted into the subsurface through various electrode arrangements and a resulting resistance is determined at the take-out electrodes. With the aid of a modelling package these resistance values are reproduced into a pseudosection of underlying resistivity distribution which is influenced by the moisture conditions of the subsurface medium. This geophysical method is primarily used for geological studies but by doing repeated surveys with the same electrode positioning, moisture fluctuation monitoring could be realised.

Use of the ERT technique is at the forefront of soil water dynamics monitoring. The main objective of this study is to propose that the ERT instrumentation could be a more efficient and more informative method of studying soil water dynamics than the traditional soil water dynamics monitoring equipment, particularly to define lateral fluxes and accumulation of subsurface water. The study site is a well instrumented transect in the Nkuhlu Exclosures in the Kruger National Park, South Africa, where ongoing soil water dynamics are monitored. The project aims to compare the ERT data to TDR data on a daily basis, over a period of three weeks, during the rain season, monitoring event based wetting and the subsequent drying phases of the soils in a 2-dimensional section.

The project and its findings are shown to be valuable to the hydrological interpretation of the subsurface water balance. The application is shown to be particularly important to ecohydrology, in the monitoring of soil water dynamics in a 2-dimensional transect and understanding how the natural cycles of water distribution and plant uptake are linked together. The study demonstrates that ERT can be used to observe changes in the water storage and lateral fluxes within a transect which supports varying vegetation and ecologies. The linking of water fluxes in the hydrology cycle to uptakes and controls in the ecosystem has been developed into the research focus known as ecohydrology The use of the ERT instrument can only benefit this research focus in the future. The study demonstrates that ERT instrumentation can be used to provide valuable understanding of subsurface water dynamics and in turn the effects on ecohydrology.

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1. INTRODUCTION

Subsurface water is vital to ecological and ecohydrological studies. One of the biggest problem facing scientists is that the observation of subsurface water dynamics is not an exact science, but even though subsurface water cannot be seen from the earth's surface, a variety of techniques can provide information on its occurrence and - under certain conditions - even its quality, from the surface. Even unsaturated soil water status and dynamics could be assesses from the surface. The Electrical Resistivity Tomography (ERT) method is a promising new method to provide these insights. This method of assessing subsurface liquid occurrence has been used extensively in the oil and geological fields with great success. Recently, this technique has been adapted to interpret subsurface water with considerable success. However, there are some pitfalls when adopting a geophysical investigation method to perform hydrological studies. Many of these pitfalls have been identified and this method of interpreting subsurface water occurrence is now at the forefront in many geophysical borehole-sighting techniques. If successfully applied to unsaturated soil water dynamics, the ERT technique could be at the forefront of subsurface water budgeting in both the vertical and lateral processes. Using the ERT approach is a "modern tool" for soil water and hillslope dynamic studies, not only in South Africa but also worldwide in the natural environments. The electrical resistivity technique uses a geophysical instrument, which has been used successfully worldwide in many geological and groundwater resources studies. The typical application has been to identify sites for water boreholes as well as to pick up fractured materials useful in identifying saturated subsurface water resources.

The vital question in most hillslope and groundwater dynamic's studies is, how and where does the water move from in the subsurface medium? If it does accumulate, where is this occurring and can the volume be quantified? How are the groundwater stores recharged and how much discharge takes place from the soil water accumulations? These are some of the questions more commonly asked in the field of subsurface water studies. In this present study some of these questions are addressed on a large field scale research site in the Kruger National Park (KNP), South Africa. It must be borne in mind that these are questions that are complex since subsurface water responds to soil matrix potential gradients, preferential flow pathways and interface controls. The challenge is to identify and observe the processes that dominate and also to understand the linking of these multidirectional soil water processes to ecological uptake processes which influence species distribution.

The objective of the study is to highlight some of the factors that control water movement in the "soil component" of ecohydrology and then link these factors to the hydrological and geologic aspects of ecohydrology. Each environment is different and there is no reason why ecohydrology should be solely concerned with particular processes (Rodriguez-Iturbe and Porporato, 2004). This project's aim is not to identify boreholes or site sources of ground water but to identify and determine if ERT can be used in conjunction with other soil water monitoring techniques [i.e. Time Domain Reflectometry (TDR)] or by itself as a method of monitoring and understanding soil water dynamics. The vital part of the study is to interpret the geophysical data in terms of matching hydrological data since the occurrence of subsurface water and the dynamics thereof are related (either directly or indirectly) to the geologies of the study area. An additional objective is to determine if the electrical resistivity method could be used in subsurface water studies in the future where the results of TDR data may not be present. This study shows an inversely proportional relationship between the TDR and ERT sets of results. The reason for the inverse proportionality is that the TDR data set provides volumetric water contents, (the more water in the profile, the higher the water content) while the ERT measures the electrical resistance in the porous medium, which decreases with increasing water content. If the conditions are dry, low volumetric water conditions result. On the other hand, the ERT technique produces a resistance value in Ohms/m and it is known that water is low in resistance compared to other geological materials. This means that the higher the moisture content in the medium, the lower the resistance values will be and *visa versa* for the drier medium conditions. The actual modelling and comparison of the two methods are discussed in more detail in Chapters 3 and 5.

The electrical resistivity data are modelled using the 2-Dimensional Inversion (2D-INV) model to produce a 2-dimensional "slice" of water content status and geological features in the subsurface. Various parameters can be altered in the modelling phase to improve the final outcome. To obtain a realistic outcome and an outcome that could be compared on a daily basis, appropriate parameters were set throughout the modelling phase. In addition some parameters were set to ensure a realistic comparison with the TDR data at the same sites. This interpretation phase of the study draws on all the other components of the study. Factors that are used in this stage of the study include rainfall, evaporation, runoff, TDR and soil/geologic data. There are three survey sites in this study and they are all situated on a transect in the KNP. The transect is highly instrumented and is served by a nearby weather station, which provides the source for most of the atmospheric data that is to be used in the interpretation phase.

The desired results from the study need to be consistent over a variety of soil and environmental conditions. To ensure this, three sites in different soils on different locations in the transect were identified. To ensure that the environmental conditions at the three sites remain constant for comparison purposes, the sites were selected in the same exclosure and on the same transect. Another reason for selecting one transect in the same area was to increase the ease of access and for logistical reasons. The transect chosen is a well instrumented transect and is being used in on-going soil water dynamics studies by the University of KwaZulu-Natal. In order to obtain accurate and adequate data, it was necessary to include a large rainfall event (greater than 25mm) and sufficient drying out phases (more than three days). The reason for this was to monitor the soil water changes over time and space and to identify any responses to the wetting and drying phases of the events.

Overall, the study proved to be a success and has opened the doors for further research into the field of subsurface water dynamics, and more specifically, the link between the hydrological cycle and ecohydrology as a whole. Once the links to ecohydrology have been made, the occurrence and dynamics of the subsurface waters will be highlighted. In order to provide the link to ecohydrological processes of plant water uptake it is important to understand the dynamics of subsurface waters, particularly those which distribute water laterally between ecotopes. Before the dynamics can be addressed the occurrence and types of media (soils and rock types) need to be understood (Todd, 1980).

The introductory chapters addresses the environmental factors which control variations in ecohydrology. The occurrence and dynamics of subsurface waters is introduced to gain an understanding and importance of the subsurface medium. Geophysical methods of identifying and monitoring subsurface waters are discussed with emphasis on the ERT instrumentation. This is followed by a discussion of TDR, which is used to determine the water content variations in a profile. The study site in the KNP is described next and this leads into the need to define soil water dynamics. The findings of the soil water observation study are presented, together with a brief account of typical problems encountered in applying the ERT and TDR techniques. The results present the dynamics of the 2-dimanesional slice of the subsurface as well as the correlation between resistivity measurements at specific locations within the lsice and the water content measurements (TDR) at the associated locations in the slice. The correlation is sufficient to conclude that the ERT technique would be a useful tool to apply to the observation of lateral flow soil water dynamics. Nevertheless, as with any scientific study, problems with the data collection and management are inevitable. This study was no different and so the numerous problems are listed at the end of the document. Most of the problems were corrected and did not influence the results negatively. By overcoming the problems encounted, valuable lessons were learnt, especially in the modelling phase of the study. Future recommendations are included in the document to guide future studies of this nature.

2. ECOHYDROLOGY

The study of ecology and hydrology as separate entities is outdated and the recent approach has been to include the various disciplines of study into one process that is interrelated in all aspects. This is the more realistic approach and has been accepted as such by many scientists, engineers and environmentalists. Ecohydrology is one such study, which is actually part of a large, highly complex interrelated system of studies that should not be broken up into smaller entities. Ecohydrology involves the study of both hydrology and ecology. However, before attempting a definition of ecohydrology, it is useful to consider how hydrology and ecology have been studied and how they are now linked. As a discipline, hydrology has a long history. Bras (1990) defines modern hydrology as "the study of water in all its forms and from all its origins to all its destinations on the earth." Implied in this definition is the need to understand how the water cycle works and how it moves through the physical and biological environment (Baird and Wilby, 1999). Also implied in this definition is the principle of continuity or the balance equation. The need to understand all the inputs and outputs and their pathways in the cycle is important.

Hydrology is also included large part of the engineering discipline concerned with water supply, waste water disposal and risk management, and in the last few years there has been a drive to also link ecology to hydrology among engineering researchers. According to Petts and Bradley (1997), in the past, hydrologists have focused on plants as roughness coefficients for the use of Manning's 1889 Universal Discharge Formula. Now an increasing number of hydrologists are concerned with how flow velocities affect plant growth in channels and the relationship between river flow regimes and ecological processes in riparian habitats. Another example is how hydrologists are studying the role of plants in the hydrologic environments in terms of evapotranspiration and rainfall interception (Davie and Durocher, 1997). In a similar fashion ecologists have become more aware and sophisticated in their appreciation of the water storage and transfer processes in the ecosystem (Baird and Wilby, 1999).

Rodriguez-Iturbe and Porporato (2004), state that the two important subjects that make up ecohydrology are soil moisture and plants. The former is at the centre of the hydrological cycle and the latter represents the primary component of terrestrial ecosystems. The analysis of their inter-relationships points at the very heart of ecohydrology, the science that studies the mutual interaction between the hydrologic cycle and ecosystems.

The history of ecology dates back to before 1866 and can be summarised as a term to describe the study of the relationship of any organism or group of organisms with their environment and one another. Ecology is therefore a study of interactions (Brewer, 1994). Ecology developed from the study of natural history and until the middle of the last century was concerned primarily with describing communities and the evolution of communities through successional processes. Ecological succession (Clements, 1916) refers to the ordered change in a community to a final stable state called the climax. Conservationists would generally welcome a clear understanding of the inter-relationships between vegetation and hydrology, to help them predict the likely effects of hydrological change upon vegetation (Wheeler and Shaw, 1995).

Ecohydrology and its theories, which for the purpose of this study comprises the interaction between the water balance and plants, is responsible for some of the fundamental differences among various biomes and for the developments of their space-time patterns. Ecohydrology has generally been applied to wet environments and only in recent years has this term been used on a wider scale (Rodriguez-Iturbe and Porporato, 2004). According to Rodriguez-Iturbe and Porporato (2004) the first objective of ecohydrology is to understand the intertwined characteristics of climate, soil and vegetation that make a biome what it is, and to relate hydrologic dynamics to the space-time response of vegetation in a region. The idea that soil moisture dynamics is at the core of water-controlled ecosystems is not new. Noy-Meir (1973) stated the soil is the store and regulator in the water flow system of ecosystems, both as a temporary store for the precipitation input allowing its use by organisms, and as a regulator controlling the partition of this input between major outflows such as runoff, percolation, evapotranspiration redistribution, and flow between the different organisms

This study's focus will address factors that control water movement in the "soil component" of ecohydrology and link these factors to the hydrology and geologic aspects of ecohydrology. Every environment is different and there is no reason why ecohydrology should be solely concerned with any particular processes (Rodriguez-Iturbe and Porporato, 2004).

2.1 Linking Subsurface Water and Ecohydrology

A groundwater level, whether it is the water table of an unconfined aquifer or the groundwater potential of a confined aquifer, indicates the elevation of atmospheric pressure of the aquifer. Differences between supply and withdrawal of groundwater, which could cause fluctuations to stream flow are closely related to subsurface water levels (Rodriguez-Iturbe and Porporato, 2004). Other diverse influences include meteorological and tidal phenomena, urbanization, and tectonically related activities.

The subsurface water component is made up of groundwater, which is under a positive atmospheric pressure and subsurface water in the unsaturated or vadose zone, which includes the capillary fringe just above the phreatic level and has a negative pore water pressure. It is very seldom that vegetation utilizes the groundwater, unless in wetland or mangrove environments. Most of the plant water relationships occur in the unsaturated zone above the phreatic surface (water table) and normally rely heavily on capillary action. It is in this zone that the ecohydrology becomes important. A few aspects will be highlighted in this section and their relevance will be linked to the ecohydrology.

2.1.1 Seasonal variations

Variations in subsurface water levels over periods of several years are known as secular variations. Alternating series of wet and dry years, in which the rainfall is above or below the mean, will produce long-period fluctuations of water levels in groundwater and water contents in the unsaturated zone. Rainfall is not an accurate indicator of subsurface water level changes, however, recharge is the governing factor (assuming annual withdrawals are constant); it also depends on rainfall intensity and distribution, and the amount of surface runoff. However, many subsurface water levels show a seasonal pattern of fluctuation, which results from influences such as rainfall and irrigation pumping that follow well-defined seasonal cycles. The amplitude of these changes depends on recharge, pumping and the type of aquifer; confined aquifers normally display a greater range in water levels than unconfined aquifers (Todd, 1976). Subsurface water levels often display characteristic short-term fluctuations governed by the primary use of subsurface water in a locality. Clearly defined diurnal variations may be associated with municipal water-supply boreholes. Similarly, weekly patterns occur with pumping for industrial and municipal purposes (Todd, 1976).

The analysis of seasonal variability in subsurface water dynamics is extremely important not only for ecohydrology (Rodriguez-Iturbe et al., 2001a; Rodriguez-Iturbe and Porporato, 2004) but also for a number of other issues such as evaluation of the most probable timing of floods and the determination of possible feedbacks between soil moisture and climate dynamics (Eltahir, 1998). The dependence of water stress on the subsurface water and soil nutrient dynamics drives the growth, reproduction, and competitive abilities of the plants. Since the different species have different responses to subsurface water dynamics, the hydrologic fluctuations continually shift the habitat preference in favour of different species and plant functional types.

2.1.2 Scale issues

The time scales of the hydrological factors forcing interaction with those of plant growth at various levels are dynamic and extremely complicated. In the case of trees, for example, these may easily span a day, to the growing season and to decadal time scales (Scholes and Archer, 1997). The dynamics are further complicated by the spatial interactions that are due to variability, plant competition, and the subsurface water dynamics. Temporal and spatial dynamics are thus highly intertwined and give rise to regular and irregular spatial patterns in continuous evolution (Rodriguez-Iturbe and Porporato, 2004).

2.2 Links to Environmental Factors which cause Ecohydrological Fluctuations

From the level of a single plant to the entire ecosystem, the action of climate, soil, and vegetation is linked to plant response by two fundamental processes: the first one concerns the subsurface water dynamics and controls the degree and duration of periods of soil-water deficit, while the second one regulates the impacts of this water deficit on plant physiology (Rodriguez-Iturbe and Porporato, 2004). Since plants get their water from the soil, many of the impacts of climate and soil affect the plants through the filter of subsurface water dynamics. Effective drought conditions for plants are determined by soil moisture availability and not necessarily by precipitation scarcity (Stephenson, 1998). Thus plants can experience drought even under favourable conditions, due to poor soil characteristics (Dagan *et al*, 2004), and different vegetation types can be found within a short distance simply because of changes in subsurface water levels (Rodriguez-Iturbe and Porporato, 2004). Ecological stress is a condition in an organism when potentially harmful levels of environmental factors cause alterations to the organism (Lauenroth *et al.*, 1978). In many ecosystems, and especially in arid and semi-arid climates, soil-moisture deficit is often the most important stress factor for vegetation. Grazing and fire are also present but their impact is frequently modulated by the effect of soil-water deficit on existing vegetation (Scholes and Archer, 1997). Likewise, heat or radiation stress mostly takes over after the cooling effect of transpiration has been reduced by the soil water deficit (Rodriguez-Iturbe and Porporato, 2004).

2.2.1 Total evaporation

Unconfined aquifers with water tables near the ground surface, such as wetlands, frequently exhibit diurnal fluctuations that can be ascribed to the uptake induced by evaporation and/or transpiration (Rodriguez-Iturbe and Porporato, 2004). Both processes cause a discharge of subsurface water to the atmosphere and have similar diurnal variations because of their high correlation with solar radiation. Evaporation uptake in the form of vapour from a subsurface water zone from the capillary fringe, increases as the water table approaches the ground surface. The rate also depends on the soil structure, which controls the capillary tension above the water table and hence the hydraulic conductivity due to the fluxes at the surface of the soil layer. For isothermal conditions, upward movement is essentially all in liquid phase, but a soil may have a high surface temperature, causing it to dry out and establishing upward vapour movement in response to a vapour pressure gradient. Where the root zone of vegetation reaches the unsaturated stratum, the uptake of water by roots equals the transpiration rate inducing an upward water gradient providing soil water is not limiting. Magnitudes of transpiration seasonal fluctuations depend on the type of vegetation, season, and weather (van Hylckama, 1974; Eagleson, 2002). Hot, windy days produce maximum drawdowns, whereas cool, cloudy days show only small variations. Fluctuations begin with the appearance of foliage damage and cease after killing frosts. Transpiration does not occur in non-vegetated areas, such as ploughed fields, or in areas where the water table is well below the ground surface (Todd, 1976; Lewis and Burgy, 1964). From a practical standpoint it is difficult to segregate evaporation and transpiration losses from subsurface water; therefore, the combined loss, referred to, as evapotranspiration (total evaporation) is typically the quantity normally measured or calculated (Baird and Wilby, 1999). Evapotranspiration is regarded as the most important flux in the hydrological cycle. Studies conducted by Trambouze in 1996, showed that at an annual scale, during a three year survey period, outflow from a plot was 32% of total rainfall, which indicates that evapotranspiration represents almost two thirds of the annual rainfall. Depending on the subsurface water state in an area, the ecology, which is dependent on evapotranspiration, will be controlled and altered accordingly.

2.2.2 Rainfall

Rainfall is not an accurate indicator of subsurface water recharge because of surface and subsurface losses as well as travel time for vertical percolation. The travel time may vary from a few minutes for shallow water tables in permeable formations to several months or years for deep water tables within underlying sediments with low vertical permeabilities. Furthermore in arid and semi-arid regions, recharge from rainfall is almost zero. Subsurface water levels may show seasonal variations due to rainfall, but often these include natural discharge and pumping effects as well (Todd, 1976). Rainfall in turn affects the ecology of an area as being one of the major factors causing environmental variations and these variations are constantly changing, mimicking the seasonal variations and hence altering the ecohydrology of an area on an on-going basis.

2.2.3 Meteorological phenomena

Changes in atmospheric pressure produce sizable fluctuations in wells penetrating confined aquifers (Todd, 1976). The relationship is inverse; the higher the atmospheric pressure, the lower the water levels and visa versa. Minor fluctuations of well water levels are caused by wind blowing over tops of wells. The effect is identical to the action of a vacuum pump. As a gust of wind blows across the top of a casing, the air pressure within the well rises and the water level falls. This effect thereof, is that with lower water levels the vegetation is placed under additional stress that in turn affects the surrounding ecology.

2.3 Occurrence and Dynamics of Subsurface Water

The subsurface water component is made up of groundwater, which is all the water under a positive atmospheric pressure and is usually found in aquifers or highly fractured material.

Groundwater is commonly understood to mean water occupying all the voids within a geologic stratum. Some strata form good aquifers, whereas others are poor. The most important requirement is that the stratum must have inter-connected openings or pores through which water can move. The nature of each aquifer depends on the material of which it is composed, its origin, the relationship of the constituent grains or particles and associated pores, its relative position in the Earth's surface, its exposure to a recharge source, and other factors (U.S.D.I.W.P.R.S., 1981).

The other component of the subsurface water component is the unsaturated or vadose zone, which includes the capillary fringe just above the phreatic level and has a negative atmospheric pressure. It is very seldom that vegetation utilizes the groundwater, unless in a wetland in mangrove environments. Most of the plant water relationships occur in the unsaturated zone above the phreatic level (water table) and normally rely heavily on the capillary fringe and capillary action. Unsaturated zones are usually found above saturated zones and extend upward to the ground surface and because this water includes soil moisture within the root zone, it is a major concern of agriculture, botany and soil science commonly classified in ecohydrology. Water can move from zone to zone in either direction (Todd, 1976). General discussions on the composition of various rock types and aquifers as well as water dynamics will follow in the sub-sections of this chapter. The understanding of this terminology is vital when dealing with the dynamics of subsurface waters.

2.3.1 Composition of the earth

The materials that make up the composition of the earth, whether consolidated and firm or unconsolidated and loose or soft are generally classified as sedimentary, igneous or metamorphic. The geologic structure, lithology, and stratigraphy of rocks in an area provide general knowledge of their potentials as aquifers (U.S.D.I.W.P.R.S., 1981). A few of the following terms related to aquifers and aquifer material will be highlighted below.

2.3.2 Sedimentary rocks

In general the best aquifers are the coarse-grained, saturated portions of unconsolidated, granular sedimentary mantle, which cover the consolidated rocks over much of the surface of the earth. The coarser grained consolidated rocks such as conglomerates and sandstones are often good aquifers, but are usually found below the unconsolidated granular sedimentary mantle. Their value as aquifers depends on the degree of cementation and fracturing to which they have been subjected. However some massive sedimentary rocks such as limestone, dolomite and gypsum may also be good aquifers. These rocks are relativity soluble and over the years fractures may develop into voids (U.S.D.I.W.P.R.S., 1981; Chand *et al* 2004).

2.3.3 Igneous and metamorphic rocks

These are not ideal aquriferous rocks but it will depend on the amount of weathering and stress to which they have been subjected to alter their initial formation. Faults caused by mechanical and other stresses cause fractures in which groundwater may occur (U.S.D.I.W.P.R.S., 1981).

2.3.4 Recharge and discharge

Natural environments may contain various structures that help regulate their hydrological environment, both to retain and to dissipate water (Baird and Wilby, 1999). Practically all subsurface water originates as surface water. Principle sources of natural recharge include precipitation, streamflow, lakes and reservoirs. Other contributions, known as artificial recharge, occur from excess irrigation, seepage from canals, and water applied to augment groundwater supplies. Even seawater can enter underground along coasts where hydraulic gradients slope downward in an inland direction. Water within the ground moves downward through the unsaturated zone under the action of gravity, whereas in the saturated zone it moves in a direction determined by the hydraulic situation (Todd, 1976). Vegetation has both positive and negative effects on recharge; positively it affects the recharge once the vegetation has died off and is in the decomposing stage. Water is able to move down the geological profiles in the channels created by the decomposed roots and rootlets. The negative effect of vegetation on recharging the groundwater is that roots, especially those of trees are able to tap deep into the soil profiles in search of the groundwater. This is known as discharge and plays a vital role in the transpiration process.

Discharge of groundwater occurs when water emerges from underground mostly as flow into surface water bodies, such as streams, lakes, and oceans; flow to the surface appears as a spring (Todd, 1976). Groundwater near the surface may return directly to the atmosphere by evaporation from within the soil or by transpiration through plants as evapotranspiration. Pumping from wells and boreholes constitutes the major artificial discharge of groundwater.

3. GEOPHYSICAL INVESTIGATIONS USED IN ECOHYDROLOGY

Subsurface water is vital to ecological and ecohydrological studies. One of the most significant problems facing scientists is that the sourcing of subsurface water is not an exact science, but, even though subsurface water cannot be seen on the earth's surface, a variety of techniques can provide information concerning its occurrence and - under certain conditions - even its quality. This can be achieved from the surface and includes the ability to assess unsaturated soil water conditions and dynamics using the Electrical Resistivity Tomography (ERT) method. Surface investigations of subsurface water are seldom more than partially successful and this leads to an incomplete hydrologic picture; however such methods are normally less costly than subsurface investigations. There are generally two geologic steps taken in subsurface water investigations:

i. Firstly, general interpretation of geological data and field reconnaissance are vital. In addition to the above are remote sensing techniques using aircraft or satellite techniques.
ii. Secondly, more accurate methods are then used, with the information from the first step as a starting point. Geophysical techniques, especially electrical resistivity and seismic refraction methods, provide indirect indicators of subsurface water occurrence.

Correct interpretation requires supplemental data from subsurface investigations to substantiate surface findings (Todd, 1980). Geologic studies enable large areas to be rapidly and economically appraised on a preliminary basis as to their potential for subsurface water development. A geologic investigation begins with the collection, analysis, and hydrologic interpretation of existing topographic maps, aerial photographs, geologic maps and logs, and other pertinent records (streamflow, well yields, nearby borehole logs, recharge and discharge of wells and water quality) (Todd, 1980). This all falls under the first point mentioned above. Studies of the depositional and erosional events in the area may indicate the extent and regularity of water bearing formations. Rock types normally suggest the magnitude of water yield. Stratigraphy and geologic history of an area may reveal aquifers beneath unsuitable upper strata, the continuity and interconnection of aquifers, or important aquifer boundaries. The nature and thickness of overlaying beds, as well as the dip of water-bearing formations, will enable estimates of drilling depths to be made. Similarly, confined aquifers may be noted and the possibility of flowing wells or low pumping lifts foretold. Landforms can often reveal near-surface unconsolidated formations serving as aquifers. Faults, which may form impermeable barriers to subsurface flow, frequently can be mapped from surface traces. Geophysical surveys are essentially the interpretation of the variations in measured response at the surface to certain forces, either naturally or artificially generated within the earth's crust (U.S.D.I.W.P.R.S., 1981). Other geologic studies are available but will not be discussed in detail in this study. Remote sensing is one such example and is based on photographs taken from aircrafts or satellites at various electromagnetic wavelength ranges to provide useful information regarding subsurface water conditions (Todd, 1976).

Geophysical exploration is the scientific measurement of physical properties of the earth's crust for investigation of mineral deposits or geologic structure (Dobrin, 1976). Oil was discovered by geophysical methods in 1926, and economic pressures for locating petroleum and mineral deposits stimulated the development and improvement of many geophysical methods and equipment. Application to subsurface water investigations was slow because the commercial value of oil overshadows that of water. Today, many organisations concerned with subsurface water employ geophysical methods.

Geophysical methods detect differences, or anomalies, of physical properties within the earth's crust. Density, magnetism, elasticity, and electrical resistivity are properties most commonly measured. Experience and research have enabled pronounced differences in these properties to be interpreted in terms of geologic structure, rock type and porosity, water content, and water quality (U.S.D.I.W.P.R.S., 1981). After the electrical resistivity method, the following methods are the most widely used;

- Seismic surveys that are based on measurements of the velocity distribution of artificially generated seismic waves in the earth's crust. The velocity of the seismic waves generated depends on the density and elasticity of the subsurface materials. The velocity is usually lowest for unconsolidated materials and increases with the degree of consolidation or cementation (Cook and Williams, 1998). This method of geophysics is not widely used in ecohydrological studies.
- The magnetic properties of the rocks affect the earth's magnetic field. In a magnetometer survey, the strength of the vertical component of the earth's magnetic field is measured and plotted on a map. Analysis of the results may indicate qualitatively the depth to bedrock and presence of buried dykes, sills, and similar phenomena and is therefore limited to mining operations. This survey is rapid and a relatively low-cost

method of determining a limited amount of subsurface geologic information (Todd, 1980).

- The gravimetric survey is the force of gravity measured at stations along a traverse or in a grid. Gravity variations result from the contrast in density between subsurface materials of various types (McGinnis et al, 1967).
- Water witching or dowsing methods lack scientific justification but are used wherever the users are able to persuade their customers. Commonly the method involves using a forked stick held in both hands and walking over the local area until the butt end is attracted downward – ostensibly by the subsurface water. This method is widely used in ecohydrological studies in terms of monitoring subsurface water fluxes.

3.1 Resistivity

The purpose of electrical resistivity is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated. The ground resistivity is related to various geological parameters such as the minerals and fluid content, porosity, degree of water saturation in the rock and dissolved ions in the water. Resistivity investigations can thus be used to identify zones with different electrical properties, which can accurately be referred to different geologic strata (Abem, 2005).

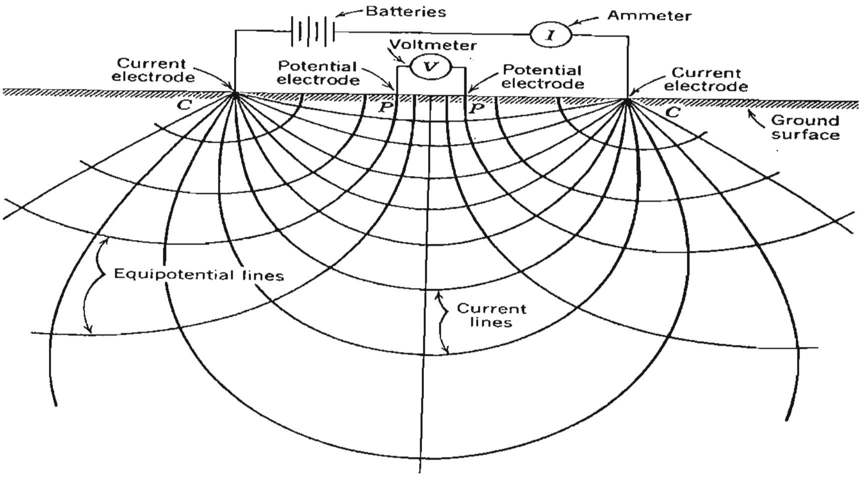


Figure 3.1 Basic electrical circuit for resistivity determination and field for homogeneous subsurface stratum (after Todd, 1980).

Electrical resistivity surveys have been used for many decades in hydro-geological, mining and geotechnical investigations. More recently, electrical resistivity methods have been used for environmental surveys. The resistivity measurements are normally conducted by injecting current into the ground through two current electrodes (electrodes C in Figure 3.1), and measuring the resulting voltage difference at two potential electrodes (P). From the current (I) and voltage (V) values, an apparent resistivity (p_a) value is calculated.

$$p_a = k\,V / I \tag{3.1}$$

Where k is the geometric factor, which depends on the arrangement of the four electrodes.

Figure 3.2 shows the common arrays used in resistivity surveys together with their geometric factors.

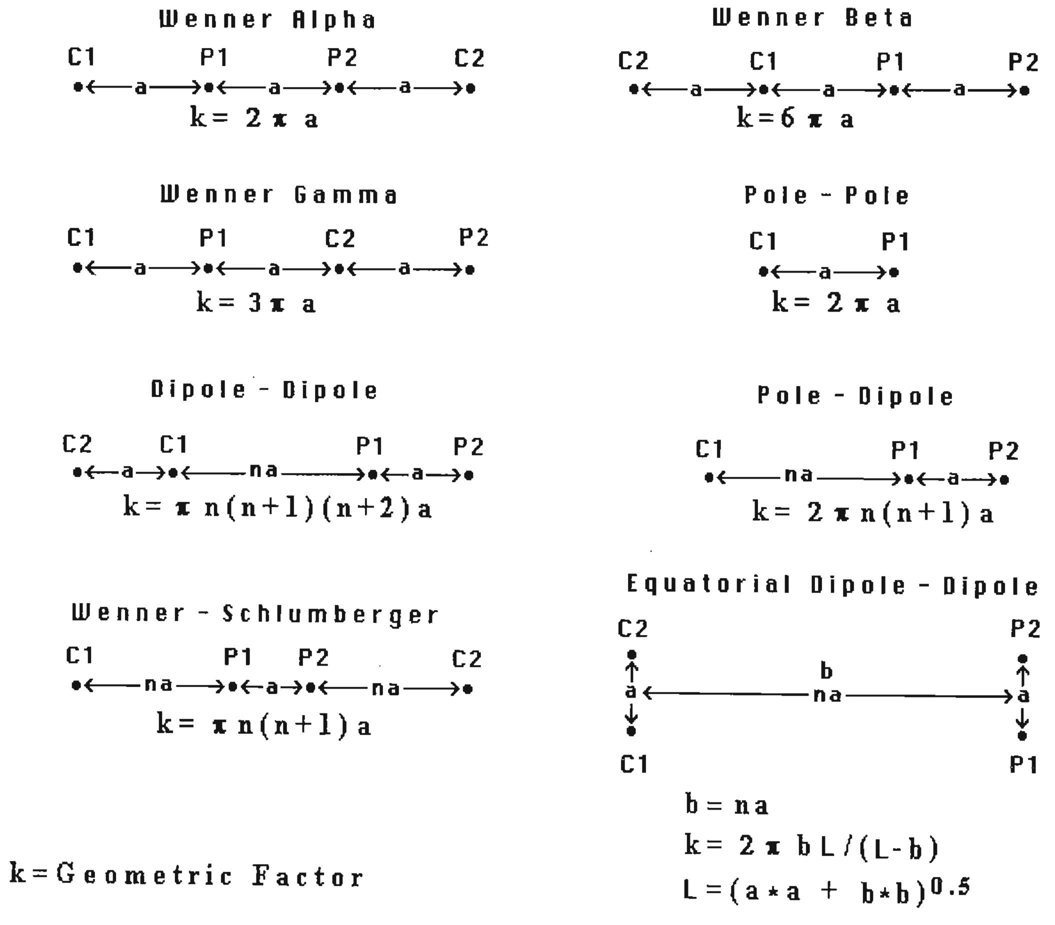


Figure 3.2 Common arrays used in resistivity surveys and their geometric factors (after Loke, 1999).

Resistivity meters normally give a resistance value, R = V/I, so in practice the apparent resistivity value is calculated by

$$p_a = k\,R \tag{3.2}$$

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

3.1.1 Traditional resistivity surveys

The resistivity method has its origin in the 1920's due to the work of the Schlumberger brothers. For approximately the next 60 years, for quantitative interpretation, conventional sounding surveys (Koefoed 1979) were normally used. In this method, the centre point of the electrode array remains fixed, but the spacing between the electrodes is increased to obtain more information about the deeper sections of the subsurface. Refer to Figure 3.1 for a conventional four electrode array to measure the subsurface resistivity also know as 1-Diemsional Resistivity (1-D Res). The measured apparent resistivity values are normally plotted on a log-log graph paper. To interpret the data from such a survey, it is normally assumed that the subsurface consists of horizontal layers. In this case, the subsurface resistivity changes only with depth, but does not change in the horizontal direction. A one-dimensional model of the subsurface is used to interpret the measurements (Refer to Figure 3.3a). Despite this limitation, this method has given useful results for geological situations (such as the water-table) where the one-dimensional model is approximately true. Another classical survey technique is the profiling method. In this case, the spacing between the electrodes remains fixed, but the entire array is moved along a straight line. This gives some information about lateral changes in the subsurface resistivity, but it cannot detect vertical changes in the resistivity and is an extremely time-consuming exercise. Interpretation of data from profiling surveys is mainly qualitative. The most severe limitation of the resistivity sounding method is that horizontal (or lateral) changes in the subsurface resistivity are commonly found. Lateral changes in the subsurface resistivity will cause changes in the apparent resistivity values, which might be, and frequently are, misinterpreted as changes with depth in the subsurface resistivity. In many engineering and environmental studies, the subsurface geology is very complex where the resistivity can change rapidly over short distances. The resistivity sounding method might not be sufficiently accurate for such situations. Despite its obvious limitations, there are two main reasons why 1-D Res sounding surveys are common. The first reason was the lack of proper field equipment to carry out the more data intensive 2-D and 3-D surveys. The second reason was the lack of practical computer interpretation tools to handle the more complex 2-D and 3-D models (Refer to Figures 3.3b and 3.3c). However, 2-D and even 3-D electrical surveys are now practical commercial techniques with the relatively recent development of multi-electrode resistivity surveying instruments (Griffiths et al. 1990) and fast computer inversion software (Loke 1999).

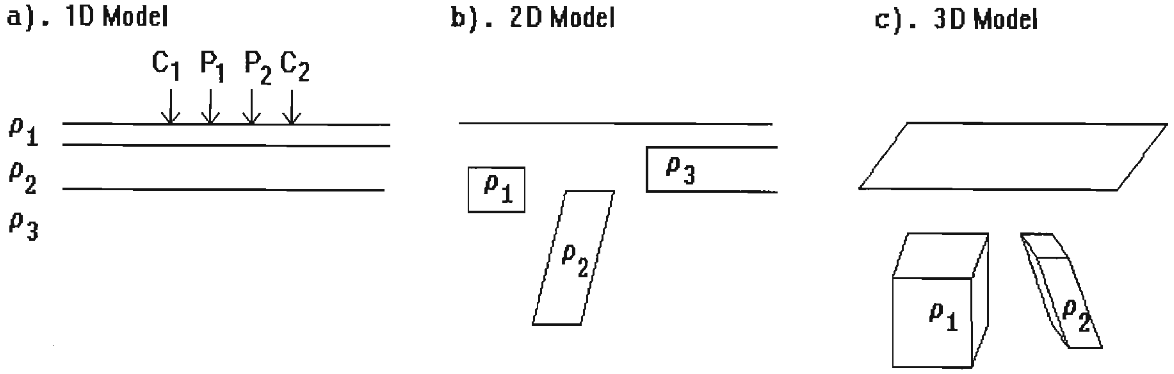


Figure 3.3 The three different models used in the interpretation of resistivity measurements (after Loke, 1999).
3a refers to normal 1 Dimensional survey (x and y co-ordinates),
3b refers to 2 Dimensional surveys (x, y and z co-ordinates) and
3c refers to 3 Dimensional surveys (x, y, z and depth perspectives)

3.1.2 The relationship between geology and resistivity

Before dealing with the 2-D and 3-D resistivity surveys, we will briefly look at the resistivity values of some common rocks, soils and other materials. Resistivity surveys give a picture of the subsurface resistivity distribution. To convert the resistivity picture into a geological picture, some knowledge of typical resistivity values for different types of subsurface materials and the geology of the area surveyed, is important. The resistivity of these rocks is normally a function of the amount and quality of water in pore spaces and fractures (Abem, 2005). The degree of connection between the cavities is also important. Consequently, the resistivity of a type of rock or soil may vary widely. (Abem, 2005). The amount of water in a material depends on the porosity, which may be divided into primary and secondary porosity. Primary porosity consists of pore spaces between the mineral particles, and occurs in soils and sedimentary rocks. Secondary porosity consists of fractures and weathered zones, and this is the most important porosity in crystalline rock such as granite and gneiss. Secondary porosity may also be important in sedimentary rocks, such as limestone. Even if porosity is low, the electrical conduction taking place through water filled pore spaces may reduce the resistivity of the material dramatically. The degree of water saturation will of course affect the resistivity, and the resistivity above the groundwater will be higher than below if the material is the same. Refer to Table 3.1 for the electrical resistivity ranges in natural waters. However, if the content of fine-grained material is significant, the water content above the groundwater surface, held by capillary forces, may be large enough to dominate the electrical behaviour of the material. The resistivity of the pore water is determined by the concentration of ions in solution, the type of ions and the temperature.

The resistivity of ground water varies from 10 to 100 ohm•m. depending on the concentration of dissolved salts. Note the low resistivity (approx. 0.2 ohm•m) of seawater in Table 3.1 due to the relatively high salt content. This makes the resistivity method an ideal technique for mapping the saline and fresh water interface in coastal areas.

Table 3.1 Electric resistivity of some types of natural waters (after Kollert, 1969).

Type of Water	**Resistivity[Ω m]**
Precipitation	30-1000
Surface water, in areas of igneous rock	30-500
Surface water, in areas of sedimentary rock	10-100
Groundwater, in areas of igneous rock	30-150
Groundwater, in areas of sedimentary rock	>1
Sea water	approx. 0.2
Drinking water (max. salt content 0.25%)	>1.8
Water for irrigation and stock watering (Max. salt content 0.25%)	>0.65

However, the variations may be limited within a confined geological area, and variations in resistivity within a certain soil or rock type will reflect variations in physical properties. Fresh crystalline rock is highly resistive, apart from that bearing certain ore minerals, but weathering commonly produces highly conductive clay-rich saprolite. Refer to Table 3.2 for the common resistivity values of igneous and metamorphic rocks. Igneous and metamorphic rocks typically have high resistivity values while sedimentary rocks, which usually are more porous and have higher water content, normally have lower resistivity values. Wet soils and fresh ground water have even lower resistivity values. Clayey soil normally has a lower resistivity value than sandy soil. The presence of clay minerals strongly affects the resistivity of sediments and weathered rock (Dahlin and Loke 1998). The clay minerals may be regarded as electrically conductive particles, which can absorb and release ions and water molecules on its surface through an ion exchange process. As the variation in temperature of the ground is generally very small, the temperature influence is normally negligible.

Table 3.2 Resistivities of common rocks/materials and selected ore minerals (Delta Mine Training Centre, 2005).

Common Rocks/Materials	**Resistivity (ohm meters)**	**Ore Minerals**	**Resistivity (ohm meters)**
Clay	1 – 100	Pyrrhotite	0.001 – 0.01
Graphitic Schist	10 – 500	Galena	0.001 – 100
Topsoil	50 – 100	Cassiterite	0.001 – 10,000
Gravel	100 – 600	Chalcopyrite	0.005 – 0.1
Weathered Bedrock	100 – 1000	Pyrite	0.01 – 100
Gabbro	100 – 500,000	Magnetite	0.01 – 1,000
Sandstone	200 – 8,000	Hematite	0.01 – 1,000,000
Granite	200 – 100,000	Sphalerite	1000 – 1,000,000
Basalt	200 – 100,000		
Limestone	500 – 10,000		
Slate	500 – 500,000		
Quartzite	500 – 800,000		
Greenstone	500 – 200,000		

Note the overlap in the resistivity values of the different classes of rocks. This is because the resistivity of a particular rock or soil sample depends on a number of factors mentioned above such as the porosity, the degree of water saturation and the concentration of dissolved salts.

Metals, such as iron, have extremely low resistivity values. Resistivity values have a much larger range compared to other physical quantities mapped by other geophysical methods. The resistivity of rocks and soils in a survey area can vary by several orders of magnitude. In comparison, density values used by gravity surveys usually change by less than a factor of 2, and seismic velocities usually do not change by more than a factor of 10. This makes the resistivity and other electrical or electromagnetic based methods very versatile geophysical techniques.

3.2 2-D Electrical Imaging Surveys

We have seen the greatest limitation of the resistivity sounding method is that it does not take into account horizontal changes in the subsurface resistivity. A more accurate model of the subsurface is a two-dimensional (2-D) model where the resistivity changes in the vertical direction, as well as in the horizontal direction along the survey line are modelled. In this case, it is assumed that resistivity does not change in the direction that is perpendicular to the survey line. In many situations, particularly for surveys over elongated geological bodies, this is a reasonable assumption. In theory, a 3-D resistivity survey and interpretation model should be even more accurate. However, at the present time, 2-D surveys are the most practical and economic compromise between obtaining very accurate results and keeping the survey costs down. Typical 1-D resistivity sounding surveys usually involve about 10 to 20 readings, while 2-D imaging surveys involve about 100 to 1000 measurements. In comparison, 3-D surveys usually involve several thousand measurements. The cost of a typical 2-D survey could be several times the cost of a 1-D sounding survey, and is probably comparable with a seismic survey. In many geological situations, 2-D electrical imaging surveys can give useful results that are complementary to the information obtained by other geophysical method. For example, seismic methods can map undulating interfaces well, but will have difficulty (without using advanced data processing techniques) in mapping discrete bodies such as boulders, cavities and pollution plumes. Ground radar surveys can provide more detailed pictures but have very limited depth penetration in areas with conductive unconsolidated sediments, such as clayey soils. Two-dimensional electrical surveys should be used in conjunction with seismic or ground radar surveys as they provide complementary information about the subsurface. Refer to Appendix K for a comprehensive operation manual that accompanies the instrument (compiled by the author of this thesis).

3.2.1 Field survey method - instrumentation and measurement procedure

One of the new developments in recent years is the use of 2-D electrical imaging/topography surveys to map areas with moderately complex geology (Griffiths and Barker 1993). Such surveys are usually carried out using a large number of electrodes, 25 or more, connected to a multi-core cable. A laptop computer, together with an electronic switching unit, is used to automatically select the relevant four electrodes for each measurement (Figure 3.4). At present, field techniques and equipment to carry out 2-D resistivity surveys are fairly well developed. The necessary field equipment is commercially available from a number of international companies. These systems typically cost from about R300 000 upwards (dated 2005). Some institutions have even constructed "home-made" manually operated switching units at a nominal cost by using a seismic cable as the multi-core cable!

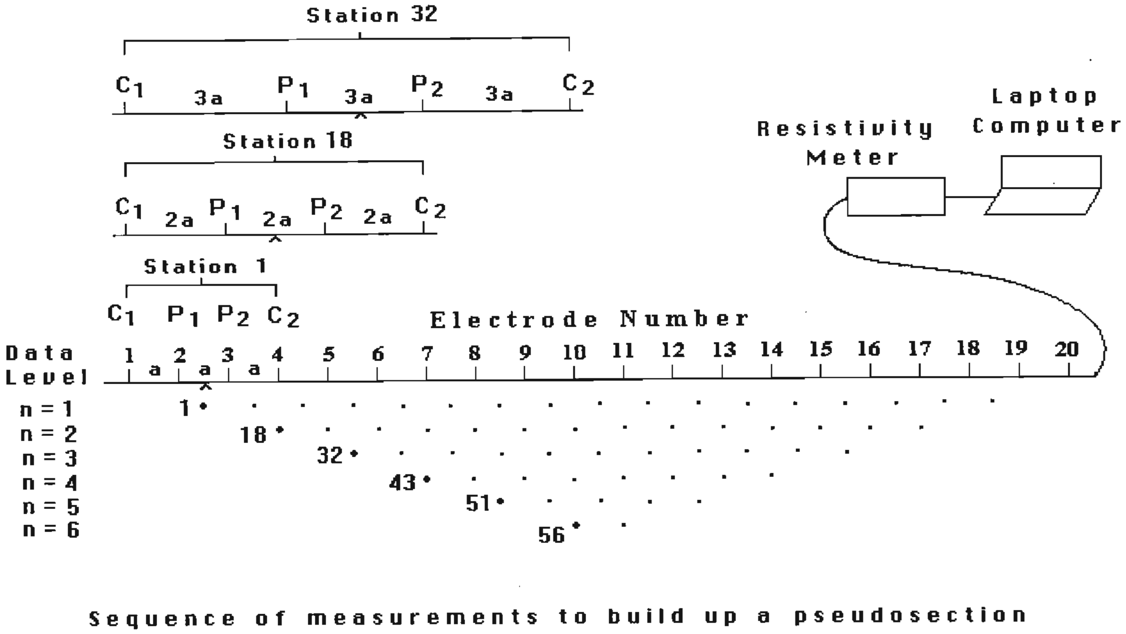


Figure 3.4 The arrangement of electrodes for a 2-D electrical survey and the sequence of measurements used to build up a pseudosection. (http://www.abem.com/software.php)

Figure 3.4 shows the typical set-up for a 2-D survey with a number of electrodes along a straight line attached to a multi-core cable. Normally a constant spacing between adjacent electrodes is used. The multi-core cable is attached to an electronic switching unit, which is connected to a laptop computer. The sequence of measurements to take, the type of array to use and other survey parameters (such as the current to use) are normally entered into a text file, which can be read by a computer program in a laptop computer. After reading the protocol file, the computer program then automatically selects the appropriate electrodes for each measurement. In a typical survey, most of the fieldwork comprises laying out the cable and electrodes. After that, the measurements are taken automatically and stored in the computer. Most of the survey time is spent waiting for the resistivity meter to complete the set of measurements.

To obtain a good 2-D picture of the subsurface, the coverage of the measurements must be 2-D as well. As an example, Figure 3.4 shows a possible sequence of measurements for the Wenner electrode array for a system with 64 electrodes. In this example, the spacing between adjacent electrodes is "a". The first step is to make all the possible measurements with the Wenner array with electrode spacing of "1a". For the first measurement, electrodes number 1, 2, 3 and 4 are used. Notice that electrode 1 is used as the first current electrode C1, electrode 2 as the first potential electrode P1, electrode 3 as the second potential electrode P2 and electrode 4 as the second current electrode C2. For the second measurement, electrodes number 2, 3, 4 and 5 are used for C1, P1, P2 and C2 respectively. This is repeated down the line of electrodes until electrodes 61, 62, 63 and 64 are used for the last measurement with "1a" spacing. For a system with 64 electrodes, note that there are 61 (64 - 3) possible measurements with "1a" spacing for the Wenner array. After completing the sequence of measurements with "1a" spacing, the next sequence of measurements with "2a" electrode spacing is made. First electrodes 1, 3, 5 and 7 are used for the first measurement. The electrodes are chosen so that the spacing between adjacent electrodes is "2a". For the second measurement, electrodes 2, 4, 6 and 8 are used. This process is repeated down the line until electrodes 58, 60, 62 and 64 are used for the last measurement with spacing "2a". For a system with 64 electrodes, note that there are 58 (64 - 2x3) possible measurements with "2a" spacing. The arrangement of electrodes for a 2-D electrical survey and the sequence of measurements are used to build up a pseudosection. The same process is repeated for measurements with "3a", "4a", "5a", and "6a" spacings until the largest possible spacings are completed. To get the best results, the measurements in a field survey should be carried out in a systematic manner so that, as far as possible, all the possible measurements are made. This will affect the quality of the interpretation model obtained from the inversion of the apparent resistivity measurements (Dahlin and Loke 1998).

Note that as the electrode spacing increases, the number of measurements decreases. The number of measurements that can be obtained for each electrode spacing, for a given number of electrodes along the survey line, depends on the type of array used. The Wenner array gives the smallest number of possible measurements compared to the other common arrays that are used in 2-D surveys. One technique used to extend the area covered by the survey horizontally, particularly for a system with a limited number of electrodes, is the roll-along method. After completing the sequence of measurements, the cable is moved past one end of the line by several unit electrode spacings. All the measurements, which involve the electrodes on part of the cable, which do not overlap the original end of the survey line, are repeated. This process was done on numerous surveys conducted in the KNP in a previous study by the BEEH and consulting geohydrologists due to the extended lengths of the transects studied. Refer to Appendix B for an earlier example of a roll along study of transect 7, in the Nkuhlu exclosures.

3.2.2 Pseudosection data plotting method

To plot the data from a 2-D imaging survey, the pseudosection contouring method is normally used. A pseudosection is picture produced once the modelling has been completed and is made up of various colour-coded resistivity ranges. In this case, the horizontal location of the point is placed at the mid-point of the set of electrodes used to make that measurement. The vertical location of the plotting point is placed at a distance, which is proportional to the separation between the electrodes.

Another method is to place the vertical position of the plotting point at the median depth of investigation (Edwards 1977), or pseudodepth, of the electrode array used. The pseudosection plot obtained by contouring the apparent resistivity values is a convenient means to display the data. The pseudosection gives a very approximate picture of the true subsurface resistivity distribution. However the pseudosection gives a distorted picture of the subsurface because the shapes of the contours depend on the type of array used as well as the true subsurface resistivity. The pseudosection is useful as a means to present the measured apparent resistivity values in a pictorial form, and as an initial guide for further quantitative interpretation. One common mistake made, is to try to use the pseudosection as a final picture of the true subsurface resistivity. Different arrays used to map the same region can give rise to very different contour shapes in the pseudosection plot. One useful practical application of the pseudosection plot is for picking out bad apparent resistivity measurements. Such bad measurements usually stand out as points with unusually high or low values and can be removed prior to modelling and producing the pseudosection. Refer to Figure 3.5 for bad point data. The objective of the plot in Figure 3.5 is to identify bad data points and remove them from the survey before modelling the data. The data points should form horizontal lines with the crosses donating the position of the data points. Points that are offset from the horizontal lines are bad data points and can be removed if desired.

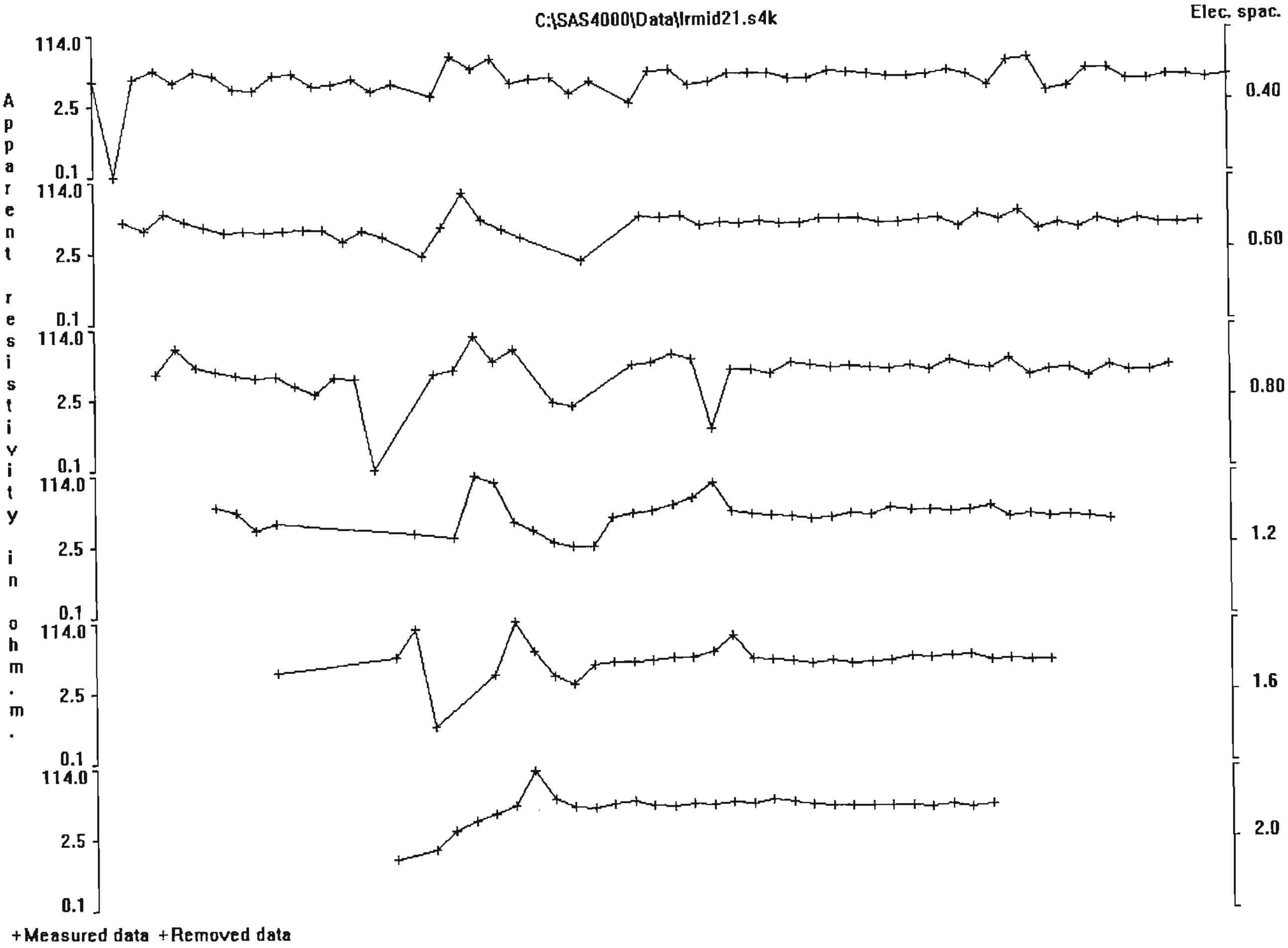


Figure 3.5 Plot to identify bad data points in the survey (Abem, 2005).

3.2.3 Forward modelling program exercise

RES2DMOD.EXE is a 2-D forward modelling program, which calculates the apparent resistivity pseudosection for a user and is defined as a 2-D subsurface model. With this program, the user can choose the finite-difference (Dey and Morrison 1979a) or finite-element (Silvester and Ferrari 1990) method to calculate the apparent resistivity values. In the program, the subsurface is divided into an array of a large number of small rectangular cells which consist of specific data points (determined by array and protocol used) which are take the surrounding cells into consideration in the modelling process. By taking the surrounding cells into consideration the pseudosections are smoothed. The array is the electrode setup while the protocol is the modelling setup within each array and this could be altered as per requirements by the user. The program is also able assist the user in choosing the appropriate array for different geological situations or surveys. The arrays supported by this program are the Wenner (Alpha, Beta and Gamma configurations - the Alpha configuration is normally used for field surveys and usually just referred to as the "Wenner" array), Wenner-Schlumberger, pole-pole, inline dipole-dipole, pole-dipole and equatorial dipole-dipole (Edwards 1977). Each type of array has its advantages and disadvantages. This program can aid in selecting the "best" array for a particular survey area after studying the protocol and carefully balancing factors such as the cost, depth of investigation, resolution and practicality. Refer to Figure 3.6 for an example of a pseudosection. The modelled pseudosection is comprised of three "sub-pseudosections". The first "section" is the measured apparent resistivity data for each data point plotted as a pseudosection. The raw data is then converted and modelled, using the Wenner's equation in this case, (uses software for whatever protocol specified by the user) and plotted as a pseudosection in the second "section". This is also known as the calculated apparent resistivity pseudosection. The "final section" is the final pseudosection once the user has removed poor data and modelled with the specified parameters. The differences in the shape of the boulder, for example, when doing a daily comparison is due to the internal modelling processes. The modelling process takes the data points (cells) in the near vicinity to the specific point and gets an average, so in actual fact the data point seen in the pseudosection is a data point that has taken the surrounding points into consideration. The lower the resistance of the surrounding points the lower the value of the data point. This will vary from day to day depending on the conditions of the surrounding material. This is the final pseudosection that is used for all the interpretations and generally the only pseudosection that is presented to represent the survey. This "section" of the pseudosection is known as the inverse model resistivity section. All the modelling and inversions are done internally in the RES2DINV program quickly and accurately.

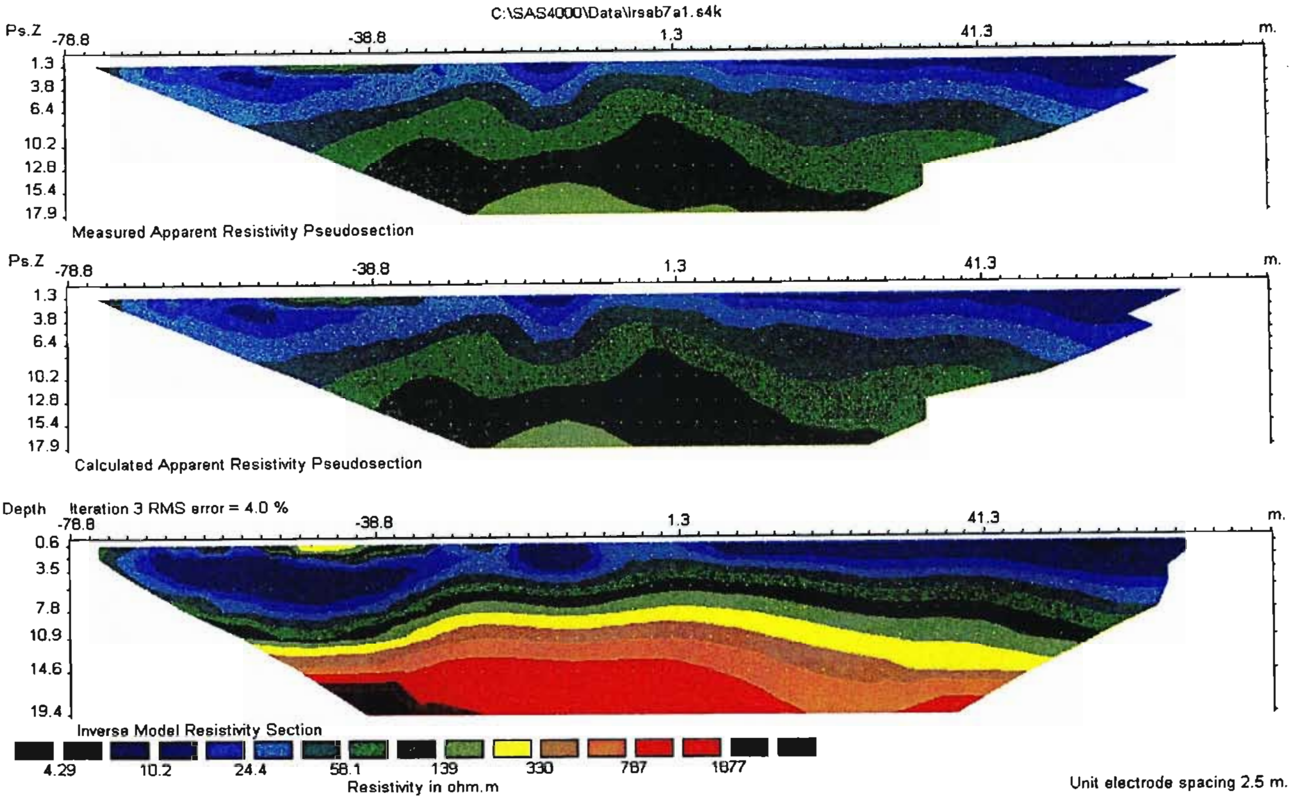


Figure 3.6 An example of the sections that make up the pseudosections.

3.2.4 Advantages and disadvantages of the different arrays

The choice of the "best" array for a field survey depends on the type of structure to be mapped, the sensitivity of the resistivity meter and the background noise level. In practice, the arrays that are most commonly used for 2-D imaging surveys are the Wenner, dipole-dipole, Wenner-Schlumberger, pole-pole and pole-dipole. Among the characteristics of an array that should be considered, are (i) the sensitivity of the array to vertical and horizontal changes in the subsurface resistivity, (ii) the depth of investigation, (iii) the horizontal data coverage and (iv) the signal strength.

The sensitivity function basically tells us the degree to which a change in the resistivity of a section of the subsurface will influence the potential measured by the array. The higher the value of the sensitivity function, the greater is the influence of the subsurface region on the measurement. Note that for all the arrays, the highest sensitivity values are found near the electrodes. At larger distances from the electrodes, the contour patterns are different for the different arrays. The difference in the contour pattern in the sensitivity function plot helps to explain the response of the different arrays to different types of structures. The median depth of investigation gives an idea of the depth to which we can map with a particular array. The median depth values are determined by integrating the sensitivity function with depth. This tells us roughly how deep we can see with an array. This depth does not depend on the measured apparent resistivity or the resistivity of the homogeneous earth model. If there are large resistivity contrasts near the surface, the actual depth of investigation could be somewhat different.

Table 3.3 The median depth of investigation for different arrays (Abem, 2005).

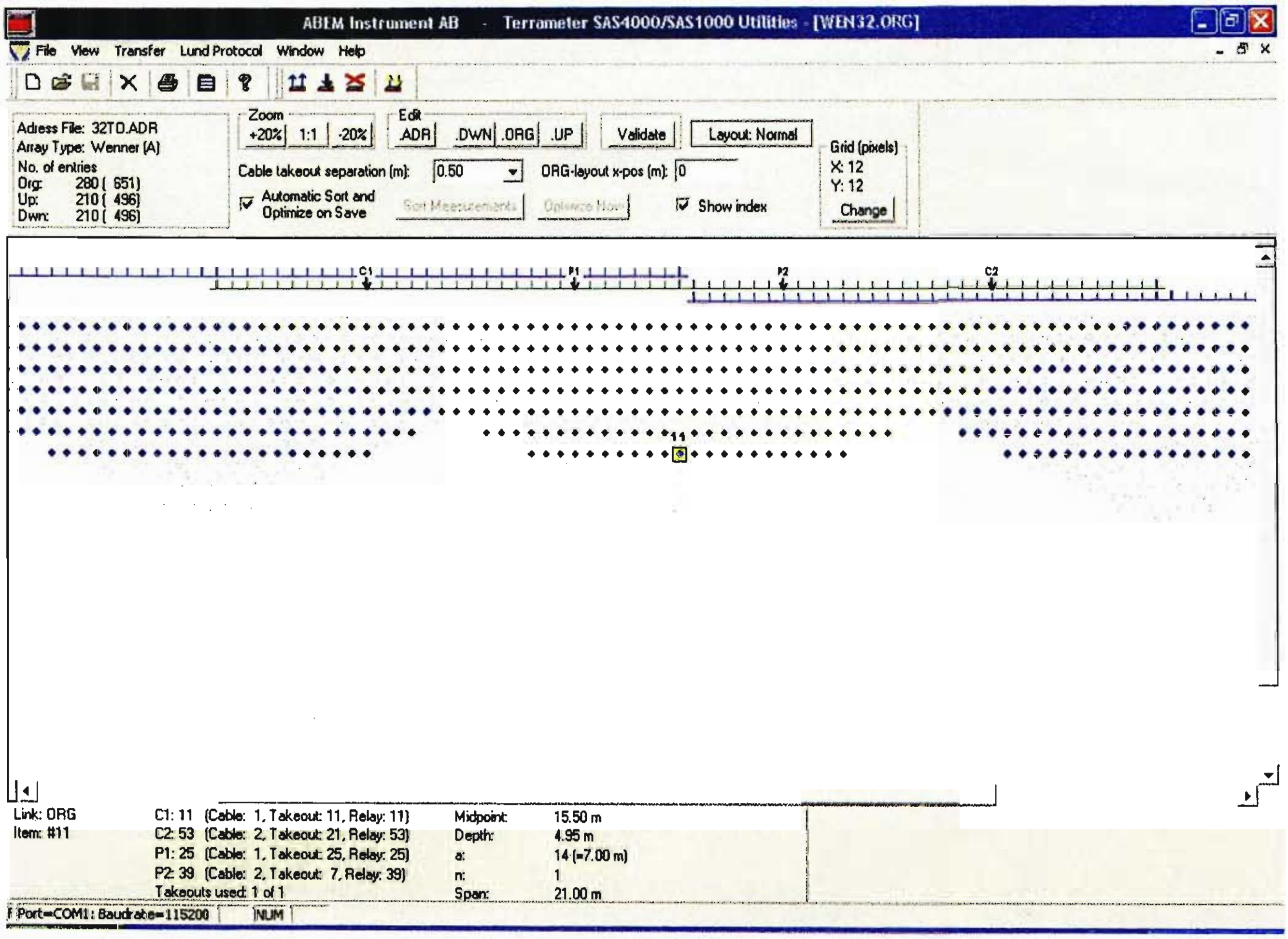
Array Type	**Depth Factor**
Wenner array	0.519
Dipole-dipole	n = 1 0.416
	n = 2 0.697
	n = 3 0.962
	n = 4 1.220
	n = 5 1.476
Wenner – Schlumberger	n = 1 0.52
	n = 2 0.93
	n = 3 1.32
	n = 4 1.71
	n = 5 2.09

To determine the maximum depth mapped by a particular survey, multiply the maximum "a" electrode spacing, or maximum array length "L", by the appropriate depth factor given in Table 3.3. For example, if the maximum electrode spacing used by the Wenner array is 100 metres (or maximum L 300 metres), then the maximum depth mapped is about 51.9 metres. For this study the Wenner array was used and will be discussed in more detail in the following section.

3.2.5 Wenner array

This is a robust array, which was popularised by the pioneering work carried by The University of Birmingham research group (Griffiths and Turnbull 1985; Griffiths *et al*, 1990).

Many of the early 2-D surveys were carried out with this array. The sensitivity plot for the Wenner array has almost horizontal contours beneath the centre of the array. Because of this property, the Wenner array is relatively sensitive to vertical changes in the subsurface resistivity below the centre of the array. However, it is less sensitive to horizontal changes in the subsurface resistivity. In general, the Wenner is good in resolving vertical changes (i.e. horizontal structures), but relatively poor in detecting horizontal changes (i.e. narrow vertical structures). For the Wenner array, the median depth of investigation is approximately 0.5 times the "a" spacing used. Compared to other arrays, the Wenner array has a moderate depth of investigation. The signal strength is inversely proportional to the geometric factor used to calculate the apparent resistivity value for the array. Among the common arrays, the Wenner array has the strongest signal strength. This can be an important factor if the survey is carried out in areas with high background noise. One disadvantage of this array for 2-D surveys is the relatively poor horizontal coverage as the electrode spacing is increased. This could be a problem if you use a system with a relatively small number of electrodes. Refer to Figure 3.7 and Appendix A for the Wenner array used in the study (old and new protocol). The green dots represent the data points that make up the array while the highlighted point 11 represents the 11th reading and it uses the electrodes marked C1, C2, P1 and P2 to obtain the reading. The information of the point is noted at the bottom of the figure and includes the depth of the point, cable positions and the span used to obtain the specific point.



Adress File: 32TD.ADR
Array Type: Wenner (A)
No. of entries
Org: 280 (651)
Up: 210 (496)
Dwn: 210 (496)

Cable takeout separation (m): 0.50
ORG-layout x-pos (m): 0
☑ Automatic Sort and Optimize on Save
☑ Show index
Grid (pixels)
X: 12
Y: 12

Link: ORG
Item: #11

C1: 11 (Cable: 1, Takeout: 11, Relay: 11)
C2: 53 (Cable: 2, Takeout: 21, Relay: 53)
P1: 25 (Cable: 1, Takeout: 25, Relay: 25)
P2: 39 (Cable: 2, Takeout: 7, Relay: 39)
Takeouts used: 1 of 1

Midpoint: 15.50 m
Depth: 4.95 m
a: 14 (=7.00 m)
n: 1
Span: 21.00 m

Port=COM1: Baudrate=115200

Figure 3.7 Wenner array protocol used in the study (Abem, 2005).

3.2.6 Computer interpretation

After the field survey, the resistance measurements are reduced to apparent resistivity values. Practically all commercial multi-electrode systems come with the computer software to carry out this conversion. In this section, the steps involved in converting the apparent resistivity values into a resistivity model section, which can be used for geological interpretation, are highlighted.

3.2.6.1 Data input and format

To interpret the data from a 2-D imaging survey, a 2-D model for the subsurface, which consists of a large number of rectangular blocks, is usually used. A computer program is then used to determine the resistivity of the blocks so that the calculated apparent resistivity values agree with the measured values from the field survey. The computer program will automatically subdivide the subsurface into a number of blocks, and it then uses a least-squares inversion scheme to determine the appropriate resistivity value for each block. The location of the electrodes and apparent resistivity values must be entered into a text file, which can be read by the program. Many professionals carrying out resistivity imaging surveys are likely to be field engineers, geologists or geophysicists who might not be familiar with the geophysical inversion theory. The RES2DINV program is designed to operate, as far as possible, in an automatic and robust manner with minimal input from the user. It has a set of default parameters, which guides the inversion process (Abem, 2005). In most cases the default parameters give reasonable results. This section describes some of the parameters the user can modify to fine-tune the inversion process.

The problem of non-uniqueness is well known in the inversion of resistivity sounding and other geophysical data. For the same measured data set, there is a wide range of models giving rise to the same calculated apparent resistivity values. To narrow down the range of possible models, normally some assumptions are made concerning the nature of the subsurface that can be incorporated into inversion subroutine. In almost all surveys, something is known about the geology of the subsurface. In some cases it is known whether the subsurface bodies of interest have gradational boundaries, such as pollution plumes or bedrock with a thick transitional weathered layer. In such cases, the conventional smoothness-constrained inversion method (deGroot-Hedlin and Constable, 1990) gives a model, which more closely corresponds with reality. This is the default method used by the RES2DINV program. In others, the subsurface might consist of discrete geological bodies that are internally almost homogeneous with sharp boundaries between different bodies. Another important factor is the quality of the field data. Good quality data usually show a smooth variation of apparent resistivity values in the pseudosection. To get a good model, the data must be of equally good quality. If the data is of poorer quality, with unusually high or low apparent resistivity values, there are several things that could be done. The first step is to look at the apparent resistivity pseudosection. If there are spots with relatively low or high values, they are likely to be bad datum points. With the RES2DINV program, you can also plot the data in profile form that helps to highlight the bad datum points, and remove them from the data set manually (Refer to Figure 3.5). If the bad datum points are more widespread and random in nature, there are two program inversion parameters that you can modify. Firstly, increase the damping factors. A larger damping factor would tend to produce smoother models with less structure, and thus poorer resolution, but it would be less sensitive to noisy data. The second setting is the robust data constrain option. The inversion subroutine normally tries to reduce the *square* of the difference between the measured and calculated apparent resistivity values (Abem, 2005). Data points with a larger difference between the measured and calculated apparent resistivity values are given a greater weight. This normally gives acceptable results if the noise is random in nature. However, in some cases, a few bad data points with unusually low or high apparent resistivity values (outliers) could distort the results. To reduce the effect of such bad datum points, the robust data constrain causes the program to reduce the *absolute* difference between measured and calculated apparent resistivity values. The bad datum points are given the same weight as the other data points, and thus their effect on the inversion results is considerably reduced. Another factor that the user can control is the size and distribution of the rectangular blocks used by the inversion model. By default, the program uses a heuristic algorithm partly based on the position of the data points to generate the size and position of the model blocks. The distribution of the datum points in the pseudosection is used as a rough guide in allocating the model blocks, but the model section does not rigidly follow the pseudosection. To produce a model with more uniform widths, the user can select a model where the number of model blocks can exceed the number of datum points.

3.2.6.2 Topographic modelling

In surveys over areas with significant changes in the elevation of the ground surface, the effect of the topography must be taken into account when carrying out an inversion of the data set. It is now generally recognised that the traditional method of using the "correction factors" for a homogeneous earth model (Fox et al. 1980) does not give sufficiently accurate results if there are large resistivity variations near the surface (Tong and Yang 1990). Instead of trying to "correct" for the effect of the topography on the measurements, the preferred method now is to incorporate the topography into the inversion model. In a earlier project in the KNP, Global Positioning System (GPS) data was used, by means of incorporating a spreadsheet into the program with the relevant data. The elevation data was collected while the resistivity surveys were conducted and were vital in the "roll along" surveys. The topography of the sections becomes vital when studying pseudosection relating to slope and gravity fed groundwater environments, as many are in the case in the KNP. The GPS used was the Trimble backpack with a base station and was downloaded daily into a spreadsheet, which was incorporated into the modelling system. For this study in the Nkuhlu Exclosures, no topography was included due to the small scale used in the surveys. There were no significant changes in the topography within each survey site. Refer to Appendix C and Appendix D for the GPS and topography data for earlier surveys and studies conducted in the KNP.

3.3 Time Domain Reflectometry

Refer to Appendix G for all the TDR data from the study in the KNP, for the month of January 2006. In the following sections the TDR will be discussed in detail, and will be linked to the ecohydrology aspect. The applications and experimentation used in the KNP will be discussed and at a later stage the results will be used in a comparison study with the ERT instrument data.

3.3.1 General uses and history

Time Domain Reflectometers (TDR) have been around for many years and remain the fastest, most accurate way to pinpoint cabling problems. Historically, the TDR has been reserved for only large companies and high-level engineers. This was due to the complexity of operation and high cost of the instruments. The TDR has therefore been greatly under utilized and the need for these instruments was recognized in the early 1980s, when the first "little TDR" was developed. The simplified digital TDR has now become a standard tool for all interested users. TDR is however a relatively new method for measurement of porous media water content and electrical conductivity (Noborio, 2001). Both of these attributes have substantial utility in studying a variety of hydrologic processes (Jones *et al*, 2002). The first application of TDR to soil water measurements was reported by Topp *et al* in 1980.

TDR depends on discontinuities in the energy storage mechanisms, which are available. Combined with knowledge of the propagation velocities of the waves in the medium being used, these discontinuities can be located by observing the change in energy levels at fixed points in the media. Energy, which does not become dissipated returns to its source. The probe tips of a TDR instrument present a discontinuity in the wave propagation path of the energy initiated at the signal source. The TDR works on the same principle as radar. A pulse of energy is transmitted down a cable. When that pulse reaches the end of the cable (probe tips), or a fault along the cable, part or all of the pulse energy is reflected back to the instrument. The TDR measures the time it takes for the signal to travel down the cable, see the problem, and reflect back. The TDR then converts this time to distance and displays the information as a waveform and/or distance reading (TSCM, 2006). The TDR probes act as a wave-guide. Impedance along the rods varies with the dielectric constant of the surrounding soil. Because the dielectric constant of soil primarily depends on the amount of water present, soil Volumetric Water Content (VWC) can be inferred from the reflected measurements. Soil bulk Electrical Conductivity (EC) is determined from the attenuation of the applied pulse.

The mathematical description of wave mechanics was developed by Schroedinger several years back (TSCM, 2006). Basically, all of the natural properties required for wave-based appliances to operate come from tradeoffs between two interlocked energy storage mechanisms. A pendulum trades off potential and kinetic energy, acoustic waves trade off transverse and longitudinal compression and expansion and electromagnetic waves trade off storage between magnetic and electric fields. The presence of water in the medium affects the speed of the electromagnetic wave (Slows it down slightly).

The accuracy of TDR measurements depends on precise measurement of time and precise calibration with the relative volumetric content of water around the probe. Some of the advantages of the TDR instruments are that they are accurate, continuous, TDR have excellent spatial and temporal resolution, generally no need for calibration and are usually unaffected by salts. The TDR technique as practised by many is indeed relatively insensitive to salinity as long as the salinity levels are low enough that a useful waveform can be returned! The big problem is that, as salinity levels increase, the signal reflection from the ends of the rods in the TDR probe is lost (Automata, Inc., 2006). This occurs because of conduction of the signal through the saline soil between the rods. The amount of conduction increases as the soil moisture increases. Thus, one can obtain quite good waveforms in a very dry saline soil and useless waveforms in the same soil when wet. It must be noted that the TDR's insensitivity to salinity means that the travel time is little affected by salinity (Automata, Inc., 2006).

3.3.2 Relationships between soil/geology/water and ecohydrology

The status of soil water content in the root zone is a key parameter to many aspects of agricultural, hydrological, and meteorological research. In agriculture, accurate knowledge of soil moisture conditions is essential for proper water resource management, irrigation scheduling, crop production, and chemical monitoring. In other aspects of research, soil moisture plays a significant role in the partitioning of available energy at the earth's surface into sensible and latent heat exchange with the atmosphere, as well as in the partitioning of rainfall into infiltration and runoff (Logsdon, 2005). Dynamic soil water content changes are important in understanding how rain water moves into the soil, how crops use soil water, and how chemicals wash through the soil. Automated devices can be linked to TDR's, to measure soil water content in the field, at hourly intervals for several locations and soil depths. Information of this nature is important for scientists who need to know soil water contents as well as field managers who use automated soil water content devices to trigger irrigation systems. The short falls such as calibration and interference within the equipment need to be known and overcome if possible (Logsdon, 2005). Another problem is that many soils often contain many large coarse fragments making it difficult to insert probes to measure soil water content. The ability of TDR to give reliable measurements of water content in soil with up to 40% coarse fragments has been done in a study in British Columbia, Canada. Physical and hydrologic soil properties were determined and the soil calibrated for TDR (Spittlehouse, 2005). In another study in southeastern Newfoundland by Lapen et al, 2005, during the summer growing season, used TDR's to estimate soil water storage dynamics in several uncultivated blanket bogs and poor fens. The purpose of the research was to evaluate links between surface moisture conditions, evapotranspiration, and recharge processes in order to elucidate factors that govern blanket peat formation in the region. Water storage changes in the peat/Sphagnum above the water table were found to be important storage terms in daily water balance estimates. Recharge via groundwater appeared to be an important factor governing moisture conditions

Water is a key resource in tropical savannas. Changes in vegetation structure due to land-use change and increased fire frequency may affect the availability of water and the flux of water through these ecosystems. A comparison of the seasonal soil moisture dynamics of two adjacent savannah ecosystems with contrasting tree densities in central Brazil, was conducted (Oliveira *et al*, 2005) where the influence of tree density on deep-water uptake, soil water dynamics and evapotranspiration was investigated. The results suggested that deep-rooted plants may contribute significantly to the water balance of cerrado ecosystems, and that the hydrological cycle of this biome could change as woody vegetation is replaced by exotic grasses and agricultural crops. TDR's were used to determine seasonal patterns of soil water availability at different soil depths in savannah ecosystems with the contrasting tree densities and the magnitude and seasonal dynamics of water flux to the atmosphere (ET) in each community.

3.4 TDR Surveying

Monitoring soil water is extremely important in understanding and completing all the links in the hydrological cycle. The need to understand the dynamics in the subsurface water components is probably the least monitored and least understood component of hydrological cycle. One method of monitoring the water contents of the subsurface medium is the TDR approach. The following sections will highlight the components used in the instrumentation and measuring phases of a study.

3.4.1 Instrumentation and measuring

The principal components of a TDR system are the CSI datalogger, TDR100 Reflectometer, TDR probes and PCTDR software. User-specific configuration provides flexibility for accurate and reliable soil water content and electrical conductivity measurement. Other applications include rock mass deformation, cable integrity monitoring, solution electrical conductivity, water level detection and laboratory time domain measurements (Cambell Scientific, 2005). Some of the features of the TDR are that it makes non-destructive, long-term, *in-situ* soil measurements, uses PCTDR software for quick and easy system setup and supports operating temperature range of -40° to 55°C. The TDR100 generates a very short rise time electro-magnetic pulse that is applied to a coaxial system, which includes a TDR probe for soil water measurements and is able to sample and digitise the resulting reflection waveform for analysis or storage. The elapsed travel time and pulse reflection amplitude contain information used by the on-board processor to quickly and accurately determine soil volumetric water content and soil bulk electrical conductivity. Up to 16 TDR100s can be controlled using a single datalogger. A 250-point waveform is collected and analyzed in approximately two seconds. Each waveform can have up to 2,048 data points for monitoring long cable lengths used in rock mass deformation or slope stability. Averaging up to 128 makes accurate measurements possible in noisy environments (Cambell Scientific, 2005). The TDR100-based system is supported by dataloggers. The datalogger is easily programmed for automatic control of the TDR100 and multiplexers as well as telecommunication functions for obtaining measurement results remotely. Multiplexers allow measurement of up to 512 TDR probes. The multiplexers use a communications protocol and can be controlled via a datalogger or a computer running PCTDR. In the KNP, dataloggers and multiplexers are used under normal operating conditions, however for the study a roaming approach was used, therefore requiring only the external power source and portable computer. The TDR soil probes act as a wave-guide. Impedance along the rods varies with the dielectric constant of the surrounding soil.

Because the dielectric constant of soil primarily depends on the amount of water present, soil volumetric water content can be inferred from the reflected measurements. Soil bulk electrical conductivity is determined from the attenuation of the applied pulse. Probes consist of three pointed, large-diameter rods and a large epoxy head allowing use in rugged environments.

The power supply requirements depend on the number of sensors measured, how frequently the data is retrieved, data retrieval method used, and location of the site. In the study conducted in the KNP, portable 12v batteries are used, and replaced on a monthly basis depending on the conditions of the power source. For the surveys conducted, a roaming approach was used to obtain real-time data, power sources and TDR100s were moved from site to site as required to perform the surveys. The reflectometer, data logger, multiplexer and power supply should be housed in an environmental enclosure to protect the equipment from weather, condensing humidity, and dust (Cambell Scientific, 2005).

3.4.2 Data collection and data interpretation

PCTDR software is used during system setup and trouble-shooting to display volumetric water content and electrical conductivity, switch multiplexer channels, collect waveforms and derivative data files, and determine probe constant values needed for electrical conductivity measurements. By using the roaming method, as in this study, a portable computer (laptop) was used to download the data on site. All the required data collection is collected into the computer automatically without using a datalogger.

All the probes require some sort of calibration. This is due to different settings used for different projects and user preferences. The standard probes are also used under varying soil and site conditions. Naturally the results will vary from study site to site and the conditions at the sites. Calibrations normally are done at laboratory scale and usually are performed with similar materials to those found at the respective study sites. Refer to a calibration example used in the KNP study in a chapter 5.

There is a link to ecohydrology with both the TDR and the ERT instrumentation and the relationship may vary from environment and requirement to other environments with different requirements. All fields including agricultural, hydrological, and meteorological research fields depend on the above instrumentation to optimise sustainable growth, development and management of ecohydrology. The consequences of this instrumentation on ecohydrology, adds and aids in the understanding of how a particular system responds to events. The behaviour in response to the event is important to ecologists in understanding the entire system.

4. SITE AND SURVEY DETAILS

The transects studied fall into an on-going investigated area that comprises some 185 ha (including a buffer zone of 150m) on the east bank of the Sabie River, approximately 20km downstream from the Skukuza rest camp, directly opposite the Nkuhlu picnic site (Refer to Figures 4.1 through to 4.4 for site locations).

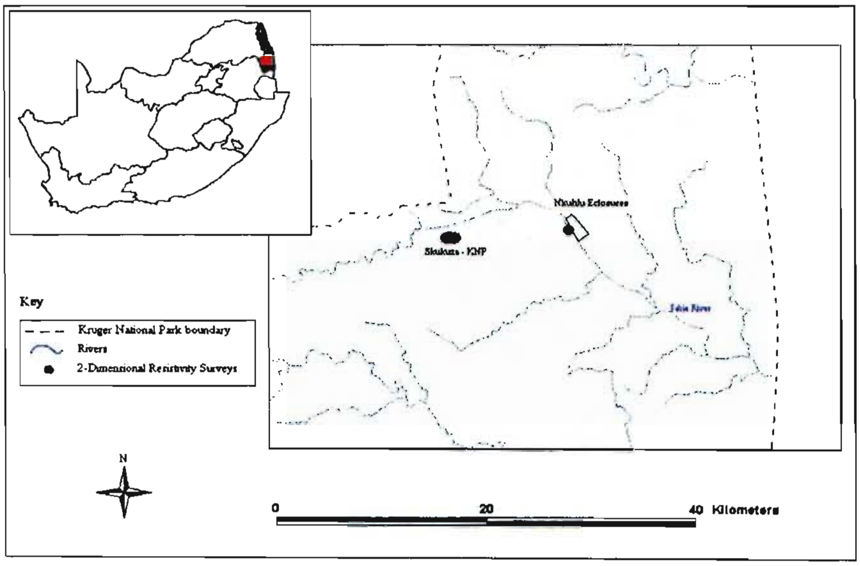


Figure 4.1 Location of survey site in the KNP.

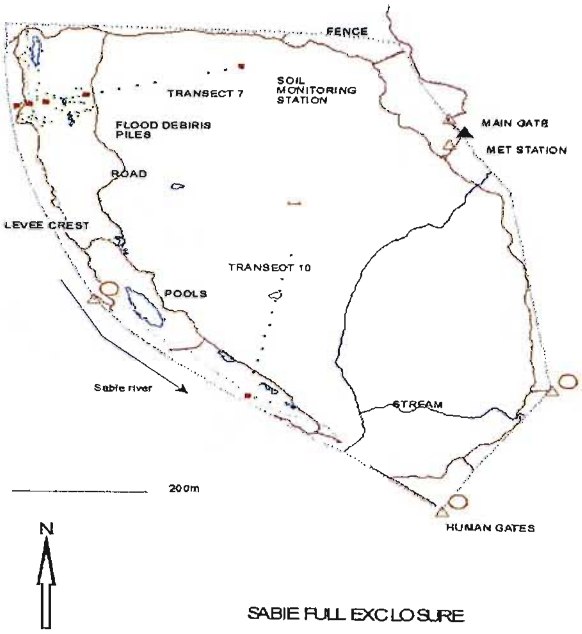


Figure 4.2 Detailed plan of the Full Exclosure. Note the position of transect 7.

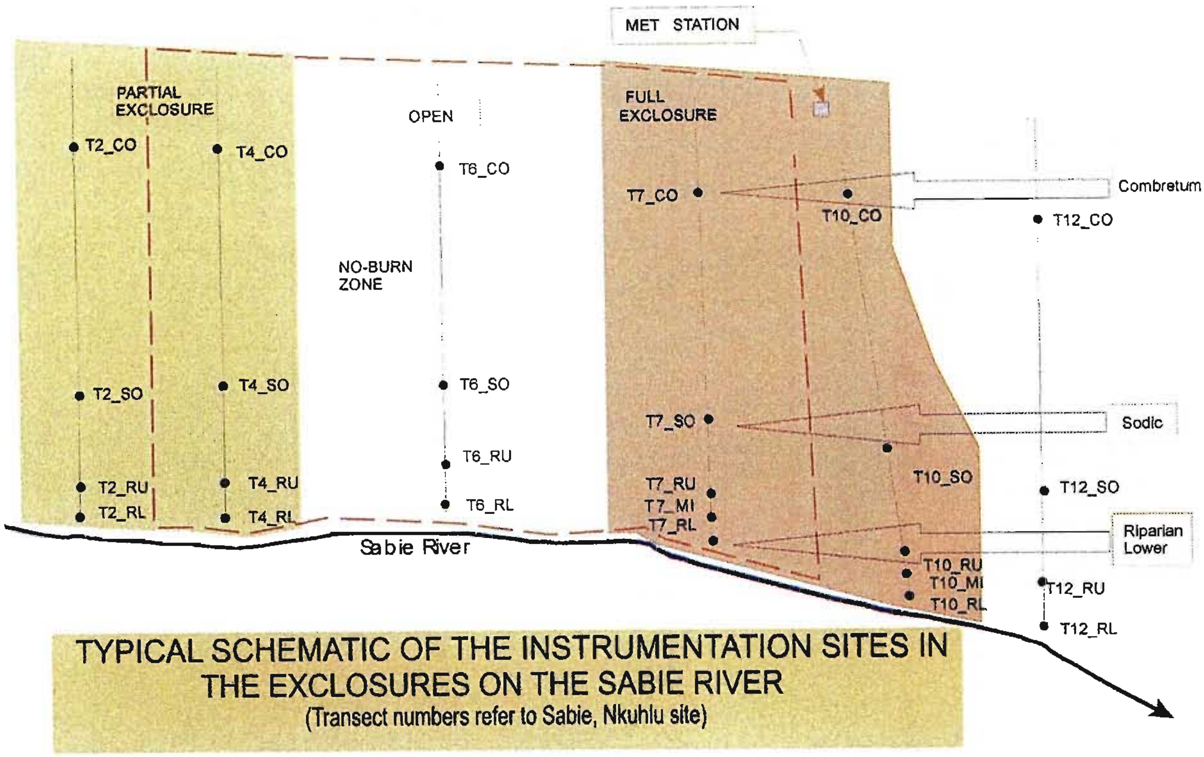


Figure 4.3 Schematic of the instrumentation sites and survey sites in the Nkuhlu Exclosures.

4.1 Location

The study site comprises a southern camp which is completely fenced off so that no animals can enter ("full exclosure"), as well as a northern camp which is fenced off to prevent elephant and giraffe from entering, but allows all other animals access ("partial exclosure"). The two camps are separated by an unfenced zone, which serves as a control area. The area of study is within the "full exclosure" on a transect (transect 7) that is highly instrumented. The transect runs parallel to the northern fence line and runs downslope towards the Sabie River. These transects are used for various different studies by different institutions and research organisations. Soil water dynamic studies have been conducted on these transects and includes runoff plots, tensiometer nests and TDR nests. A permanent weather station is located within the exclosure and all data is logged at 30-minute intervals. The following data is obtainable from the weather station – temperature (Min and max), solar radiation, relative humidity, rainfall, wind speed and wind direction among others. Most of this data will be useful in the analyses of the surveys and studies to be conducted.

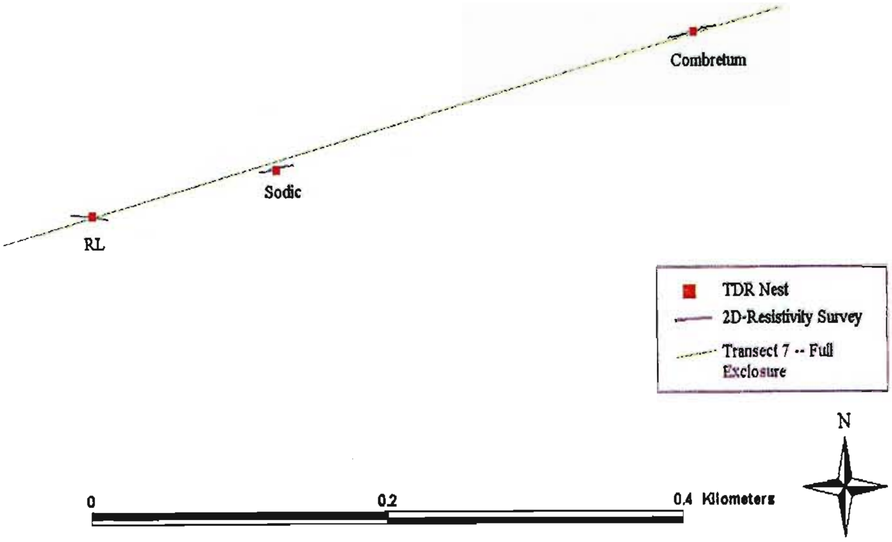


Figure 4.4 Schematic of the three survey sites on Transect 7, Nkuhlu Exclosures.

The sites of the surveys were located on this transect at three TDR nest sites. The site, Riparian Lower, was a survey that is 12.8m long and ran parallel to transect 7 with the centre point being located at the TDR Riparian Lower nest. The Sodic survey site was situated parallel to transect 7 with the centre point being located at the Sodic TDR nest and this transect was also 12.8m long. The third and final survey site was located further up the slope in the Combretum zone on the crest of the slope. The survey was also set up parallel to transect 7 with the centre point being at the TDR nest. The survey was however 32m long. All three surveys were set up with the starting points being downslope of the TDR (centre points) nests. The reason for this set up was for more accurate modelling and interpretation simplicity.

Figure 4.5 Photograph of Riparian Lower site on Transect 7, Nkuhlu Exclosures.

Figure 4.6 Photograph of Sodic site on Transect 7, Nkuhlu Exclosures.

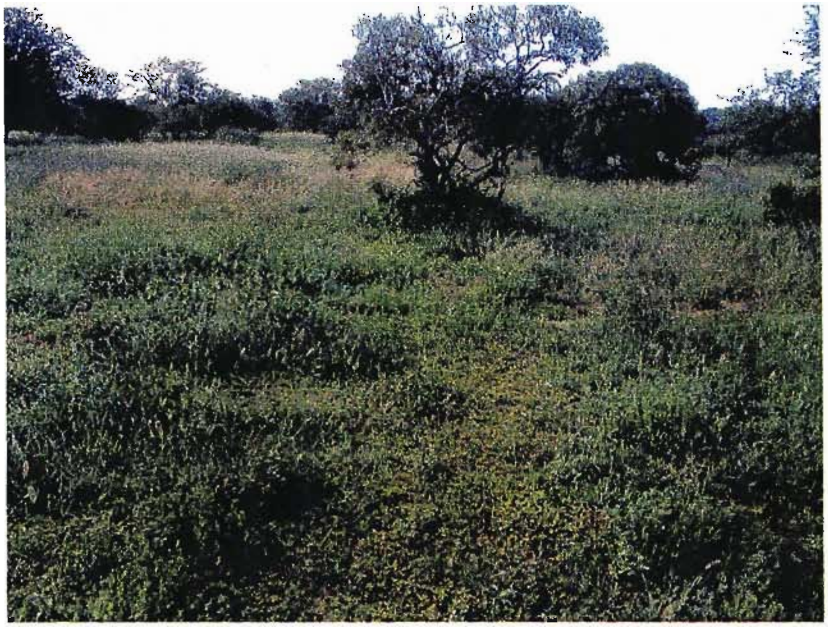


Figure 4.7 Typical cross-section of the Sodic site on Transect 7, Nkuhlu Exclosures.

Figure 4.8 Photograph of the Combretum site on Transect 7, Nkuhlu Exclosures.

4.1.1 Terrain

The study area consists of sloping topography, with average slopes of between 3% and 5%, sloping westward to the Sabie River. Close to the river, the slopes are gentler, usually less than 1%, and in fact there are some areas where the riverbank forms a small levee, so that the terrain slopes slightly up to the riverbank. Two seasonal streams drain the area, one in each exclosure. Refer to Figure 4.2 for the location of the stream that drains the full exclosures. A small stream flows through the partial exclosure, with the larger Shibandkukile stream, with a side tributary, flowing through the full exclosure. The altitude lies between 210m and 250m above sea level (Paterson and Steenekamp, 2003).

4.1.2 Geology

The geology of the Lowveld is one of the oldest rock formations to have formed on earth. Particularly unique to the region, and to the south of the KNP, is the Barberton Mountain Land, which forms part of the Kaapvaal Craton. This constitutes the oldest exposed rock on the planet and has provided a wealth of insight into the formation of the planet for geologists.

The geology of the area is organised into broad bands, oriented in an approximately north-south direction. The bands represent successive layers, once horizontal but now tilted downward towards the east by the immense forces that were associated with the shifting of the continents. As one travels west into the heart of South Africa the geologies age considerably, from a mere 50 million years ago to the beginning of the world well in excess of 3,600 million years ago (Geology of the Kruger National Park, 2006).

The evolution of the Lowveld landscape dates back to the break-up of Gondwanaland and the opening of the Mozambique Channel, which initiated drainage to the Indian Ocean. At that time, Karoo sediments and lavas covered the whole area. The greater part of the area was underlain with Archaean Old Granite and, in the case of the Murchison Range, even more ancient metamorphic rocks of the Primitive System (Geology of the Kruger National Park, 2006).

Westwards, the old rocks are covered in turn by igneous and sedimentary rocks of the Witwatersrand and Dominion Reef systems. A subsequent tectonic uplift in the Miocene era and major warping that produced the Lebombo range in the east, accelerated erosion, planation, scarp recession and drainage producing in time the great escarpment of the Drakensberg.

The study site is situated well within the Nelspruit Suite. The suite is mostly made up of biotite-granite, which is white to grayish in colour (Walraven, 1989). In the KNP potassic gneiss and magmetite dominate the area with medium to coarse phenocrysts. The granites and gneiss of the Nelspruit Suite are made up of k-feldspar, plagioclase, quartz, biotite and various minerals. It is uniform however near the Drakensberg Cap, where varied amounts of chemical weathering have taken place and variations are common. The Granite/Gneiss is commonly overlain by sand deposits near the surface at the crest of the profiles. These soils are often classified as lithosols and are shallow, usually gravely, and greyish-brown to reddish-brown soils. Many outcrops indicating intrusions of darker, more fine-grained basic igneous rock (probably dolerite or diabase) are present, especially in the east of the study area (Walraven, 1989).

4.1.3 Soil data

The Nkuhlu Exclosure site has a somewhat complex soil distribution. The shallow, greyish-brown soils and shallow, dark brown soils cover most of the upper portion the study area with a small area of slightly deeper, yellow-brown apedal soils. Zones of deeper, more structured brown calcareous soils, with sparser vegetation, occur at the foot of the slope. The strip of deeper, siltier brown alluvial soils along the Sabie River becomes narrower and eventually pinches out in the north (Paterson and Steenekamp, 2003).

The soils generally increase in depth as you move down the slope, although possibly not with as great a variation in soil forms. The exceptions are the soils found on the higher areas of the exclosures, which consist of deeper soils than surrounding soils. The shallower soils on the midslopes and crests have (coarse) sandy textures, with higher gravel content. They are slightly acidic, mainly due to the parent material (Refer to Appendix E and F). The alluvial strip has similar light textured soils (but with a fine to medium grade of sand), and higher silt levels, due mainly to their deposition by alluvial processes, which are extremely common along the banks of the Sabie River. These soils are slightly alkaline (Paterson and Steenekamp, 2003).

The adjacent soils show a clay increase to the subsoil, are moderately to strongly alkaline and have high sodium contents in the subsoil. The EC values of these subsoils are also generally very high (>300 mS $^{m-1}$), meaning that the soils will be classified mostly as *saline-sodic* soils. The two main effects of these soils on plant growth are high in sodium content, meaning that species which are tolerant of raised Na levels will not thrive and secondly, a tendency for the exposed soil surface to seal and form a crust, restricting infiltration and increasing erosion susceptibility (Paterson and Steenekamp, 2003). This is borne out by the presence of several small areas of rill erosion within the region. The soils near the Sabie River, the Riparian Lower zone is predominantly made up of alluvial deposits from historic floods. In more detail this alluvial strip [unit comprising of a Oakleaf formation, more particular the Oakleaf Ritchie (Oa 1110)] has similar light textured soils (but with a fine to medium grade of sand), and higher silt levels, due mainly to their deposition by alluvial processes. The soils are slightly alkaline and are mostly deep (shallower in south); greyish-brown, weakly structured, sand to sandy loam topsoil on brown to reddish-brown, weakly structured, sandy loam subsoil. Some rock outcrops occur in places, usually in the Sabie river bed (and on the river bank in the south of the unit). Refer to Appendix E for the Soil Survey data of the three sites conducted by Paterson and Steenekamp in 2003. Refer to Appendix F the soil analyses of the soils found at the three study sites. The sodic site is made up the Montagu Esperanza (Mu 1120) soil form and is characterised by of deep; greyish-brown, weakly structured, sandy loam topsoil on weakly (occasionally moderately) structured, calcareous, yellow-brown sandy clay loam subsoil, usually with signs of wetness (grey colours and mottling) deeper in the profile with some loss of topsoil in places, especially close to the Sabie river in the north of the unit. The soils that are found in the Combretum site are mostly of the Mispah Myhill (Ms1100) and Glenrosa Tsende (Gs 1211) forms. These soils are generally characterised by shallow; greyish-brown to yellowish-reddish brown, unstructured, gravelly loamy sand to sandy loam topsoil directly overlying weathering rock. Surface stone and rock outcrops occur in places in the unit.

4.1.4 Climate

The climate of the Kruger National park is classified as tropical continental (savannah) climate which are characterised by temperatures that are high throughout the year, but there is a short, slightly cooler season. The temperatures may drop slightly at the onset of the rainy season and for most of the year the cloud amount is limited allowing the diurnal temperatures to exceed 25 degrees Celsius (Waugh, 1995). The main characteristic of this climate is the alternating wet and dry seasons. The wet season occurs when the sun moves overhead bringing with it the heat equator of the Intertropical Convergence Zone (ITCZ) and the equatorial low pressure belt. Heavy convection storms can give 80 per cent of the annual rainfall total n four or five months (The Mean Annual Precipitation of the Southern KNP is 750mm). The dry season corresponds with the moving away of the ITCZ leaving the area with strong, steady trade winds. Humidity is also low during this season.

4.2 Methods

In order to obtain reliable, realistic and relevant results some desirable criteria were set prior to the study. The two most desirable criteria were:

1) To conduct three ERT and TDR surveys over a period of three weeks on a daily basis using the same electrode positioning. The reason for the same electrode positioning was to ensure that the geological features were constant throughout the study period.
2) And to determine daily electrical resistance differences. Because the geologies of the three sites remain constant (same electrode positioning and same array used for the survey period), the only changes in the resistance changes should be water-induced differences. The water induced differences could be caused from surface waters percolating through the profile down to the water table, or could be due to lateral subsurface water discharge down the transect from a zone of accumulation and/or possible recharge to a zone of accumulation.

In order to test whether the ERT results are reliable and transferable, matching instrumentation is also required in the verification phase. This instrumentation is to ensure that the results obtained from the ERT instrument are realistic and can be mapped against water content data for specific locations in the 2dimensional subsurface survey. The problem with the process is that the ERT instrument and package is a geological instrument. The aim of the study is to determine if the geological instrument, the ERT instrument, could be used in unsaturated subsurface water dynamics observations. The spatially distributed, 2-dimensional resistivity measured by the ERT instrument therefore needed to be correlated against the local water contents observed through the TDR technique.

There are various methods of validating and verifying the ERT instrument in the subsurface water field at present. However for this study the TDR method was used because TDR instruments had been installed at the start of the Exclosures experiment in 2000. All the instruments were calibrated for the conditions and provide realistic and valuable data for an on-going monitoring phase. The study sites were chosen according to the above characteristics shown at all of the TDR nests. The surveys take up three hours to conduct but depend on the cable setup and protocol used. Three sites were selected for the study because of the daily time constraints of doing the ERT surveys. The three sites also varied in soil conditions, topology and soil water characteristics, hence the choice of these locations. The TDR data is normally captured on a two weekly or monthly basis by manual measurements or by means of down loading the data from loggers matched to the TDR probes. The logged recording intervals are every 12 minutes. For the duration of the study, the data loggers were removed and readings were taken by means of a manual roaming TDR method and readings were taken at the same time as the ERT surveys were being conducted. This means that every ERT survey has a corresponding set of TDR readings, in real time. Because the ERT survey produces a real-time "picture" of the transect surveyed, it is vital to obtain concurrent TDR data. The manual TDR method is ideal for this, in that, VWC and bulk EC are given. The VWC can then be compared to the resistivity data.

4.3 Instrumentation

In this chapter the general instrumentation setup and procedures will be highlighted. The three survey sites will be discussed in some detail. All three sites were comprised of ERT instrument setups as well as TDR instruments. All the supplementary instrumentation such as runoff plots, tensiometers and the weather data was used in the interpretation phases of the study. The Trimble GPS instrument captured all the GPS data before the surveys were conducted.

4.3.1 Riparian site

The site, Riparian Lower, was a survey that is 12.8m long and ran parallel to transect 7 with the centre point being on the TDR nests. The centre point is located at $24^0$59’23.81”S and $31^0$46’12.07”E with the starting point of the survey at $24^0$59’23.78”S, $31^0$46’11.87”E and end point at $24^0$59’23.84”S, $31^0$46’12.30”E. The ERT survey started at the downslope (West) of the TDR nest. The reason for this set up (downslope – upslope) was to assist in a more accurate modelling and interpretation phase of the study. The array used was the Wenner array and an electrode spacing of 0.2m was used. The short spacing was used to increase the shallow subsurface detail. A pair of 32 core cables was used for the survey and the centre points were not overlapped as usually in the larger scale surveys. This meant there were 64 stationary electrodes and the span was 12.8m in a west to east direction with the centre point at the Riparian TDR nest. The take out points (64) on the cables were connected to the electrodes by means of electrical copper wiring. The reason for not using “crocodile clamps” for this study was an issue of cost and ease. The clamps are bulky and space was a limiting factor at the survey sites because of the small electrode spacing. The depth attained from the Wenner arrangement with electrode spacings at 0.2m is approximately 1m. A depth of 1m was selected because most of the TDR instrumentation is found in the top 1m of the soil profile, which was required for comparing the two data sets. The ERT cables were moved between the three survey sites on a daily basis to complete the three surveys required per day. The electrical copper wire was removed from the electrodes once the surveys was completed, then re-attached to the next site in the transect. The electrodes remain fixed in the ground for the duration of the study, only the cables and ERT instrument were moved on a daily basis between the three sites. Only once the study was completed, were the electrodes removed from the site, while the TDR instruments were reconnected to the data loggers to continue with the logging as in the past.

The TDR instruments are made up of electrical probes that have been buried in the profile at various depths. These probes are connected to cables, which in turn are connected to the data loggers housed in a waterproof box on the surface of the profile. There are numerous probes in one nest and vary from site to site according to depth of profile and soil conditions. At the Riparian site there are four probes set at different depths in the profile to record the changes within the profile. The four depths are 2.0m for channel 1, 1.0m for channel 2, 0.5m for channel 3 and 0.3m for channel 4. Together with the TDR instrumentation in the TDR nest, are tensiometers and these tensiometers were installed at the same time as the TDR probes when the long-term experiment started in the exclosures. Unfortunately tensiometers require a high level of maintenance, in terms of replenishing and downloading data and the tensiometers in the exclosures have not produced reliable results for some time prior to the study, hence the reason to adopt real-time TDR data. The data loggers and batteries are also housed in the same instrument box as the TDR loggers.

4.3.2 Sodic site

The Sodic survey site was set-up identically to the Riparian site, with the only difference being its location. The site was located higher up the hillslope in a sodic zone. These zones are areas situated along the major rivers of the KNP and are characterised by the high levels of salts in the soils. The vegetation is sparse and the general soils contain a high clay/silt component. The survey is also 12.8m long and runs parallel to transect 7 with the centre point being located at the TDR nest. The start of the survey is downslope of the TDR nest and runs upslope from the west to east. The centre point is located at 24^{0}59’22.92”S and 31^{0}46’16.12”E with the starting point of the survey at 24^{0}59’23.01”S, 31^{0}46’15.89”E and end point at 24^{0}59’22.88”S, 31^{0}46’16.33”E. The ERT array used is also the Wenner array with 64 electrodes at 0.2m spacing. At the Sodic site there are also four TDR probes set at different depths in the profile to record the changes within the profile. The four depths are 0.92m for channel 1, 0.7m for channel 2, 0.5m for channel 3 and 0.2m for channel 4. Together with the TDR instrumentation in the TDR nest, are tensiometers that once again had not been that successful in the build up to the study.

4.3.3 Combretum site

The third and final survey site was located further up the slope (crest) in the Combretum zone. The survey was set up the same as the previous two sites downslope. The big difference at this site was that the electrode spacing was increased to 0.5m, which meant that a greater depth was attained to identify possible abnormalities in the profile. The array used was the Wenner array with 64 take-out points. The survey was however 32m long and a depth of 2.4m was obtained. Once again the surveys ran from the west to the east in an upslope direction with the centre point being at the TDR nest. The centre point is located at $24^0$59’20.48”S and $31^0$46’25.23”E with the starting point of the survey at $24^0$59’20.56”S, $31^0$46’24.72”E and end point at $24^0$59’20.32”S, $31^0$46’25.77”E. In this survey the TDR nest was comprised of three electrical probes (other two sites each comprised of four electrical probes) and this was because of the “poor” soil conditions at the site. There are numerous boulders and rocky outcrops near the site and installation of the TDR probes was almost impossible. At the Combretum site the depths of the three probes are 0.84m for channel 1, 0.5m for channel 2 and 0.21m for channel 3. The tensiometer nest is slightly offset from the survey line. The reason for the tensiometer and TDR instruments not sharing the same instrument box is the due to the make up of the soil profile at the site. The boulders in the vicinity of the survey make any form of instrumentation difficult and this can be seen in the results, which follow.

5. RESULTS AND ANALYSIS

Results obtained from the various studies and experiments (TDR and ERT) in the KNP Nkuhlu exclosures are interpreted (using precipitation, runoff and temperature data) and the findings are used to determine if the ERT package is a reliable, accurate and efficient instrument to benefit future ecohydrological studies relating the groundwater components, either directly or indirectly. With a permanent weather station in the exclosures, precipitation and temperature data were used in the interpretation of the TDR and ERT responses. Precipitation events were noted to see how the soil moisture fluxes respond to the events, both the wetting and drying out phases after a particular event. The following methods that will be analysed are the TDR data, and then analysing the ERT data in detail. Once the two data sets have been analysed for the soil moisture fluxes, the linking of the two data sets will then be discussed in this chapter. The results and findings of the study will follow with assessments of the anomalies. In both data sets, the TDR and ERT, there are periods of missing data. This was because of unfavourable weather conditions and inaccessibility to the site during those periods. The problems will be discussed in more detail in Chapter 6.

5.1 Precipitation

Precipitation is the fundamental driving force and pulsar input behind most hydrological processes and is the most variable hydrological element (Hamlin, 1983). This variability is important to the soil water balance, which is so often misunderstood and misrepresented, in hydrological studies. All interpretations of the TDR and ERT data need to be linked to the precipitation data. A permanent, fully operational weather station is situated in the Exclosures and all the data pertaining to the site was downloaded from the weather station. Once again all the data was real-time data, which eliminates the problem of study sites with inadequate historic data and missing data.

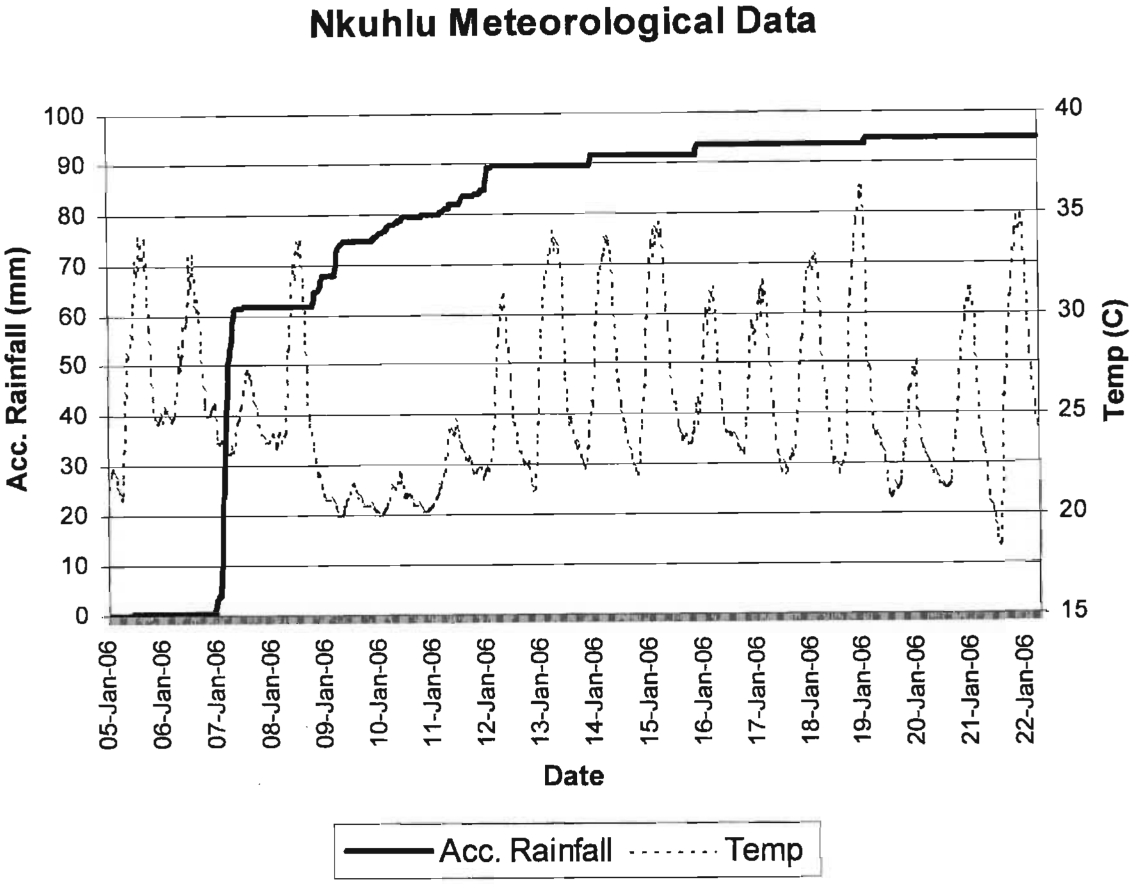


Figure 5.1 Accumulated precipitation and temperature data from the Nkuhlu weather station in the Nkuhlu Exclosures, KNP during the study period.

A large rainfall event takes place early on the morning of the 7th January 2006 (64mm of rain) (Refer to Figure 5.1). The following week is characterised by intermittent precipitation, overcast conditions and cooler than normal weather. The week starting on the 14th January 2006 is the start of the "drying out" phase in the project. Temperatures return to normal and there is no significant precipitation. During the week of extreme rainfall, the Sabie and Sand river levels rise considerably due to heavy precipitation in their respective catchments. This rise in the river levels meant that most of the low-lying areas in the KNP were inaccessible for an extended period. It is during this period that there are missing data in the TDR and ERT data sets. Nevertheless, the timing of the study was ideal, as it encompassed both a large rainfall event and the subsequent drying out phase, which is vital to see how the subsurface water balance reacts to the various driving forces. Most of the dynamics of the subsurface water components are ideally captured in the two different measurement methods.

Other instrumentation in the exclosures that could have been used in the interpretation phase, such as the runoff plots which could act as a guide to the soil water retaining properties, the lagging effect of the soil on an event. Unfortunately, the data from these plots was inadequate and very sparse. All the runoff data were recorded on a logger that is dependant on an external power source, and should be downloaded at a regular interval. The poor results obtained in the exclosures were a result of adverse weather conditions and their effects on tensiometers and TDR instrumentation.

5.2 Uncalibrated TDR data

All the TDR instrumentation in the KNP Nkuhlu Exclosures is set to read water contents and electrical conductivity at pre-determined depths. The depths vary from site to site but are predominantly located in the top 1m of the soil. The depths are dependant on the soil conditions at the site (refer to previous chapters for the locations, soil conditions and TDR set-up). All the raw TDR data obtained from the daily roaming method is graphed for each of the three sites at the respective depths; Riparian lower, Sodic and Combretum Sites. TDR values were obtained on a daily basis at the same time as the ERT surveys are being conducted. This is to be able to compare the responses of the two instruments and to ensure the two methods are done in conjunction (no possibility of time difference problems for later comparisons and interpretations). Figures 5.2 to Figure 5.4 show the TDR100 reading on a daily basis for the three survey sites. These water contents are uncalibrated at this stage of the study.

5.2.1 Riparian Lower TDR readings

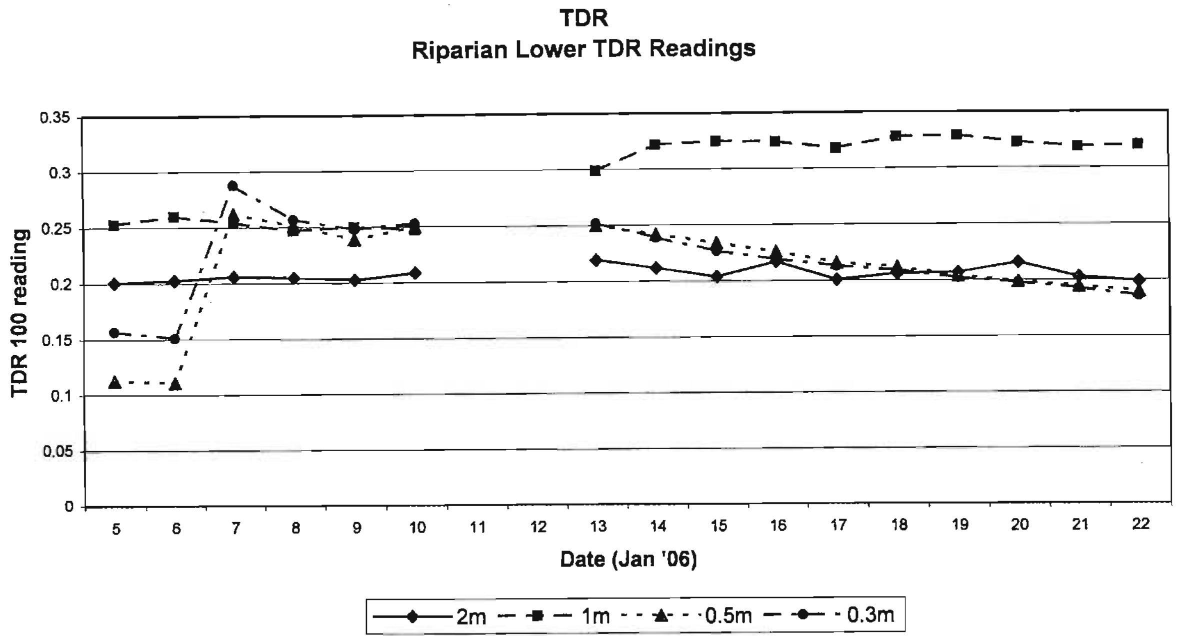


Figure 5.2 Riparian Lower TDR readings at various depths.

The near surface TDR's (0.5m and 0.2m) respond to rainfall and drying out events extremely well at the Riparian Lower site. (Refer to Figure 5.2) This is possibly due to the poor soil conditions where the soils are predominately of an alluvial sandy make-up and wetting fronts are sharper. The TDR 100 readings rise at the onset of the rainfall event on the morning of the 7th January 2006, and continue to remain in the 0.25 range. At the start of the "drying out" phase (13th-14th January 2006), the TDR readings drop as the soils dry out. By the end of the study period (22nd January 2006), the TDR readings had not returned to the "pre-event" state, which suggests that there is an additional influx of subsurface water recharging the profile, or the small amounts of precipitation throughout the study period are substantial enough to keep the TDR readings from dropping to the "pre-event" state in the profile.

The two deeper TDR's (1m and 2m) react differently to the shallower TDR's in that there is a delayed response to a precipitation event and the magnitude of the response is very small. This delayed response could be as a result of different textured soils deeper down the profile and the dissipating wetting front in time; with less alluvial sands dominating which retain water better than the pure alluvial sands. The alternative reasoning could be that most of the water entering the top of the profile from precipitation and other forms of recharge could be lost from the profile as lateral discharge at an increased rate in the sandy alluvial soils at the surface of the profile. This does not explain the higher TDR readings during the drying out phase of the study. With the site being situated on the river bank, it is possible that the higher TDR readings could be induced by a higher water table or rising water table as the subsurface water contributions from the upslope reaches move downslope or as the river levels rise at the time of flooding.

5.2.2 Sodic TDR readings

The Sodic Site is situated further up the slope and is characterised by the sodic soils common along the major drainage networks in the Transvaal Lowveld. The sodic soils that are characterised by a clay increase to the subsoil are moderately to strongly alkaline and also have high sodium contents in the subsoil. These soils are classified mostly as *saline-sodic* soils and one of the main attributes of these soils is a tendency for the exposed soil surface to seal and form a crust, restricting infiltration and increasing erosion susceptibility (Paterson and Steenekamp, 2003). This is borne out by the presence of several small areas of rill erosion within the region. The overall trend is very similar to that of the Riparian Lower Site.

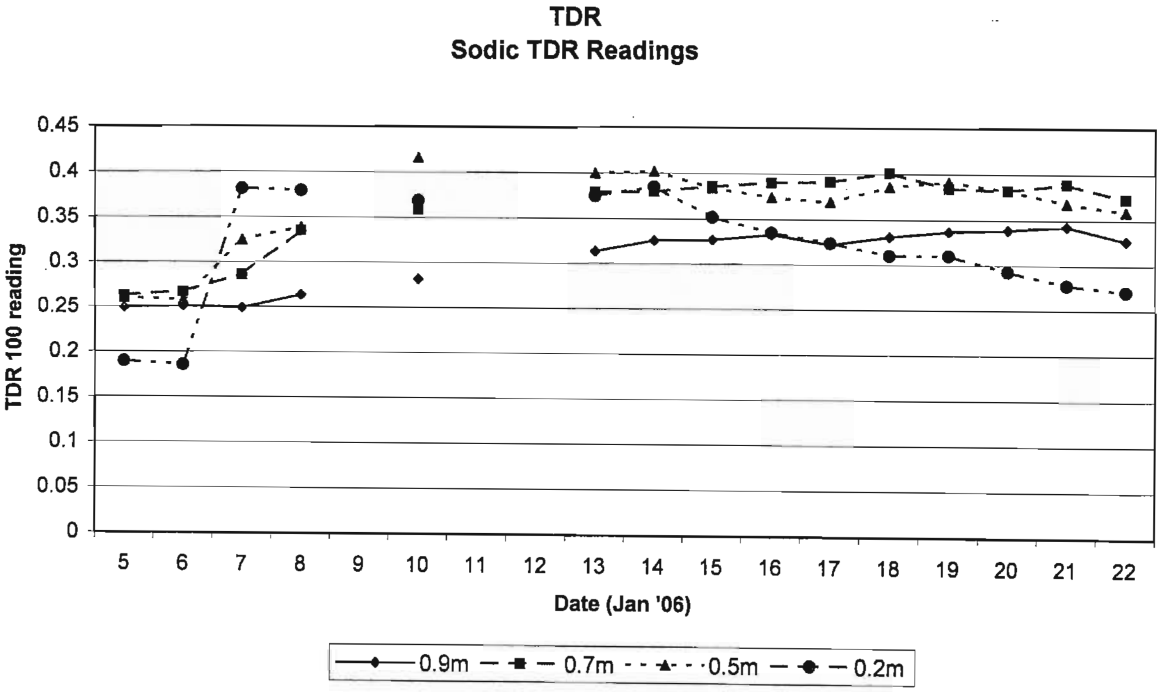


Figure 5.3 Sodic TDR readings at various depths.

The near surface TDR's (0.5m and 0.2m) respond to the rainfall and drying out events extremely well as in the Riparian Lower site. (Refer to Figures 5.2 and 5.3) The TDR readings rise at the onset of the rainfall event on the morning of the 7th January 2006, and continue to remain in the 0.35 range. The major difference is that at the start of the "drying out" phase (13th-14th January 2006), the TDR readings do not drop at the same rate as in the Riparian Lower Site. By the end of the study period (22nd January 2006), the TDR readings were still relatively high (0.30 - 0.35) and had not returned to the "initial" state, which suggests that the higher clay content of the sodic soils dominate the recharge and discharge of water in these soils. As in the Riparian Lower Site, it is also suggested that there is an additional influx of subsurface water recharging the profile, or the small amounts of precipitation later on in the study are substantial enough to keep the TDR readings from dropping to the "initial" state in the profile.

The two deeper TDR's (0.7m and 0.9m) also show a slight delayed response to a precipitation event and the magnitude of the response is very small. This delayed response could be as a result of different textured soils deeper down the profile, with a higher clay and silt content which will retain water better than the top of the profile. Because the sodic soils are characterised by crusting it is possible that less water is lost to the atmosphere as evaporation. There is a reduced plant cover on these soils, which will also reduce evapotranspiration and ultimately water loss from the soil. The accumulation in the sub-horizons of the profile could be discharging from upslope accumulations. By calculating the delayed readings in the TDR's could be a possible method of determining the rates of discharge and more importantly the recharge to these soils (knowing that crusting is dominant in these soils, which results in a reduction of infiltration).

5.2.3 Combretum TDR readings

The Combretum Site is situated further up the slope on the crest and is characterised by shallow soils with numerous boulders and rocky outcrops common along the crests along the Sabie River. The overall tend of the TDR data is very similar to that of the sites lower down the profile. The TDR probes used in the Combretum Site are not the standard probes used as in the lower two sites. This is because of the soil conditions at the Combretum Site. The high concentration of boulders and rocky outcrops make installation of the standard probes almost impossible, without having to disturb the surrounding soils. The probes used at the Combretum Site were specifically designed and made for the site. Only three probes were installed and the deepest probe was installed at a depth of 0.8m, which is the depth of the bedrock. Refer to Figure 5.4 for the Combretum Site TDR results. The near surface TDR (0.2m) respond to the rainfall and drying out events extremely well as in the two previous sites. (Refer to Figures 5.2 and 5.3) The initial TDR readings rise at the onset of the rainfall event on the morning of the 7th January 2006 to 0.14, and continue to rise to approximately 0.15 on the 13th January 2006. From the 13th January 2006 the "drying out" phase starts and the TDR readings drop to 0.07 by the 22nd January 2006, as the soil dries out.

The two deeper TDR's (0.5m and 0.8m) do not show a great response to the initial precipitation event and the magnitude of the response is very small. There is a large response in the 0.5m TDR where the TDR readings rise from 0.03 – 0.11 (8th – 13th January 2006). The 0.8m TDR readings remain constant throughout the study period and the reason could be that the TDR is positioned on the bedrock or boulder and depending on the shape of the rock, which could in turn decrease any subsurface accumulations while increasing the discharge from the surrounding area. The response after the event of the 0.5m TDR is very similar to the 0.2m TDR, which means the soil profile, is very uniform. The TDR readings indicate that the soil profile at this site is not a high water retaining soil, but a well-drained profile that has a high rate of discharge from the profile.

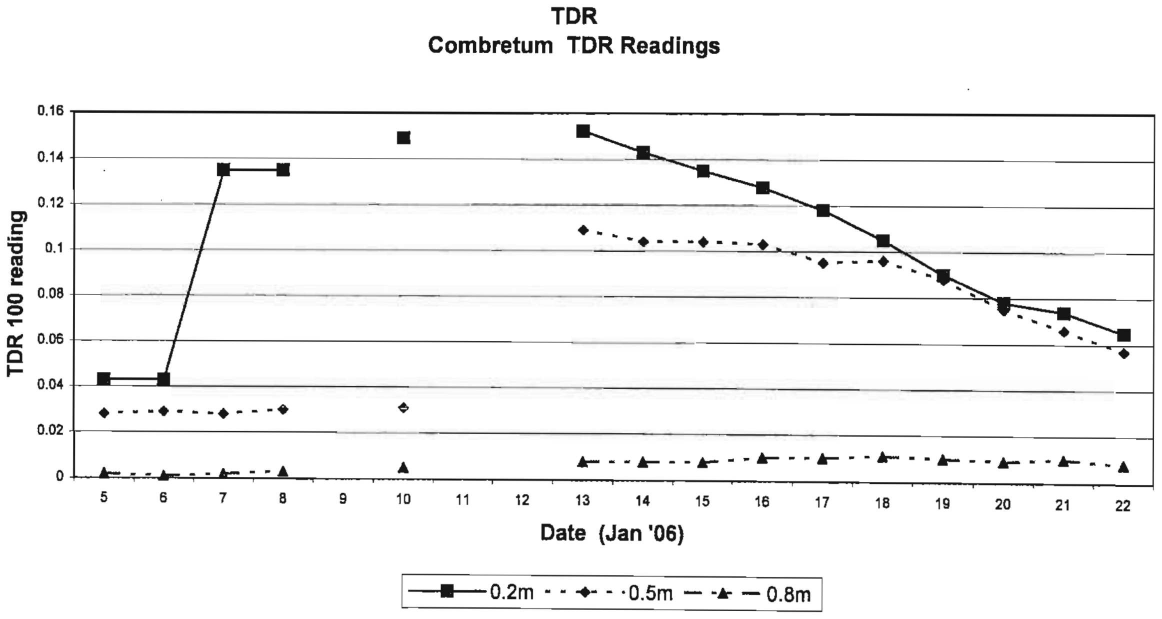


Figure 5.4 Combretum TDR readings at various depths.

5.3 Calibrated TDR data

As with any scientific equipment used in field studies, calibration is vital. The TDR is no different in that calibrating the probes is of paramount importance before utilizing the results. The TDR probes in the Riparian Lower and Sodic Sites are standard Cambell Scientific probes, which require calibration. The School of Bioresources Engineering and Environmental Hydrology (BEEH) did all the calibrations prior to the installation in the Nkuhlu Exclosure. Refer to Figure 5.5 for the calibration curve and equation of the probes used at the two lower sites. The Combretum Site, as mentioned earlier, uses a specially designed probe because the soil conditions are not able to accommodate the standard Cambell Scientific probes. This probe also requires calibration, and this was also done in the BEEH Soils laboratory, upon returning from the fieldwork section of the study. Calibration was done using a probe identical to the probe installed at the Combretum Site, and a standard soil sample used by the BEEH, where all the characteristics are known. There are no previous calibrations on record in the BEEH for this specific probe. Refer to Figure 5.6 for the Combretum probe calibration curve and equation. The standard procedure is to convert all the recorded TDR data according to the calibration curve or equations to get the true VWC. The following VWC graphs in Figures 5.7 to 5.9 are all the averaged VWC for each site. The reason for averaging the VWC is to enable a comparison between the ERT data and the TDR data. The ERT instrument produces data at a coarser depth scale than the TDR; therefore by averaging the TDR data in the upper horizons of the profile, a comparison is possible. The averaging was done by taking all the TDR data (3 or 4 different depth VWC readings) at a site and averaging the VWC and then substituting that into the calibration equation for the specific site. The Figures 5.7 to 5.9 are more important in the trends produced than the VWC. These trends will be compared to the trends of the ERT data to see how compatible the two instruments are.

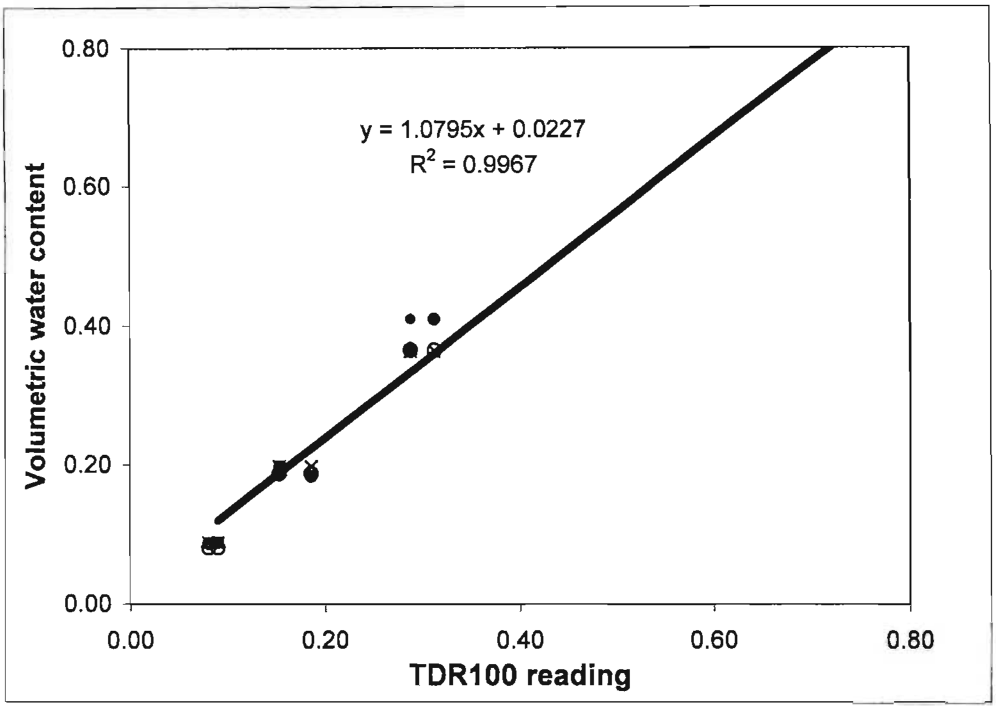


Figure 5.5 Calibration curve and equation for the Sodic and Riparian Lower Site TDR probes.

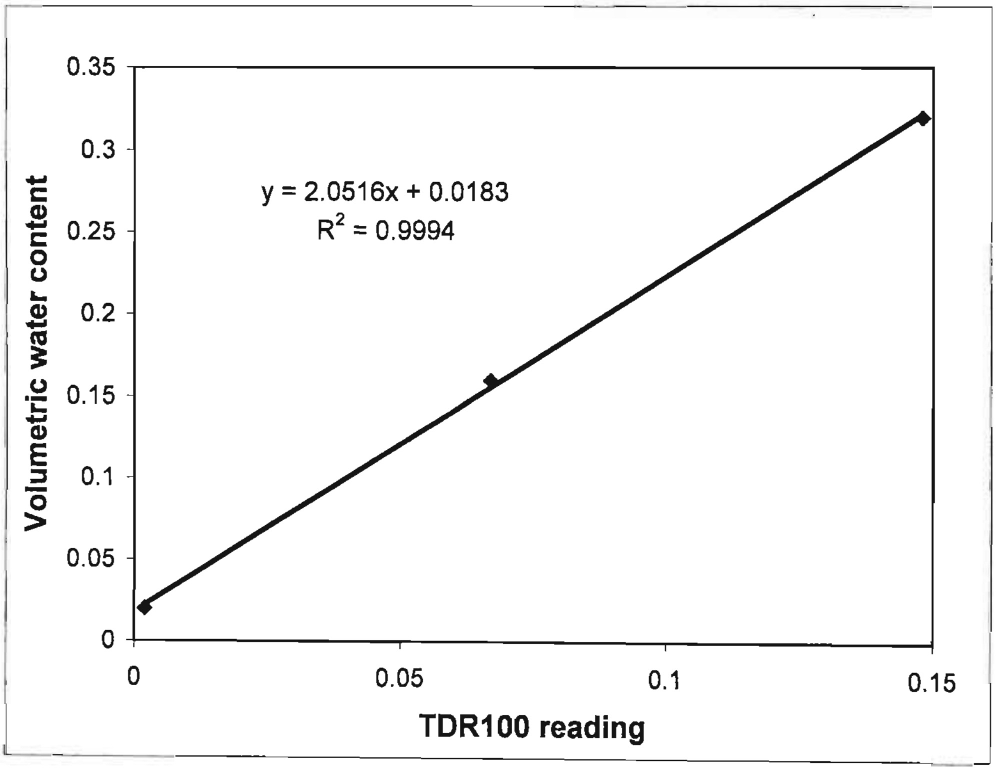


Figure 5.6 Calibration curve and equation for Combretum Site TDR probes.

5.3.1 Riparian Lower site averaged WC

The general trend of the averaged WC for the Riparian Lower site is almost identical to the trend in the TDR 100 results. Refer to Figure 5.2 and Figure 5.7 for the comparisons. At the onset of the precipitation on the 7th January 2006, there is a definite increase in the VWC from 0.14 – 0.22, where it gradually levels off before dropping into the "drying out" phase which starts on the 14th January 2006. By the end of the study period the VWC drops off to 0.18, but has not yet reached the "pre-event" state of the soil.

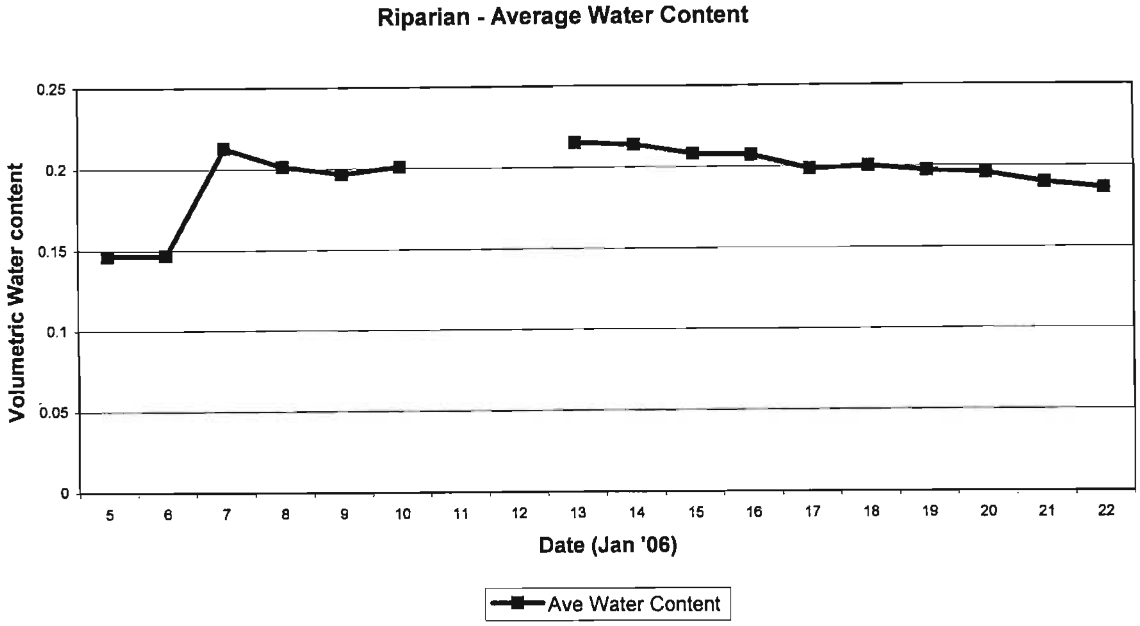


Figure 5.7 Riparian Lower averaged WC.

The missing data in the data set from the 10th – 13th January 2006, co-insides with the poor weather and inaccessibility to the site during that period. A possible suggestion for the reduced rate of drying out of the profile could be that there is an additional influx of subsurface water recharging the profile, or the small amounts of precipitation throughout the study period are substantial enough to keep the VWC from dropping to the "pre-event" state in the profile. Another possibility, mentioned earlier could be the influence of the nearby Sabie River (which at the time of the study was full) on the water table. A water table that is higher than normal could mean that the VWC of the profile should be higher, due to the forces of capillary action acting in the sandy soils.

5.3.2 Sodic site averaged WC

Once again the general trend of the averaged VWC for the Sodic Site is almost identical to the trend in the TDR 100 results. Refer to Figure 5.3 and Figure 5.8 or the comparisons. At the onset of the precipitation on the 7th January 2006, there is a definite increase in the VWC from 0.2 – 0.28, and then a further rise to 0.33 on the 14th January 2006, where it gradually levels off before dropping into the "drying out" phase which starts on the 15th January 2006. By the end of the study period the VWC drops off to 0.28, but again as in the Riparian Lower Site has not yet reached the "pre-event" state of the soil.

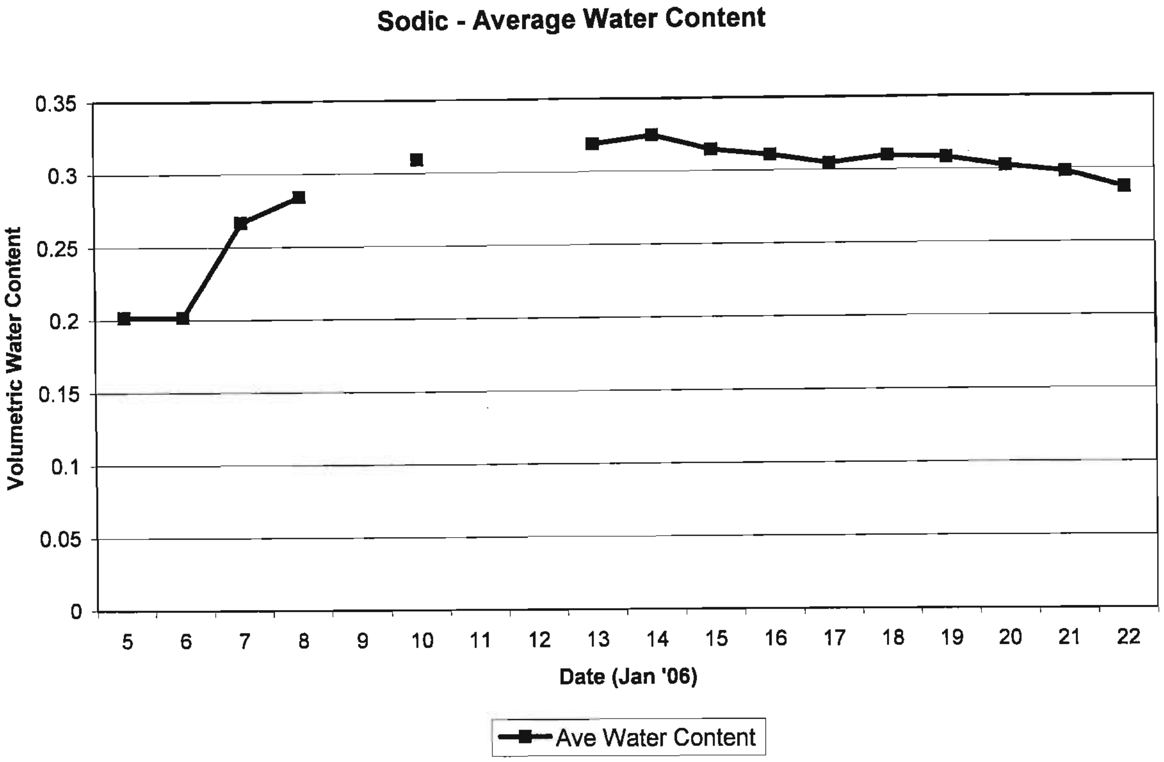


Figure 5.8 Sodic averaged WC.

The missing data in the data set from the 8th – 13th January 2006, co-insides with the poor weather and inaccessibility to the site. The reason for more data in the Riparian Lower Site is that on the morning of the 9th January 2006, a power problem with the ERT instrument was encounted and no further fieldwork was done on that day. All the instrumentation was packed up and the exclosures were evacuated, while the problem was rectified back at Skukuza, KNP. All the surveying started at the Riparian Lower Site every day and then progressed upslope to the Sodic Site then finished off with the Combretum Site. During the period of missing data the VWC rises to a maximum of 0.32, which shows a delayed response to the large rainfall event. A possible reason for this is because of the higher clay content of the soil and hence the delayed response times. The higher clay content in the soils will also explain the slow drop in the VWC's through the study period. Clayey soils retain water better, therefore reducing the discharge rates from the profile.

5.3.3 Combretum site averaged WC

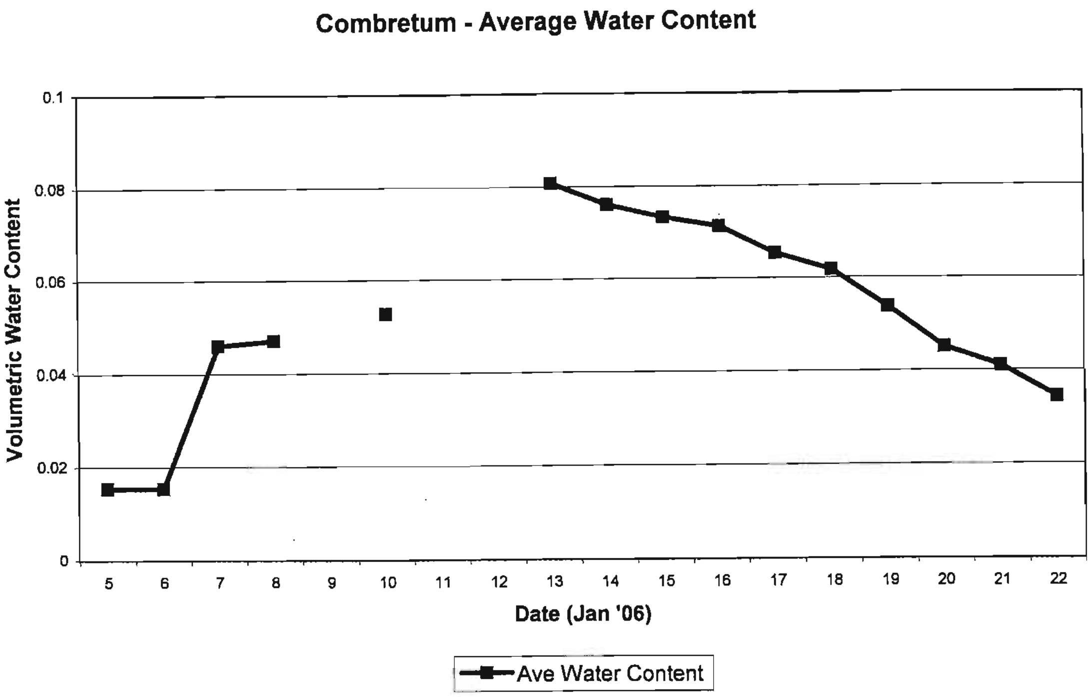


Figure 5.9 Combretum averaged WC.

Refer to Figure 5.4 and Figure 5.9 for the comparisons of the TDR 100 readings and the calibrated readings for the same period. At the onset of the precipitation on the 7th January 2006, there is a definite increase in the VWC from 0.015 – 0.048, and then a further rise to 0.08 on the 14th January 2006, where it gradually levels off before dropping into the "pre-event" phase which starts during the period where no data was collected. By the end of the study period the VWC drops off to 0.035, and has almost reached the "normal or dry" state of the soil. The missing data in the data set from the 8th – 13th January 2006, co-insides with the poor weather and inaccessibility to the site. It is disappointing that there is missing data over this period because there is no evidence as to when the VWC starts to drop, characteristic of the "pre-event" phase.

The overall tend of the TDR data is very similar to that of the sites lower down the profile with the major difference being that the soils at this site are not high water retaining soils, but are well drained soils that have a high rate of discharge from the profile.

5.4 ERT data

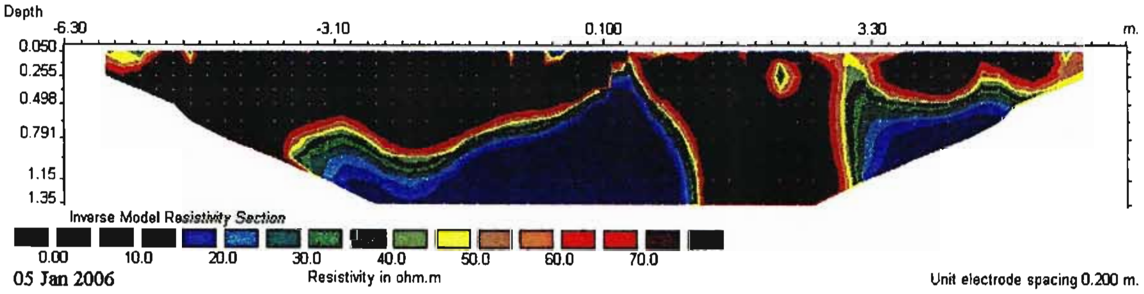
All the ERT surveys in the KNP Nkuhlu Exclosures were adapted to survey extremely shallow sections of the profiles in geological terms. The adaptations and changes to the geological instrument were discussed in chapter 4. The depths of the surveys vary from site to site but are predominantly located in the top 1m of the soil. The depths of the surveys are depended on the soil conditions at the site (refer to previous chapters for the locations, soil conditions and ERT set-up). All the ERT data obtained from the daily surveys was modelled using the RES2DINV model for each of the three sites; Riparian lower, Sodic and Combretum Sites. ERT surveys were conducted at the same time as the TDR values are obtained on a daily basis at the various sites. This was to obtain real time data sets for the two instruments and to ensure the two methods were done in conjunction (no possibility of time difference problems for later comparisons and interpretations). The fieldwork component of the ERT surveys was time consuming and the instrumentation was difficult because of the conditions and the scale of the surveys.

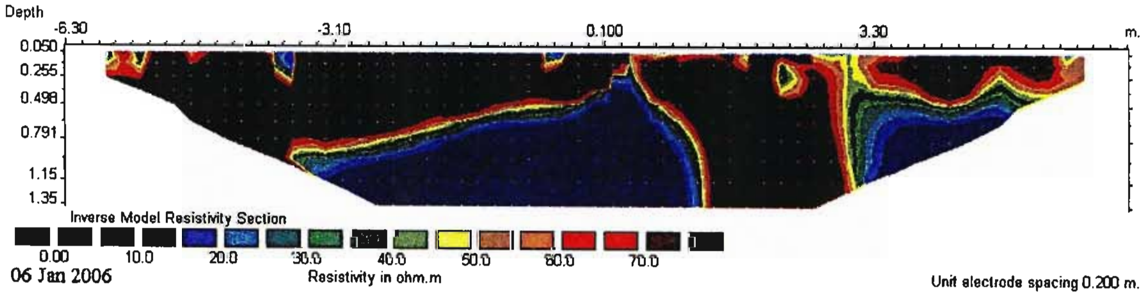
The following approach was used in the data collection, modelling and interpretation phases of the study. All the electrodes remained fixed at the three survey sites for the duration of the study. The ERT surveys obtain numerous (280-285 data points per survey) data points that were modelled to produce pseudosections on a daily basis for the survey sites. The discrepancy in the number of data points was due to the altered protocol used in the study. To compare the ERT data to the TDR data, all the data points in the pseudosection were averaged according to their depths. The final outcome was one average value (ohms) of electrical resistance for each depth of the survey but the depths vary according to protocols used. These averaged values were plotted on a daily basis for all the depths for each of the survey site. By averaging the ERT data it was possible to compare the resistivity values to the recorded TDR vales for the corresponding sites. The TDR water content values give an indication of the moisture conditions in terms of VWC - the drier the conditions the lower the water content values will be and *vice versa* for the wetter conditions. The ERT results on the other hand, should be slightly different in that the drier the conditions the higher the values will be while the wetter conditions produce lower resistivity values. In other words the TDR and ERT should produce opposite results to each other. Using the RES2DINV inversion package and RES2DMOD program (modelling program) pseudosections are produced. The modelling is done using a linear approach and a cut-off factor of 75ohms has been set for all the pseudosections. This cut-off factor has been applied because the most of the water falls into a range below 75ohms. Geology is not the main topic of study so it is ignored at this stage of the study. This means that for the purpose of this study any material with an electrical resistance higher than 75ohms is simply ignored and it makes the interpretation easier. The higher electrical resistance material is still modelled, it is just "excluded" in the plotting of the pseudosections. All the original data is initially cleaned and poor data is removed as discussed in earlier chapters. There is a fine line as to how much data to remove and at what stage in the study does the data become useless. Once the data set is satisfactory, the final pseudosections are modelled with no topography data as the pseudosections are extremely short (Maximum being 30m).

Producing the pseudosections was the easier of the steps in this study. The interpretation phase is usually challenging to even the most experienced geohydrologist/geologist and depending on the background and data sets the results may vary considerably. As mentioned earlier this is not an exact science because without drilling hundreds of test holes at astronomical costs, nobody can "exactly predict" the subsurface materials and abnormalities. The interpretation of the pseudosections in this study was linked to various other sets of additional data and included all the site data, soil data, rainfall and runoff data. A contracting geologist as well as the Abem representative, Mr. G. Barkhuisen, assisted with the interpretations of the surveys.

The interpretations are visual interpretations of the pseudosections for each site on a daily basis. The most important aspect to look for when interpreting pseudosections in a study where repeated surveys are conducted at the same location is to identify the major structures and features and make sure they are consistent in all the pseudosections. An example of this would be to identify a fault or a definite tree root. The daily changes in the pseudosections over the study period are linked to the rainfall events for the month. By studying the pseudosections it is possible to identify the wetting fronts and get an idea of the response times either in the wetting or drying phases by studying the fluxes in the lower resistance materials. Once the sequences of pseudosections have been identified and interpreted, they are linked to the interpretations of the TDR data. The comparisons and differences of the two major data sets (TDR and ERT) are discussed and linked to other data sets to get full interpretation. Once the initial interpretations are completed, a detailed explanation and summary of the findings is presented. The explanations include the possible reasons for the differences between the two data sets after linking them to the additional relevant data and these differences are presented in graphical and pictorial format in the chapter. Any abnormalities or outliers will be discussed with possible reasons. The general interpretations and selected sequences of pseudosections will be discussed and highlighted in the following subchapters.

5.4.1 Riparian Lower ERT survey





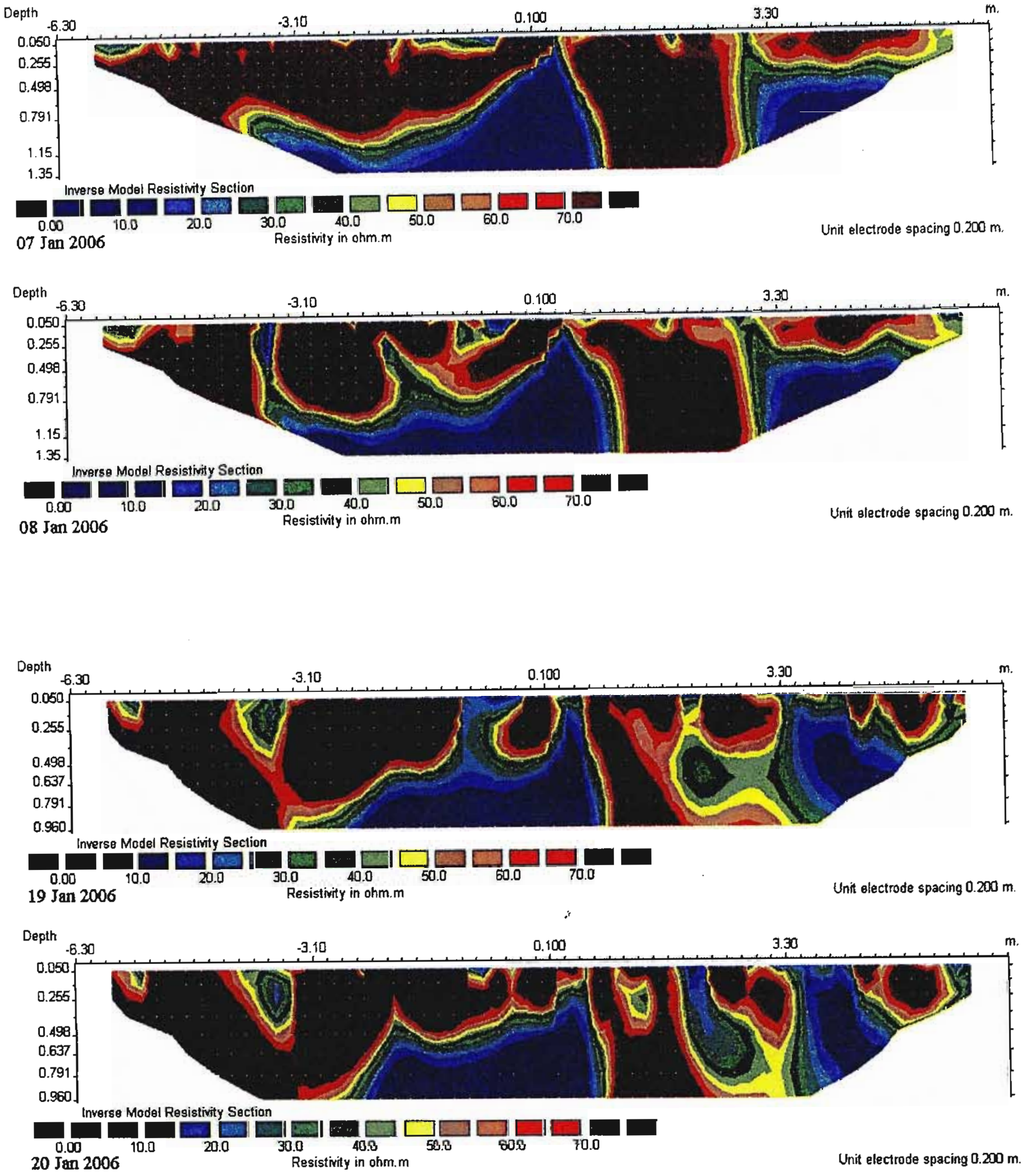


Figure 5.10 Riparian Lower ERT survey pseudosections (selected daily sequences).

Refer to Figure 5.10 for the following interpretations of the surveys conducted at the Riparian Lower site during the January 2006. Not all the pseudosections have been included in this set of interpretations but have been included in Appendix H., for further referencing. Important in the interpretation phase of the study is the linking of the precipitation data to the ERT data. Refer to Figure 5.1 for the accumulated precipitation and temperature data from the Nkuhlu weather station in the Nkuhlu Exclosures, KNP. The reason for including the first four pseudosections, from the 5th - 8th January 2006 and then the two pseudosections at the end of the study, 19th and 20th January 2006, is to highlight the importance of the response to the rainfall events which are reflected as the wetting and drying phases. When interpreting the pseudosections in a time series, it is important to identify zones containing fixed structures such as faults, boulders and possible aquifers. When referring to the pseudosections in Figure 5.10 and the completed set in Appendix H, there are major structures that are prominent in all the pseudosections. Starting at the left hand side of the pseudosections (-6.3m to 6.3m) and moving through the centre to the right hand side, the major structures will be identified. The scale used is 0.2m in the pseudosections, which is the same as the electrode spacing. The area between the –6.3m and the –4.5m is characterised by lower resistance material. This could be due the poor contact in the alluvial sands or the influence of the Sabie River, as this is the downslope section of the survey. From –4.5 to 0.5m, the surface materials are made up of higher resistance materials while there is a definite area of low resistance material extending downwards from a depth of about 0.5m. This could be an accumulation of subsurface waters and this body could be linked to the nearby river network. The area between the 0.5m and 2.5m is characterised by high resistance material and is dominant throughout all the sections. This is possibly as a result of a band of resistant material that caused accumulations of alluvial sands. An important aspect to note is that the scales of variations are incredibly small; refer to Figure 5.11 for these variations before cut-off factors for water (low resistance) were included in the modelling process.

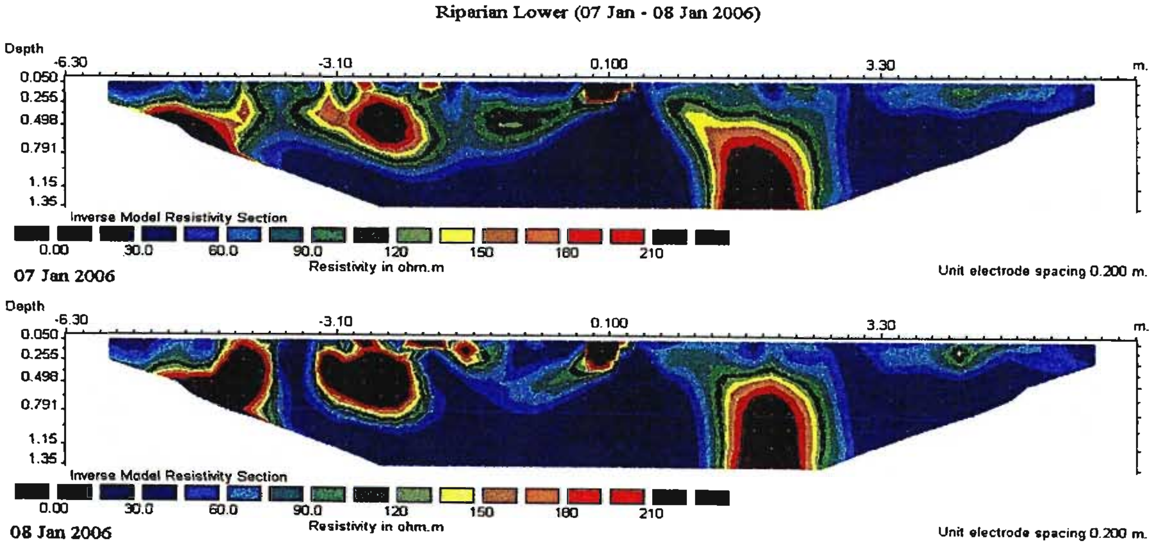


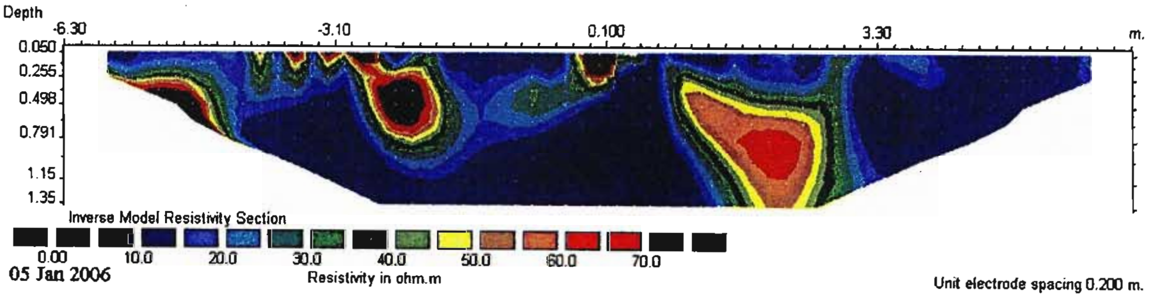
Figure 5.11 Riparian Lower ERT survey pseudosections for the 7th and 8th January 2006. No water cut-off factor was incorporated in these pseudosections. Note how low the resistance values are.

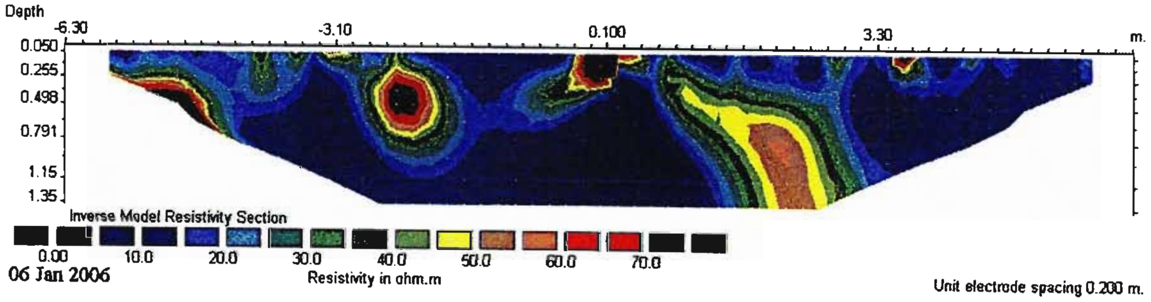
The high resistance material in the -0.1m to 0.1m and extending down to at least 0.5m, is the interference of the instrumentation at the TDR and tensiometer nests. The nests are housed in boxes, which are planted in the ground on metal stands, which show up as the high resistance material in that area. The higher resistance material to the right of the 4.0m area is a tree root. It is interesting to note how the tree roots respond to the precipitation events and how they affect the dynamics of subsurface water. The Sodic site is characterised by a large tree and the affects are more noticeable at that site, which will be discussed in more detail in the Sodic site interpretations.

Refer to Figure 5.10 to note the responses to the precipitation during the month of January 2006. The pseudosections of the 5th and 6th January 2006 are very stable and uniform, which meant the ERT surveys were accurate and reliable. At this stage of the study the conditions were dry and hot with no visible signs of water at the surface or deeper down the profile. The early hours of the morning of the 7th January 2006, was the start of the rainfall event that produced in excess of 65mm rainfall. The survey conducted on the morning of the 7th January 2006 was done in the rain. There is no direct response to the precipitation on the 7th January 2006, according to the pseudosection produced. The initial response noted was in the pseudosection produced on the 8th January 2006. The noticeable difference in this pseudosection is that the subsurface distribution of lower resistance material has increased which is an increase in the water content. The increase is from lower down in the soil profile and is moving up the profile to the soil surface. This is possibly due to the increased subsurface water contents, which resulted from the accumulation of water from upslope subsurface water discharge. Being close the Sabie River, another possible reason could be the influence of a rising water table as the Sabie River level rose. These pseudosections with increased lower resistance materials dominate for the next few days, and only on the 17th January 2006, do the surrounding soil conditions return to the "pre-event". The reason for the extended lower resistance conditions in the pseudosections are due to the continual influx of water from upslope areas and the influence the raised Sabie River has on the water table at the Riparian Lower site. The continual overcast conditions and small precipitation events that followed for a week after the initial events also meant that the profile was continually topped up with water and the normal rates of evaporation and transpiration were lower. All of these factors need to be taken into account when interpreting the pseudosections. It is at this stage of the study that the importance of ecohydrology is highlighted. Towards the end of the study period, conditions are almost returned to the "normal states" but are still dominated by the lower resistance materials. The following conclusions can be deduced from this data set. There is a slight delayed response of subsurface water movement to precipitation events. The delay is relatively small, but with soil conditions as in the Riparian Lower site, the initial thought was that there would be no delay due to the soil conditions and composition. Another important finding is that the response to the precipitation events in the drying out phase is also delayed and extended. This could be due the continual influx from higher upslope soils and/or the link to the water table rise due to the abnormally high Sabie River water levels. These responses and delays are important in understanding the dynamics of the subsurface waters and more importantly the influence and link to the ecohydrology component.

5.4.2 Sodic ERT survey

Refer to Figure 5.12 for the following interpretations of the surveys conducted at the Sodic site during the January 2006. Not all the pseudosections have been included in this set of interpretations but have been included in Appendix I, for further referencing. Important in the interpretation phase of the study is the linking of the precipitation data to the ERT data.





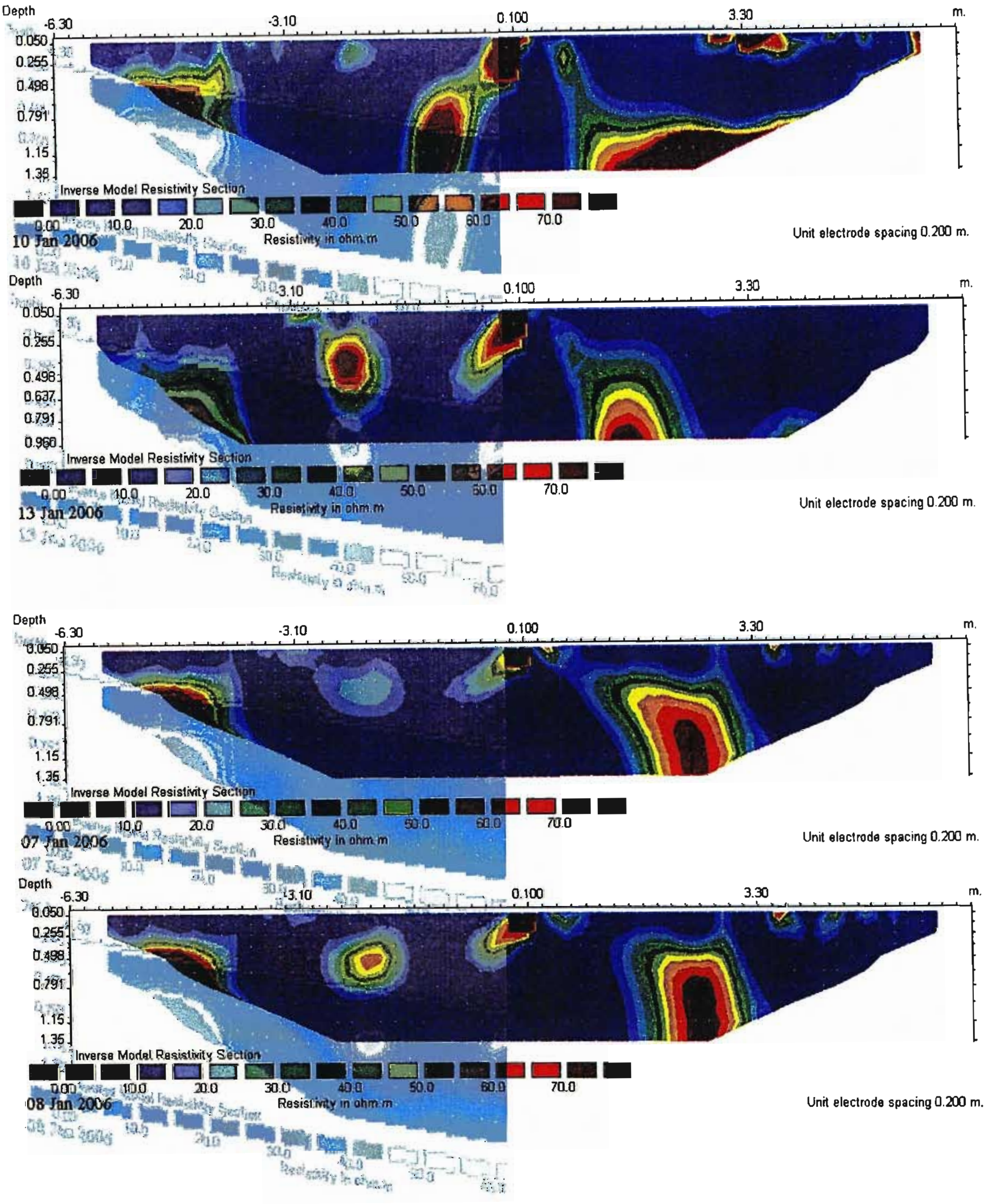


Figure 5.12 Sodic ERT survey pseudosections (selected daily sequences).

Refer to Figure 5.1 for the accumulated precipitation and temperature data from the Nkuhlu weather station in the Nkuhlu Exclosures, KNP. The reason for including the first six pseudosections, from the 5th - 8th January 2006 and the 10th and 13th January 2006, is to highlight the importance of the response to the rainfall events which are reflected as the wetting and drying phases. When interpreting the pseudosections in a time series, it is important to identify zones containing fixed structures such as faults, boulders and possible aquifers. When referring the pseudosections in Figure 5.12 and the completed set in Appendix I, there are major structures that are prominent in all the pseudosections. Starting at the left hand side of the pseudosections (-6.3m to 6.3m) and moving through the centre to the right hand side, the major structures will be identified. The scale used is 0.2m in the pseudosections, which is the same as the electrode spacing. The area at the base of the pseudosection between the –6.3m and the –4.5m is characterised by lower resistance material. This is a boulder in the section and is evident in all the pseudosections of the study. The area around the 2.0m-point is also characterised by high resistance material, which is also a boulder. The differences in the shape of the boulder are due to the internal modelling processes. The modelling process takes the data points in the near vicinity to the specific point and gets an average, so in actual fact the data point seen in the pseudosection is a data point that has taken the surrounding points into consideration. The lower the resistance of the surrounding points the lower the value of the data point. This will vary from day to day depending to the conditions of the surrounding material. The point -2.3m (0.5m deep) is a tree root and is constant in all the pseudosections. It is interesting to note how the tree's root responds to the precipitation events and how it affects the dynamics of subsurface water. The high resistance material in the -0.1m to 0.1m and extending down to at least 0.5m is the interference of the instrumentation at the TDR and tensiometer nests. The nests are housed in boxes, which are planted in the ground on metal stands, which show up as the high resistance material in that area.

Refer to Figure 5.12 to note the responses to the precipitation during the month of January 2006. The pseudosections of the 5th and 6th January 2006 are very stable and uniform, which once again confirmed the ERT surveys were accurate and reliable. At this stage of the study the conditions were dry and hot with no visible signs of water at the surface or deeper down the profile. The darker blue colours that donate lower resistance materials are due to the higher clay and silt contents in the profile, bearing in mind this is a sodic site. It is possible to identify the changes in the moisture contents (i.e. more blueish colours and darker blue colours) because the soil composition does not change. The early hours of the morning of the 7th January 2006, was the start of the rainfall event that produced in excess of 65mm rainfall. The survey conducted on the morning of the 7th January 2006 was done in the rain. Opposite to the Riparian Lower site there is an instant direct response to the precipitation on the 7th

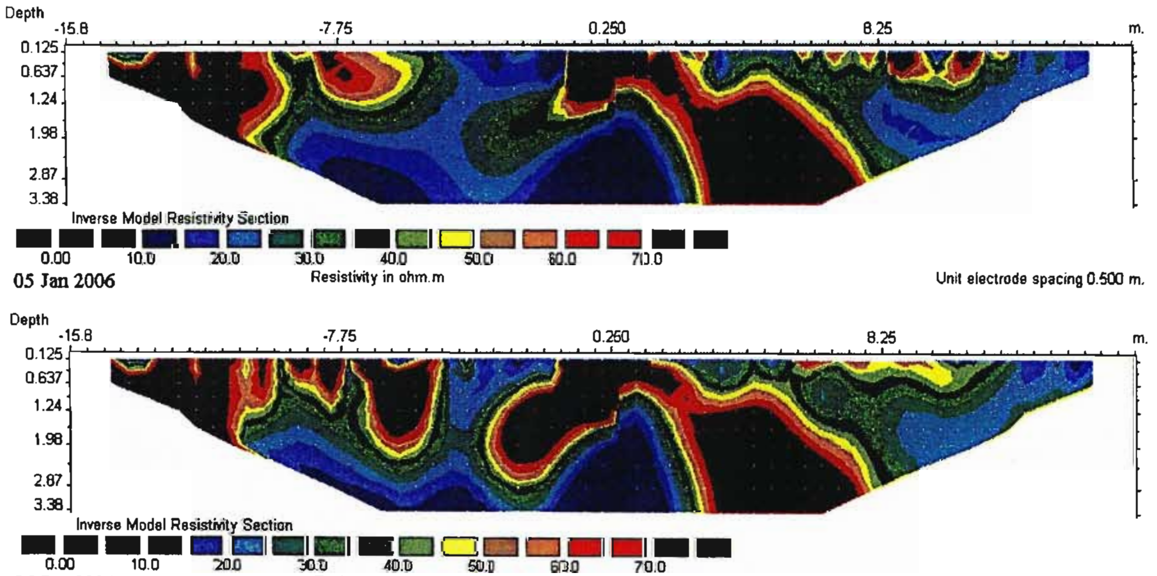
January 2006, according to the pseudosection produced. The noticeable difference in this pseudosection is that the tree's root and the surrounding materials have a definite decrease in electrical resistance. The general subsurface distribution of lower resistance material has increased which is an increase in the water content. The increase in the moisture or lower resistance in the Sodic site is from the surface and not from the bottom (water moving up the soil profile or moving into the area from upslope discharges) as in the Riparian Lower site. This is due to the increased ponding and accumulation on the surface of the sodic soils, which are characterised by crusting or surface sealing. The increased water on the surface of the sodic soils affect the data points deeper down the profile due to the averaging-modelling approach used with the ERT package. This ponding and accumulated water then quickly moves down the profile and is absorbed by the finer materials such as the silts and clays. Notice how quick the response of water use by the tree root is and as soon as the precipitation ceases the tree root dries out again. The drying out of the tree root could also be due to the surrounding soil constitution being predominantly clayey and silty material, which absorbs and retains water well.

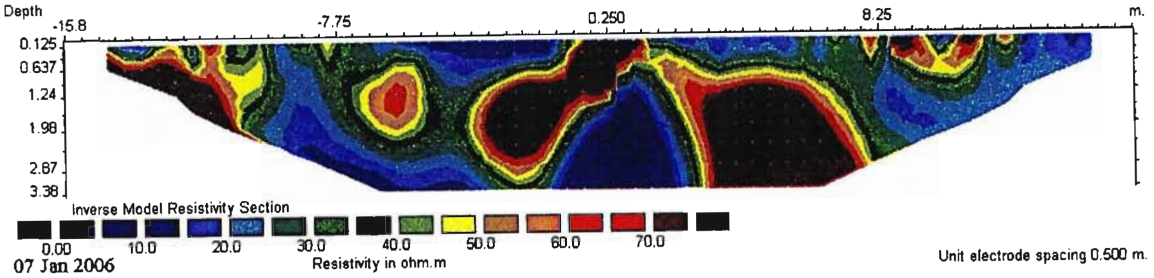
These pseudosections with increased lower resistance materials dominate for the next few days of the study and the soil conditions do not return to the "pre-event" before the precipitation event. An added reason for the extended lower resistance conditions in the pseudosections is due to the continual influx of water from upslope areas. The continual overcast conditions and small precipitation events that followed for a week after the initial events also meant that the profile was continually topped up with water and the normal rates of evaporation and transpiration were lower. Refer to Appendix I for the completed set of pseudosections for the Sodic Site. Notice the influence of the tree's root on the immediate surrounding material. It is at this stage of the study that the importance of ecohydrology is highlighted. The last three pseudosections of the Sodic site are not as accurate as required and this is due to poor electrode contact because of the daily use.

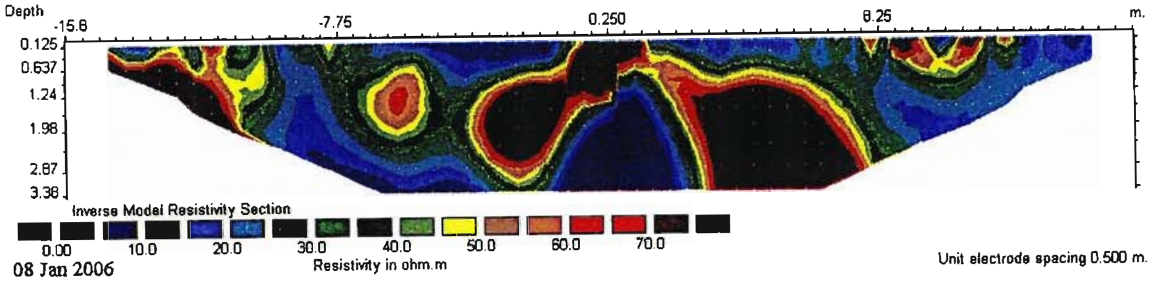
The following conclusions can be deduced from this data set. There is a slight delay in response times of subsurface water movements in response to precipitation events. Another important finding is that the response to the precipitation events in the drying out phase is also delayed and extended, which could be due to the continual influx from higher upslope soils and/or the composition of the soil. These responses and delays are important in understanding the dynamics of the subsurface waters and more importantly the influence and link to the ecohydrology component.

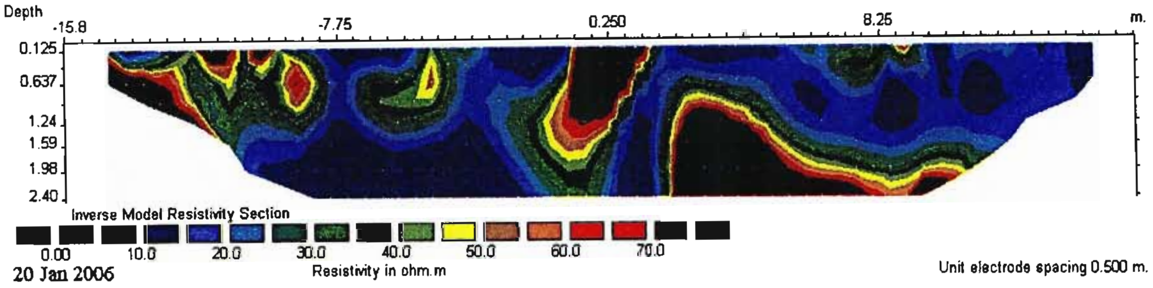
5.4.3 Combretum ERT survey

Refer to Figure 5.13 for the following interpretations of the surveys conducted at the Combretum site during the January 2006. Not all the pseudosections have been included in this set of interpretations but have been included in Appendix J, for further referencing. Important in the interpretation phase of the study is the linking of the precipitation data to the ERT data. Refer to Figure 5.1 for the accumulated precipitation and temperature data from the Nkuhlu weather station in the Nkuhlu Exclosures, KNP.









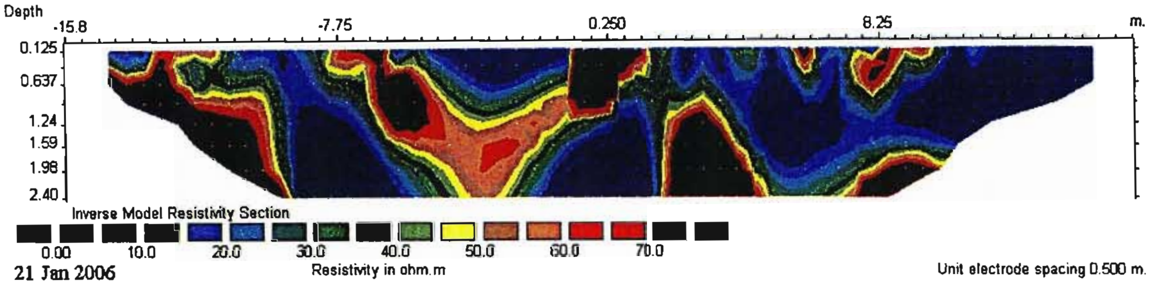


Figure 5.13 Combretum ERT survey pseudosections (selected daily sequences).

The reason for including the first four pseudosections, from the 5th - 8th January 2006 and two near the end of the study on the 20th and 21st January 2006, is to highlight the importance of the response to the rainfall events which are reflected as the wetting and drying phases. When interpreting the pseudosections in a time series, it is important to identify zones containing fixed structures such as faults, boulders and possible aquifers. When referring the pseudosections in Figure 5.13 and the completed set in Appendix J, there are major structures that are prominent in all the pseudosections. Starting at the left hand side of the pseudosections (-15.8 m to 15.8m) and moving through the centre to the right hand side, the major structures will be identified. The electrode spacing was 0.5m, which gave a span of 32m. The whole area of the Combretum site is characterised by rocky outcrops and boulders, and is evident in the pseudosections in this section. At the left hand base of the pseudosection, a large boulder is evident. Another large boulder is situated at the 4m point of the survey and extends down into the profile below the pseudosection. This boulder forms an outcrop near the centre point of the pseudosection and tails off the left. The differences in the shape of the boulder are due to the internal modelling processes. The modelling process takes the data points in the near vicinity to the specific point and gets an average, so in actual fact the data point seen in the pseudosection is a data point that has taken the surrounding points into consideration. The lower the resistance of the surrounding points the lower the value of the data point. This will vary from day to day depending to the conditions of the surrounding material and hence the slight changes from day to day. The point approximately -6m (1m deep), is a large tree root and is noted in most of the pseudosections. It is interesting to note how the tree's root responds to the precipitation events and how it affects the dynamics of subsurface water. The high resistance material in the -0.5m – 0.5m and extending down to at least 0.5m is the interference of the instrumentation at the TDR and tensiometer nests and the boulder below. The nests are housed in boxes, which are planted in the ground on metal stands, which show up as the high resistance material in that area.

Refer to Figure 5.13 to note the responses to the precipitation during the month of January 2006. The pseudosections of the 5th and 6th January 2006 are very stable and uniform, which once again meant the ERT surveys were accurate and reliable. At this stage of the study the conditions were dry and hot with no visible signs of water at the surface or deeper down the profile. This is not ideal from an ecological viewpoint in that the water holding capabilities of the soil are not too good. There is a possibility that the darker blue colours that donate lower resistance materials such as the boulders. The early hours of the morning of the 7th January 2006, was the start of the rainfall event that produced in excess of 65mm rainfall. The survey conducted on the morning of the 7th January 2006 was done in the rain. Similar to the Lower Riparian site there is an instant direct response to the precipitation on the 7th January 2006, according to the pseudosection produced, but is only noted at the tree root. There is a noticeable difference in this pseudosection in that the tree's root and the surrounding materials have a definite decrease in electrical resistance. The general subsurface distribution of lower resistance material has however not increased at the rates of the other two sites, which are located further down the catena. Notice how quick the response of water use by the tree root is and, as soon as the precipitation ceases, the tree root dries out again. The drying out of the tree root could also be due to the surrounding soil constitution and position being high up on the catena (crest) and little storage is possible because most of the water is lost downslope. The dark blue area under the boulder to the left of the centre could be identified as an area of possible water accumulation or a weak confined aquifer. There is a definite confining material that separates the surface materials from the possible aquifer below. This is highlighted in the pseudosections that follow after the rainfall event. There is definite reduction in the resistance values of the shallow surface materials (above the boulder), which is possibly water, induced. This is evident in the later pseudosections of the 20th and 21st January 2006, in the dark blue area under the boulder, the confined aquifer remains constant throughout the study period. Refer to Appendix J for the full set of pseudosections of the Combretum site. The continual overcast conditions and small precipitation events that followed for a week after the initial events also meant that the profile was continually topped up with water and the normal rates of evaporation and transpiration were lower and can be seen in the last few pseudosections for the Combretum site.

The following conclusions can be deduced from this data set. There is a slight delay in response times of subsurface water movement in response to precipitation events at the Combretum site. Another important finding is that the response to the precipitation events in the drying out phase is also delayed and extended. This could be due the continual overcast weather and smaller precipitation events that keep the profile topped up. Another important finding by using the ERT instrument and the modelling package is the discovery of a possible confined aquifer at the Combretum site. This is important when trying to determine and identify possible subsurface water sources for water extraction. This is another added benefit of using the ERT instrument in order to understand the soil water dynamics and locations and more importantly the influence and link to the ecohydrology component.

5.5 Comparing TDR and ERT data

In this section of the study describes the accuracy and realiability assessment of the instrumentation. The general criteria for evaluation used in this section is how well the TDR and ERT instruments represent the natural environmental processes and how compatible the two methods are to each other. Ideally the two instruments should produce results that are inversely proportional to each other. The following assumptions have been made and applied.

- An averaged TDR reading was used for each site in order to compare to the ERT data. The averaged WC is taken over the three (Combretum) / four (Sodic and Riparian Lower) different probe depths.
- The ERT data were also averaged at each site. The averaging position was taken at the average depth of the TDR probes, 0.4m. The raw ERT data ware averaged with 10 data points taken at or as near to the 0.4m depth of the survey at the lateral position corresponding to the TDR nest.
- Raw data from both the ERT and TDR should be used to produce the graphs. The TDR data was calibrated to produce realistic results for the specific site conditions.
- A visual comparison of the data sets must be complimented by plotting a VWC vs. ERT graph, fitting a trend line and determining an R^2 value determined for each data set. If R^2 is close to unity, then the prediction of one term (water content) from the other (Resistivity) is sound (Trade Ideas LLC, 2006).

The three sites, namely the Riparian lower, Sodic and Combretum sites have been included in the sections that follow with an explanation of the graphs and the links between the two different data sets (TDR vs. ERT).

5.5.1 Riparian Lower site comparisons

Refer to Figures 5.14 – 5.16 for the Riparian Lower comparisons of the TDR vs. ERT instrumentation. The ideal visual comparison between the TDR and ERT graphs would be a direct inverse proportional image. This would mean that the two instruments are compatible and produce the same results making the ERT instrument ideal for subsurface water studies, especially the dynamics thereof.

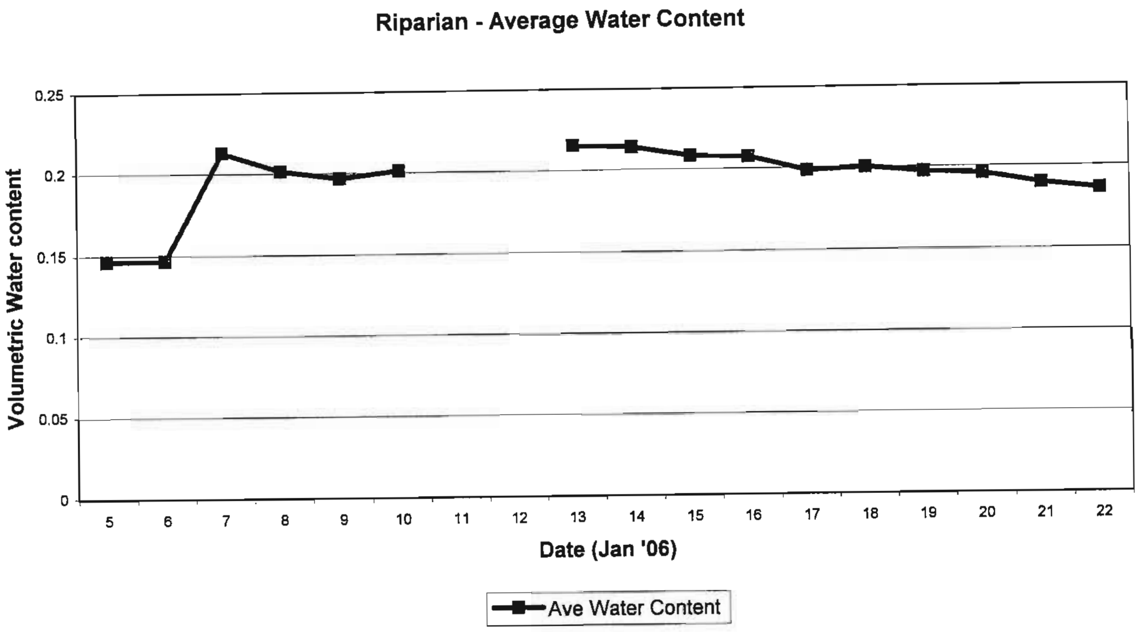


Figure 5.14 Averaged WC for the Riparian Lower site (TDR).

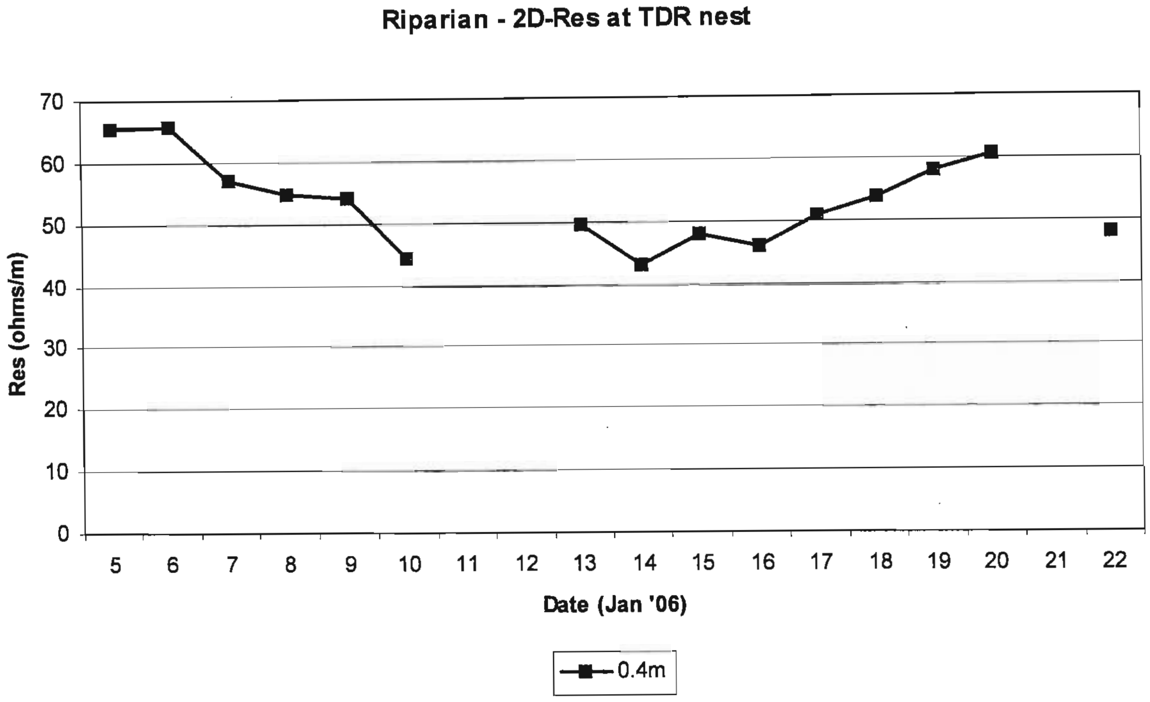


Figure 5.15 Averaged electrical resistivity for the Riparian Lower site.

Figures 5.14 and 5.15 are relatively inversely proportional to each other. The area of concern is the period of missing data (discussed in detail in earlier chapter) because in both figures there is no convincing proof of the periods of extreme wetness. In figure 5.14, the WC should rise, as the conditions get wetter, which they do after the onset of the precipitation on the 7th

January 2006. The area of concern is how high does the WC rise to on the 12th January 2006? From the 13th January 2006 there is a general drying out of the profile as the WC drop steadily. Figure 5.15 shows the opposite in that as the conditions get wetter, the resistivity values drop. Similarly at what point do the resistivity values reach the lowest point before the conditions start the drying out phase? The periods of uncertainty are the same as in Figure 5.14 and there is a definite link between the two methods in the different stages of the study. The rise in the WC and the dip in the resistivity in both Figure's 5.14 and 5.15 on the 15th January 2006, are represented very accurately and coincide with the precipitation (Figure 5.1).

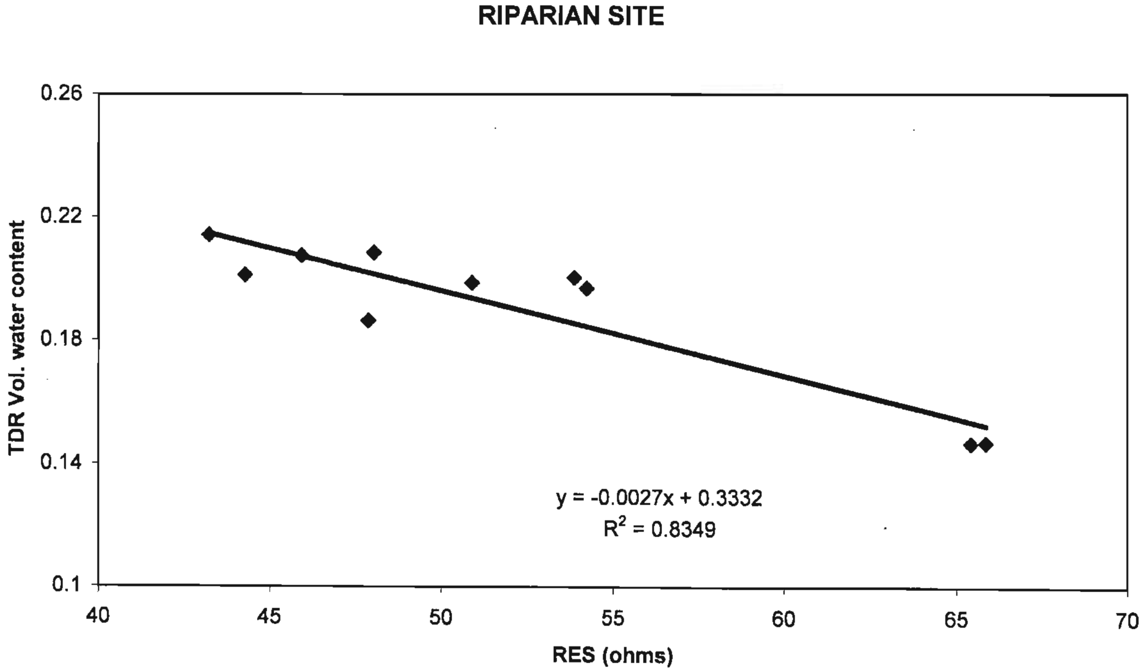


Figure 5.16 The comparison plot for the TDR vs. ERT data for the Riparian Lower site.

The statistical comparison of the two methods is represented in Figure 5.16 where the WC and resistivity are statistically compared and plotted. A trend line is added to the scatter and the equations of the line is $Y = -0.0027x + 0.3332$ and has an $R^2 = 0.8349$. Considering the natural system being monitored, the R^2 is very acceptable. From the above results it is evident that the two different methods of instrumentation provide realistic and accurate results in relation to each other.

5.5.2 Sodic site comparisons

Refer to Figures 5.17 – 5.19 for the Sodic site comparisons of the TDR vs. ERT instrumentation. Figures 5.17 and 5.18 are relatively inversely proportional to each other. The area of concern is the period of missing data as in the Riparian Lower data set (discussed in detail in earlier chapter) because in both figures there is no convincing proof of the periods of extreme wetness.

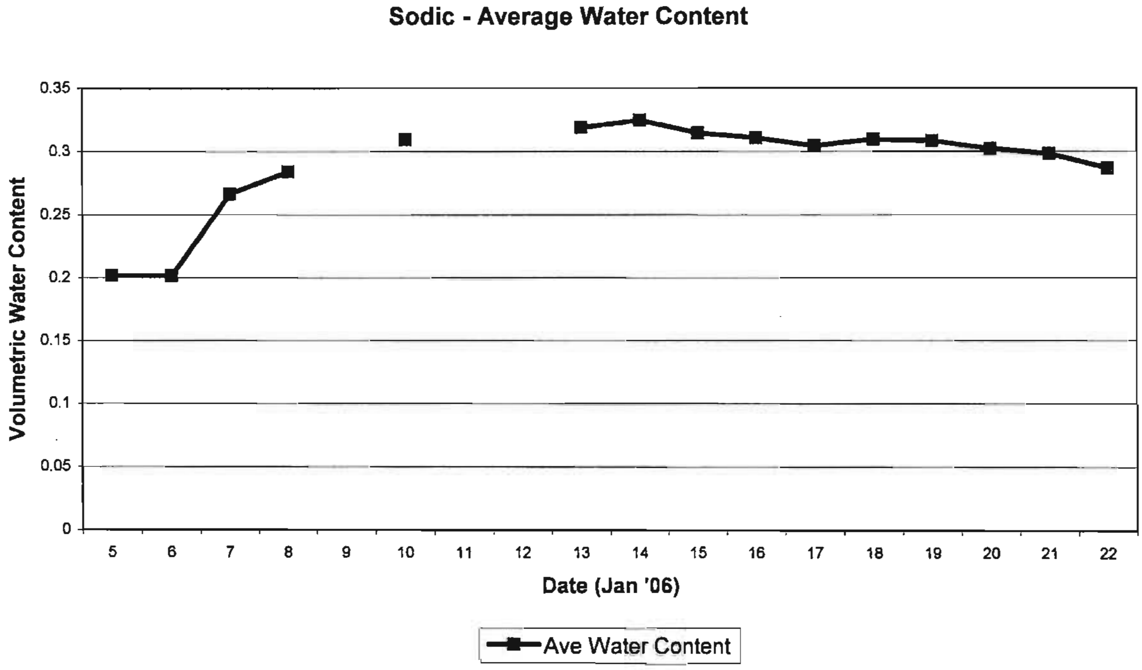


Figure 5.17 Averaged WC for the Sodic site (TDR).

In figure 5.17, the WC should rise, as the conditions get wetter, which they do after the onset of the precipitation on the 7th January 2006. The WC rises to the maximum on the 14th January 2006 and then drops from the 15th January 2006. This is a general drying out of the profile as the WC drop steadily.

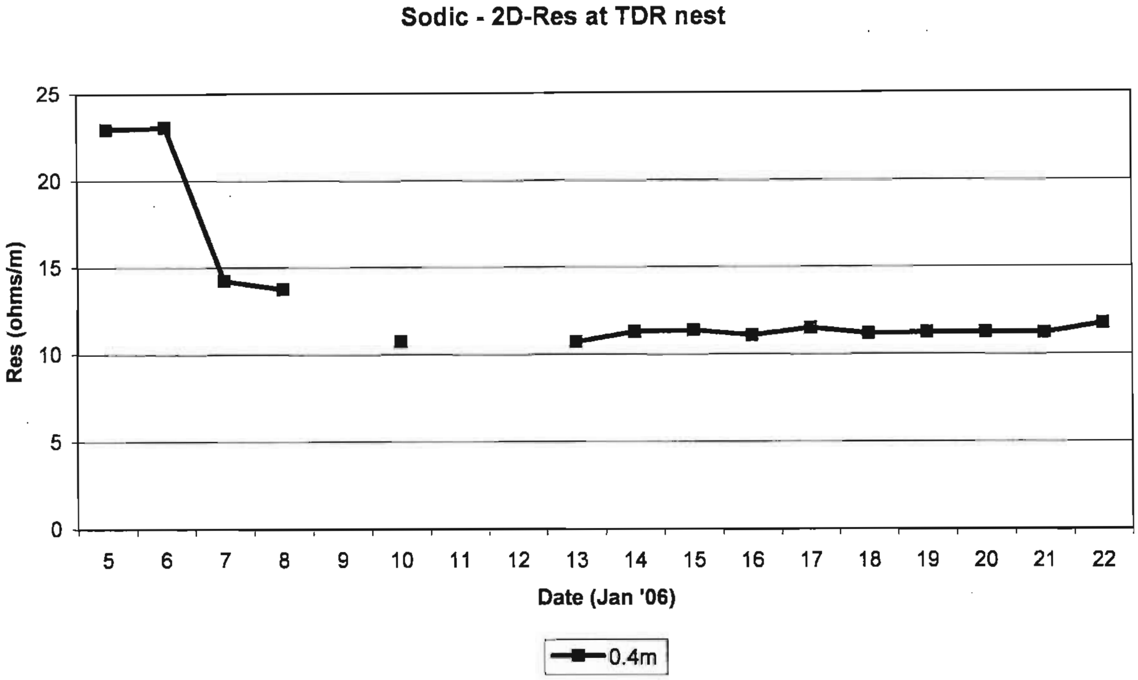


Figure 5.18 Averaged electrical resistivity for the Sodic site.

Figure 5.18 shows the opposite in that as the conditions get wetter, the resistivity values drop. Similarly at what point do the resistivity values reach the lowest point before the conditions start the drying out phase? The periods of uncertainty are the same as in Figure 5.17 and there is a definite link between the two methods in the different stages of the study. Notice how similar the tailing off or "drying out" phases of the study are in the TDR and the resistivity data plots, which imply that the ecohydrology could be accurately studied in the future.

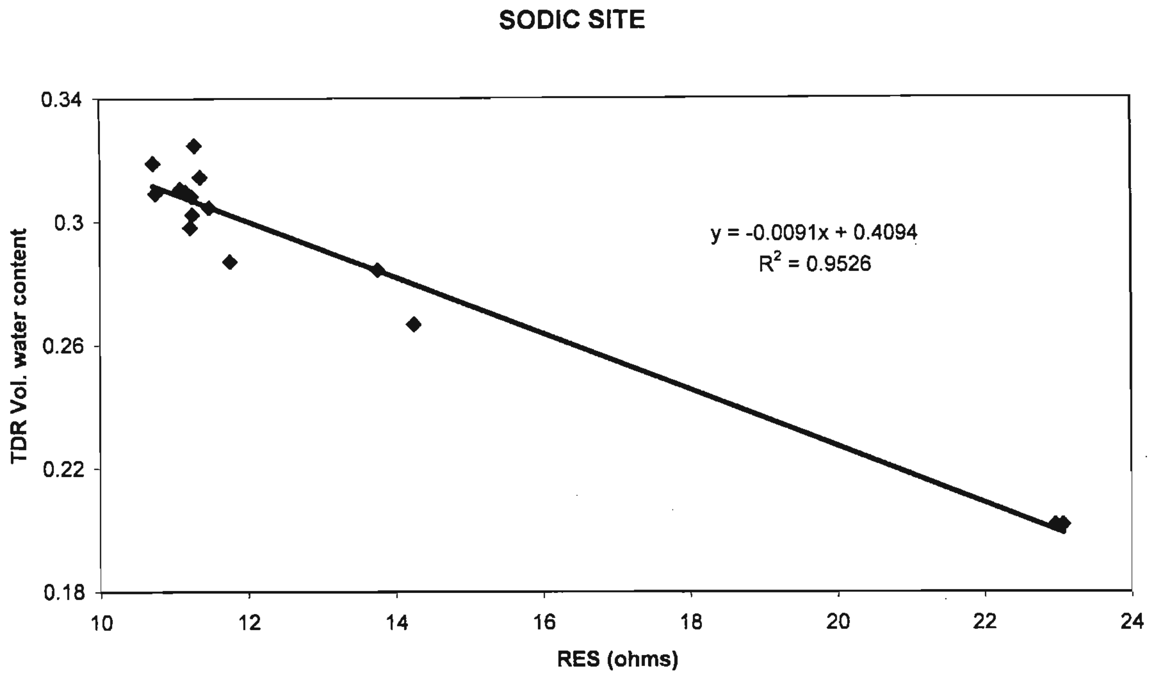


Figure 5.19 The comparison plot for the TDR vs. ERT data for the Sodic site.

The statistical comparison of the two methods is represented in Figure 5.19 where the WC and resistivity are statistically compared and plotted. A trend line is added to the scatter and the equations of the line is Y = -0.0091x + 0.4094 and has a R^2 = 0.9526. Considering the natural system being monitored, the R^2 is the acceptable. It is evident that the two different methods of instrumentation provide realistic and accurate results once again at this site under these conditions.

5.5.3 Combretum site comparisons

Refer to Figures 5.20 – 5.22 for the Sodic site comparisons of the TDR vs. ERT instrumentation.

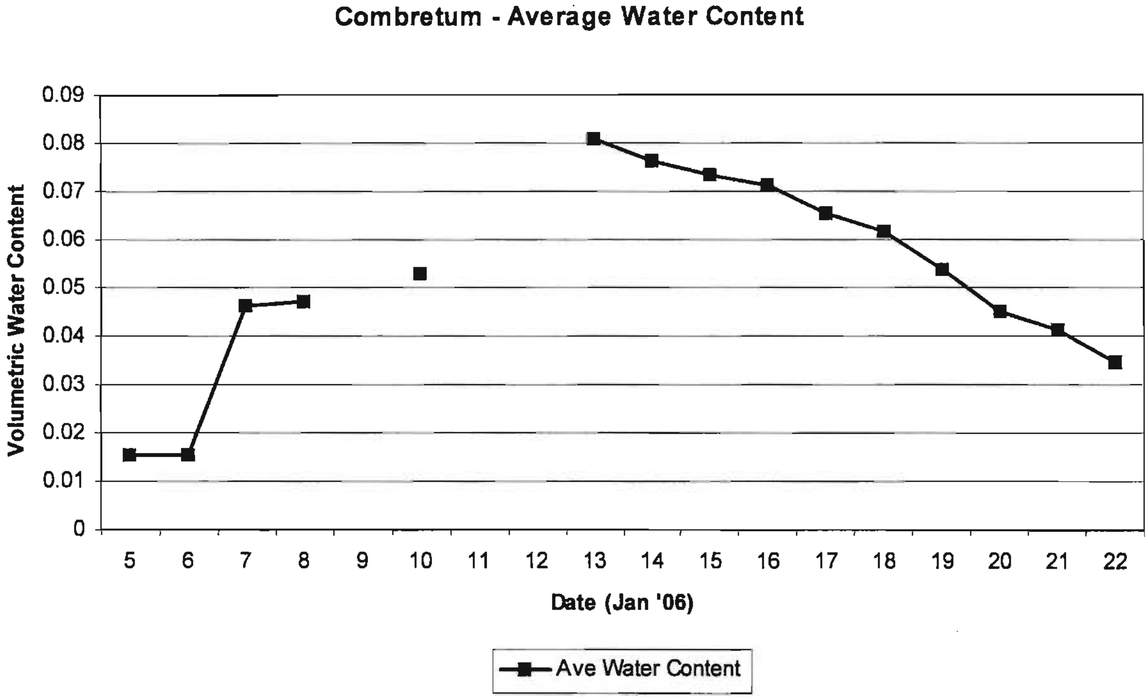


Figure 5.20 Averaged WC for the Combretum site (TDR).

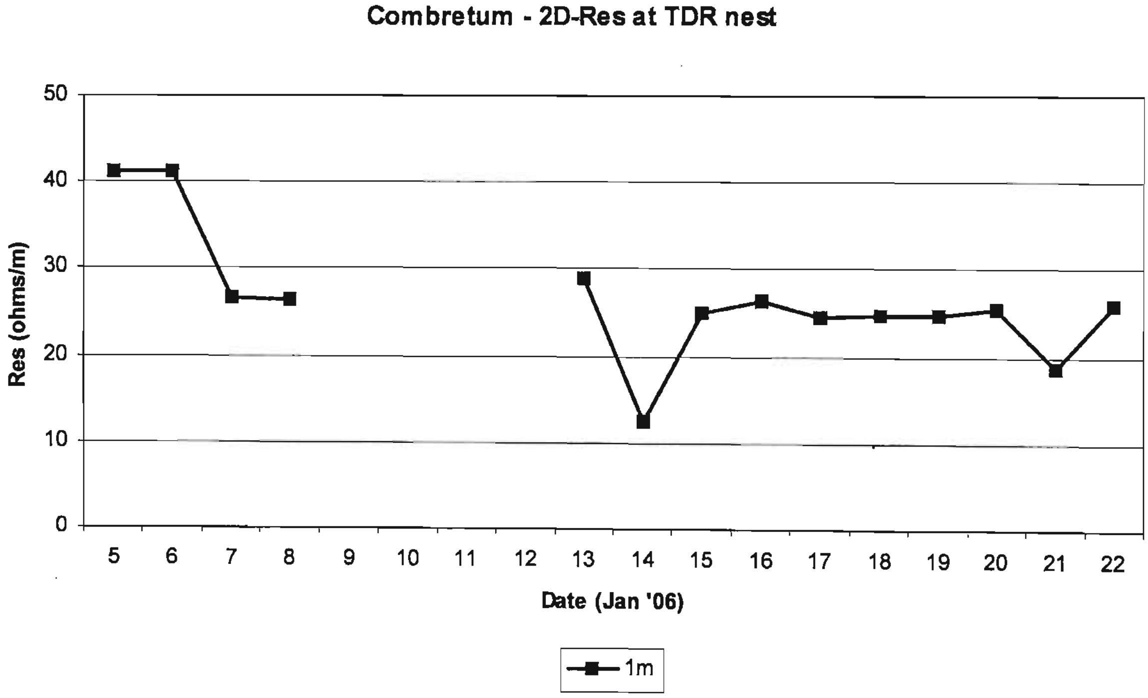


Figure 5.21 Averaged electrical resistivity for the Combretum site.

Figures 5.20 and 5.21 do not show perfect inversely proportionality to each other. The area of concern is the period of missing data as in the two previous data sets (discussed in detail in earlier chapter) because in both figures there is no convincing proof of the periods of extreme wetness. Another concern is the period after the missing data. In figure 5.20, the WC should rise, as the conditions get wetter, which they do after the onset of the precipitation on the 7th January 2006. The area of concern is how high does the WC rise to in the period of missing data, and does it rise higher than it is on the 13th January 2006? From the 13th January 2006 there is a general drying out of the profile as the WC drop steadily. Figure 5.21 shows the opposite in that as the conditions get wetter, the resistivity values drop. The periods of uncertainty are the same as in Figure 5.20 but as in the previous two sites there is only a definite link between the two methods in the early stages of the study. The area of concern is the "drying off" phase in the ERT data; the data does not mimic the TDR in that it remains fairly stable throughout the "drying off" phase with two relatively large drops in resistivity on the 14th and 21st January 2006. The WC tends to drop as expected to produce a uniform "drying off" phase. A possible explanation of the unexpected resistivity data could be due to the depth of the averaged data set now being 1.0m as opposed to the 0.4m of the previous two sites. This is due to the electrode spacing being larger in this survey; hence the depths attained are greater. More importantly the TDR instruments are generally shallower than the other two sites because of the subsurface conditions (the probes used were especially designed for the site). In concluding, the comparison of the two data sets at the Combretum site is not ideal and should not be used in defining the water dynamics in future studies. The changes in the water dynamics definitely determine the ecohydrological relationships of the site.

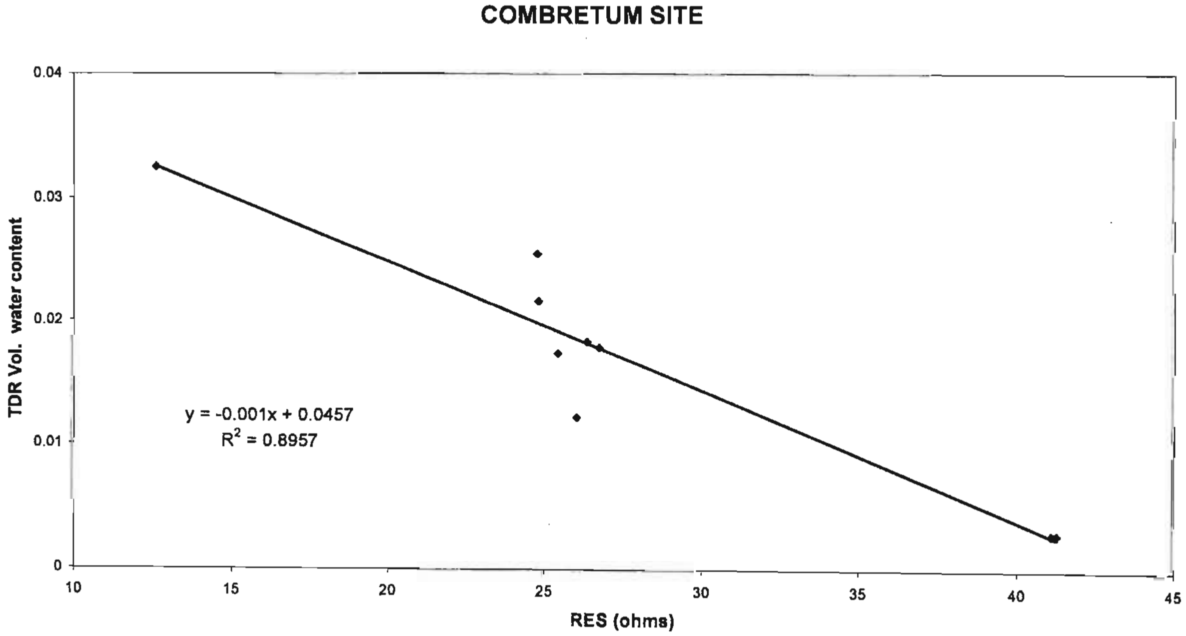


Figure 5.22 The comparison plot for the TDR vs. ERT data for the Combretum site.

The statistical comparison of the two methods is represented in Figure 5.22 where the WC and resistivity are statistically compared and plotted. A trend line is added to the scatter and the equations of the line is $Y = -0.0001x + 0.0457$ and has a $R^2 = 0.8957$. For this study under the extremely difficult conditions and the various problems encounted, the R^2 is still a strong correlation. As mentioned earlier there were comparison problems at the Combretum site and the results from this site are not recommended for detailed studies in the future. The reason is that the TDR probes were designed for and installed in shallow site conditions, while the resistivity data that was used in the comparison process was extracted from below this level, since the ERT layout and protocol did not capture the shallow resistivities. Due to the electrode spacing, this was the best possible data set from both methods of instrumentation. This is a valuable lesson that needs to be addressed in future studies and is linked to the specific protocol writing for the adapted ERT studies.

Overall, apart from the data and plots produced for the Combretum site, the other two sites produce very encouraging data that is realistic and accurate. The Sodic site is relatively wetter than the Riparian and Combretum sites. This is possible due to the influence vegetation has on the water balance as well as the fine soils with high retention characteristics at this site. In the Sodic regions there is less vegetation and therefore less water usage by vegetation, so the dynamics of subsurface waters is reduced. The study has highlighted the need for this data and the important links that can now be closed in the bigger picture of hydrology and more importantly, ecohydrology. The fluxes in the subsurface waters are definitely influenced by the ecohydrological factors. This has been demonstrated by the localised patches of wetting supporting specific rooting zones, by the wetter characteristics of the sodic materials and by accumulations observed in the riparian site.

6. PROBLEMS ENCOUNTERED

In any data set there are problems with data, either in data collection or linked to instrument failure and this data is then referred to as "weak data." In most scientific studies there are problems encounted with data management and data collection. In this study, problems were also encountered; the way in which scientists address these problems make the study a success or not. The ERT instrument is a complex instrument, imported from ABEM Instruments, Sweden with one agent in South Africa serving most of Sub-Sahara Africa.

During the first week of the study after the rainfall event on the 6th and 7th January 2006, an instrument failure was encounted. An internal fuse blew, the reason is not clear, but the cause has been put down to wear and tear. The instrument is supplied with numerous spare fuses, meaning this is a possible weak point of the instrument. Being at the study site in the KNP, the conditions are not ideal for Information Technology (IT) repairs and diagnosis. The fuse was replaced after numerous telephone calls to the South African agent and the manufacturer in Sweden, in an attempt to get the instrument functioning again. The blown fuse precipitated a second problem in that all the software and protocols had been lost in the reformatting process. After re-installing the software and programs with the up-dated software directly from Sweden, the desired project protocols and arrays were not compatible with the new software. Together with the help of the agent, the program was re-written (attempting to remember the old protocol), but ultimately resulted in a difference in pseudosection depths. The old protocol was made up of 280 readings and gave a uniform detail pattern throughout the profile, which meant the pseudosection attained a depth of 1.35m with the 0.2m electrode spacing, and 3.38m for the 0.5m electrode spacings. The newly developed protocol was made up of 285 readings, both using the Wenner array. The difference between the two protocols is that the new protocol has a slightly more detailed covering nearer the surface, which meant that the measurement depths for the 0.2m and 0.5m electrodes spacings were 0.96m and 2.4m respectively. This was actually better for the purpose of the study as the study was concentrated at the surface of the soil profile. However, the lack of compatibility between the "before and after" data sets confounded the calibration process. One of the major problems that have since been noted, is that because all of the protocols were taken from geological protocols (being a geological instrument), there were problems in depth adjustment. In geological studies the area and depth of interest is usually hundreds of meters below the surface, looking at large geological structures and features. The protocols used in this study were converted and adapted from these large-scale protocols. By taking the geological protocols and converting them to study extremely shallow portions of soil profiles, the conversion process meant that the most detailed readings should have been located at the surface. In this study of water dynamics the first 5cm to 10cm of the soil profiles were not tested. This might be a shortfall in the application of the technique. Future studies and related studies will require protocols to be specifically written for the project requirement. Fortunately in this study the modelling overcame the problem to a large extent so the results are reliable.

Another problem encounted that limited the functioning of the instrument was the fact that the study site received the abnormal amount of rainfall. This not only limits the functioning of the instrument, but the poor weather also limited access to the site, with numerous roads closed in the KNP due to flooding of the rivers. Working with the ERT instrument in the rain is extremely risky, as the instrument should not get wet, particularly the cables. One of the objectives of the study was to include a rainfall event and the subsequent drying out phases. Protective packaging was used during the rainfall events to obtain the relevant data during the events.

The study site, based in the exclosures meant that no animals could access the area, meaning that the natural vegetation is able to flourish without hindrance from grazing and browsing. The site, being near a natural water course is dominated by thick vegetation and grass and with the late spring rainfall, meant the exclosures were extremely well vegetated. This made it difficult to perform the surveys without clearing the survey transects to some degree. Another problem that only became apparent after a few weeks into the study was the poor soil conditions that are dominated by alluvial sandy deposits along the river. The poor soil conditions were only a major concern in the Riparian Site and became significant in the last week of study where the contact with the electrodes was reduced. This was due to the electrodes being stationary throughout the study period and daily use of the electrodes to perform the surveys. The cables were attached to the electrodes by means of electrical wiring and attaching the wiring to the electrodes on a daily basis meant that the contact with surrounding soil was not ideal. Due to the study focusing on the water component of the soil, water could not be applied to improve the contact between the surrounding soil and the electrodes. In normal geological studies it is general practice to pour water on the electrodes to improve the contact between the electrodes and the surrounding soil. However, with the short spacing of electrodes in this study, this practice was deemed to influence the subsurface water contents being measured and so was avoided. Soil around the electrodes was compacted with a hammer to improve the contact. The issue of contact in this study was a concern at the Riparian Site, but all the researching parties were well aware of this problem towards the completion of the study. Improving the interpretations of the Riparian Lower Site and linking the data with other soil water data in the interpretation phase overcame the problems of electrode contact.

A problem that is generally encounted in all scientific studies is the fieldwork component that requires the instrumentation to be calibrated. All instrumentation is initially calibrated before it is installed in the field. The ERT instrument is not calibrated but the resistivities of the various materials have certain ranges that they fall into. These ranges can be seen in various tables and charts (earlier chapters) and generally have a wide range. The resistivities of the different materials are standard electrical resistance values. The reason for the wide ranges is that geologies differ due to conditions and environments in which they occur. It is therefore extremely vital to perform the correct field reconnaissance and to obtain an idea of the general field layout, dominant processes and geologies. By linking the ranges of the resistivities to the field data, the calibration of the instrument is covered. The calibrations for the TDR instrument are slightly different in that the calibration issue is usually done at laboratory scale under known conditions. These conditions are usually varying soil conditions and differing moisture conditions. Once the calibrations are completed the instruments are installed into the soil profile at the desired depths and the data collection is initiated. Once the data has been collected, analysed and calibrated to their corresponding calibration curves, the data is then usable for scientific purposes. The calibration of the ERT data was calibrated in the interpretation phase of the study while the TDR data was calibrated according to calibration curves for the specific TDR instruments. The calibrations were done by the BEEH prior to installation. Once the data of both instruments (ERT and TDR) were calibrated, the interpretation of the data and comparing phases were possible.

7. CONCLUSIONS AND DISCUSSIONS

Ecohydrology has become a vital link in the natural sciences in the past decade, and this is because ecohydrology incorporates all the related fields in one group. Water controlled ecosystems are complex, evolving structures whose characteristics and dynamic properties depend on many inter-related links between vegetation, climate and soil (Rodriguez-Iturbe and Porporato, 2004). Subsurface water is the key variable synthesizing the action of climate, soil, and vegetation on the water balance. For this reason more needs to be known about the whereabouts, quantity and quality, and more importantly, to the research in this case, of the mobility and paths taken by subsurface water. Water is essential to the environment and the largest available source of fresh water lies in the subsurface environment. Increased demands for water worldwide have simulated development of underground water resources. As a result, techniques for investigating the occurrence and movement of subsurface waters have been improved and concepts of resource management have been established. To understand this source of subsurface water it is vital to understand the medium that holds this water in order to gain a better understanding of how subsurface water moves (Todd, 1980). The resistivity method is a method that will become increasingly important in the understanding and investigation of the subsurface environments. The results from this study show that the resistivity instrument is at the forefront in terms of ecohydrological studies relating to the subsurface water interactions, and if fully utilised, could possibly replace present scientific equipment and procedures. At the present time, ERT surveys are the most practical economic compromise between obtaining very accurate results and keeping the survey costs down. If the resistivity methods are used in conjunction with other methods, the shortfall of the resistivity method (once-off picture in an on-going event) could be minimised. This is going to be the biggest challenge to scientists in the future. Once the above problems are solved, the process of linking ecohydrology to the resistivity studies will become the focal point in not only ecohydrology studies but also various studies remotely linked to the ecohydrology field. An additional benefit would be the increased savings in terms of costs and reliable accurate data required in this field. Refer to Appendices L through O, for additional studies conducted with the ERT instrument, highlighting the varying conditions and environments that ecohydrological studies have been conducted since the acquisition of the instrument (the interpretations accompany the pseudosections). Numerous other studies have been conducted and yielded encouraging results, not only in an ecohydrological sense, but in a geological sense as well.

The study of ecology and hydrology as separate entities is outdated and the approach in recent times is to include various disciplines of study into one thought process that is interrelated in all aspects. This is the more realistic approach and has been accepted as such by all interested parties. Ecohydrology is one such study but is actually a part of a large highly complex interrelated system that should not be broken up into smaller entities. Ecohydrology is the study of both hydrology and ecology. According to Rodriguez-Iturbe and Porporato, (2004) there are two important subjects in this study, namely, soil moisture and plants, with soil moisture being the centre of the hydrologic cycle. There is a definite link between ecohydrology and specific ecology with all other matters on the globe. The subsurface water component is one of the more important components of the ecological system hence its importance in ecohydrology.

This study is the first of its kind in South Africa and possibly worldwide in the natural environments. Similar studies have been conducted at laboratory scales and under controlled environments. Studying subsurface water dynamics and hillslope processes using a geophysical instrument is at the forefront of science and can only improve with time. The subsurface water component of the hydrological cycle is definitely the weakest link in the cycle. This is purely because of the difficulty in studying this component. With the aid of geophysical instruments scientists can get a better insight as to how water bodies and stores fluctuate, and re-act to numerous conditions that are continually changing. Important to note that this is not an exact science, because up until present, nobody can be sure of the subsurface conditions, hence most of the results are educated assumptions.

From the study conducted in the KNP it can be concluded that this type of study is reliable, accurate and can be used to obtain quicker results than the more conventional methods previously used, in this case the TDR method. One of the limitations is that this method must be used in conjunction with other scientific instrumentation and methods to provide reliable and accurate results or guidelines. Numerous studies put little emphasis of the subsurface components of the study. The main advantage of the ERT instrument is that it is a geophysical instrument with a strong emphasis on the geological or subsurface components. The limitation is in the converting or interpretation phase, where the main aim was to study the subsurface waters and dynamics thereof as opposed to the geologies.

Staff of the BEEH feel that most of the subsurface waters and water dynamics are heavily reliant on the geologies and make up of the soils, hence the reason for going in this direction of research. If the interpretation phase together with other instrumentation could be accurate this is definitely the route to follow in future subsurface water studies. This is a cost and time saving approach to close the hydrological study with extreme accuracy if used in conjunction with other instrumentation.

In most subsurface water studies, instrumentation (numerous different instrumentation) is usually installed after rigorous calibration and extraordinary high costs at study sites that require huge efforts in man-hours and effort to ensure reliable and realistic results are obtained. In many of the research catchments and study sites in South Africa, there are usually problems with security of the instrumentation, and especially the portable power sources, such as batteries, which are highly sought after in the rural regions. This in turn means that together with the vandalisation, there is a loss of valuable data which means the projects are bound to fail. With the ERT instrument, real-time data is produced, which means less chance of theft, and more realistic data. By being on site for the duration of the study the other instrumentation used in conjunction with instrument and can be monitored and optimally controlled normally. The problem is that some historic data is required at some stage of study from the supplementary instrumentation. Another strong point in using the ERT instrument is that it could be used as a quick simple once-off method of identifying areas for further study or areas of interest.

The study in the Nkuhlu Exclosures, KNP, produced very interesting and pertinent results to subsurface water studies. Using the TDR instrument in conjunction with the ERT instrument to identify and determine subsurface water dynamics, proved to be a huge success. The results and findings proved to be very acceptable and reliable with the most important aspects being the interpretation and modelling phases of the study. In all three-study sites there was a strong correlation between the two data sets produced and the R^2 values were very close to 1 in all three data sets. With the help of geologists and geohydrologists the interpretation and conversion of the protocols from geological to hydrological protocols and ways of thinking were done without a problem. The general weather conditions were ideal (included a large rainfall event and subsequent drying out), but the site conditions (soils very sandy at one site) were not ideal for the study. Numerous problems were encounted, and included instrument failure, inaccessibility due to flooding and site conditions, but overall the study was a step in the right direction and the results suggest that the ERT instrument could be used as an important link in closing the water balance, particularly the soil water component, provided the method is combined with other electromagnetic methods.

8. RECOMMENDATIONS

Ecohydrology is a new term discussed in hydrological circles worldwide and it can only become more important as the understanding of the whole concept improves. Using the ERT instrumentation as the basis of this study compliments the enquiries into soil-plant interrelationships and the results should hopefully encourage similar studies, enabling scientists, hydrologists and ecologists to fully understand and estimate the subsurface water dynamics, and in so doing close the hydrological cycle.

It is recommended that the ERT instrument be used for the study of subsurface water dynamics as it will aid in future studies related to the hydrological and ecohydrological dependencies. The main benefit is that there is minimal site disturbance and the results are produced within a few hours, making it an extremely cost effective and reliable method of determining various aspects of the related fields of study. There is no initial time period needed to ensure the instrumentation has "settled" well to produce the historic results that are entered into databases. The data produced is real-time data that is accurate and realistic. There are fewer chances of problems with continual monitoring, theft, replacing power sources and general maintenance that is the downfall of many alternative methods of monitoring subsurface moisture conditions. This is a "one-man" operation and the instrument is easily maintained in the field. Furthermore, the instrument allows for a 2-dimaensional insight into subsurface water distribution and dynamic that will impact on ecosystem survival.

It is however recommended that the use of the ERT instrument should be performed by a qualified operator, to eliminate any possible errors. It is also recommended to link the work and results of the ERT instrument to other instrumentation, where possible. This is purely to obtain a more holistic set of data and to aid in interpretation. By combining the ERT methods to the TDR instrumentation and results, possible areas of concern can be compared and analysed. This approach has been conducted under a laboratory scale as an experiment with reliable accurate results. More field studies need to be conducted in the near future to determine if this method of research is indeed as informative as this study. It is also recommended to perform similar tests on different scales and in different soils and environments. The scale used in this study was very small and climatic conditions between the three sites were similar.

Certain questions remain: How will the results compare if a study is to be conducted in wetland environments or arid environments for example? Will the outcomes mimic the results obtained from the study conducted in the KNP? These are questions and issues that need to be addressed in some detail regarding future studies in this field. How good will the comparison of a neutron probe data be, compared to the ERT instrument data. Many geologists and geohydrologists believe the ERT instrument is purely useful for the geological aspect of the study. From the study conducted in the KNP, it is evident that the ERT instrument is an extremely diverse tool and, depending on the interpretation of the data, could be useful in many fields.

Another aspect that needs to be addressed with care in future studies is the writing of protocols. The ERT instrument is a geological instrument and all the standard protocols used are geologically based protocols. In other words the emphasis of the protocol is to distinguish prominent features such as fractures, faults and seams of a specific ore. When conducting shallow surveys with a greater emphasis on the moisture component, the protocols need to be adjusted accordingly. More detail is required at the surface of the profile and the depth is not (up to 80m deep) usually required for these studies. Careful consideration needs to be given to the comparisons between instrumentation and the working conditions. Surveys may need to be re-run over a longer period to encompass a season, for example. One rainfall event will not be sufficient for a more detailed study in the future; a full wet season will probably be more appropriate. "Back-up" data and instrumentation will be required as in all scientific studies. Weather data, runoff data, borehole data and drilling logs may be required to ensure a full study can be conducted with a high level of confidence. Deeper surveys may be needed to get an understanding of the underlying geologies and dominant physical features of a study site.

Overall the ERT instrument and modelling packages are going to remain at the forefront of scientific research in the near future. The system is cost effective yet extremely accurate in helping various scientists in different fields understand the broader picture of ecohydrology. The subsurface water component is certainly an important and vital link in all ecohydrology studies and needs to be addressed. Using the ERT instrumentation together with other geophysical or soil water sensing instrumentation, this is now possible.

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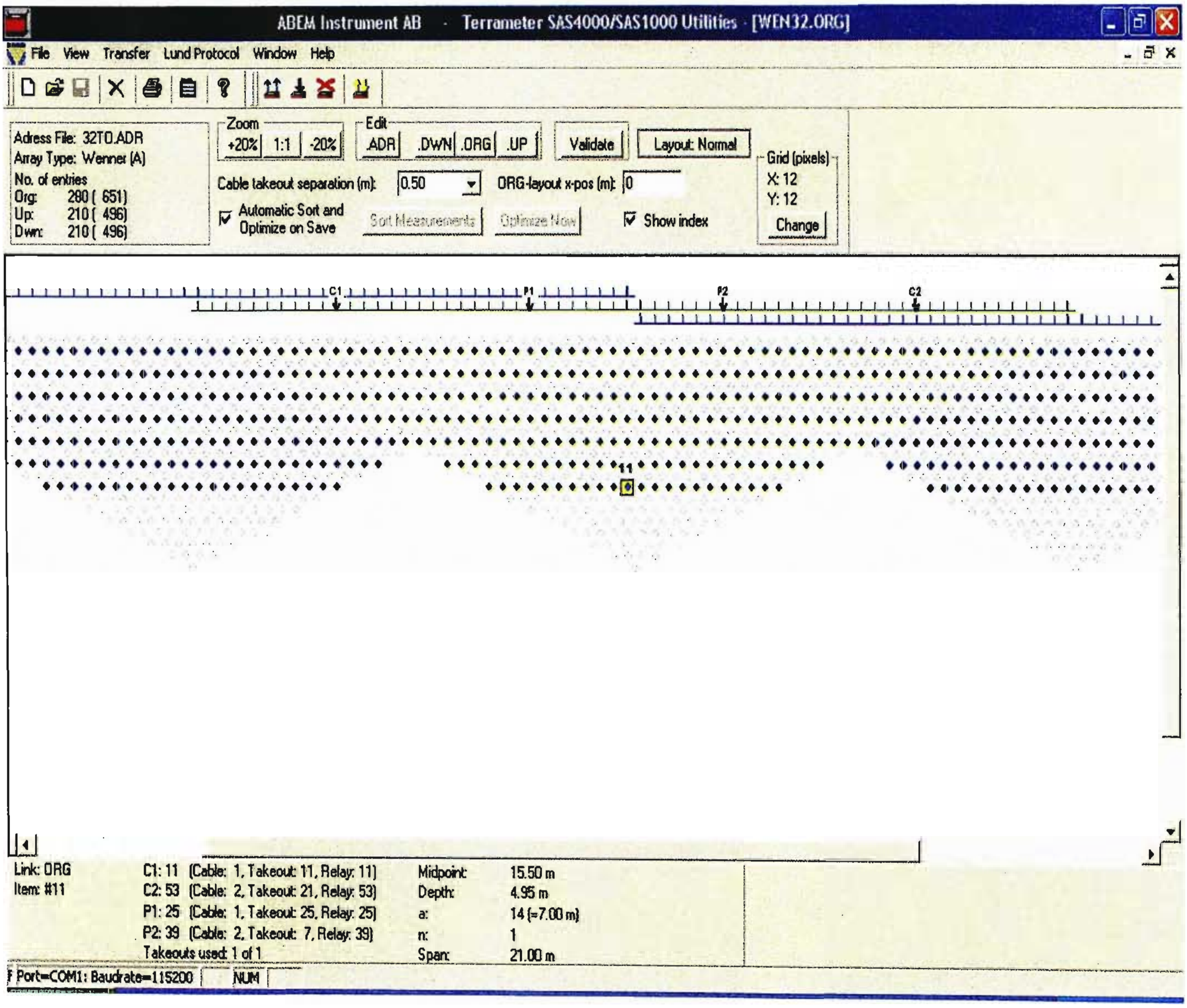
10. APPENDICIES

APPENDIX A

Different protocols used in KNP.



Adress File: 32TO.ADR
Array Type: Wenner (A)
No. of entries
Org: 280 (651)
Up: 210 (496)
Dwn: 210 (496)

Cable takeout separation (m): 0.50
ORG-layout x-pos (m): 0
☑ Automatic Sort and Optimize on Save
☑ Show index

Grid (pixels)
X: 12
Y: 12

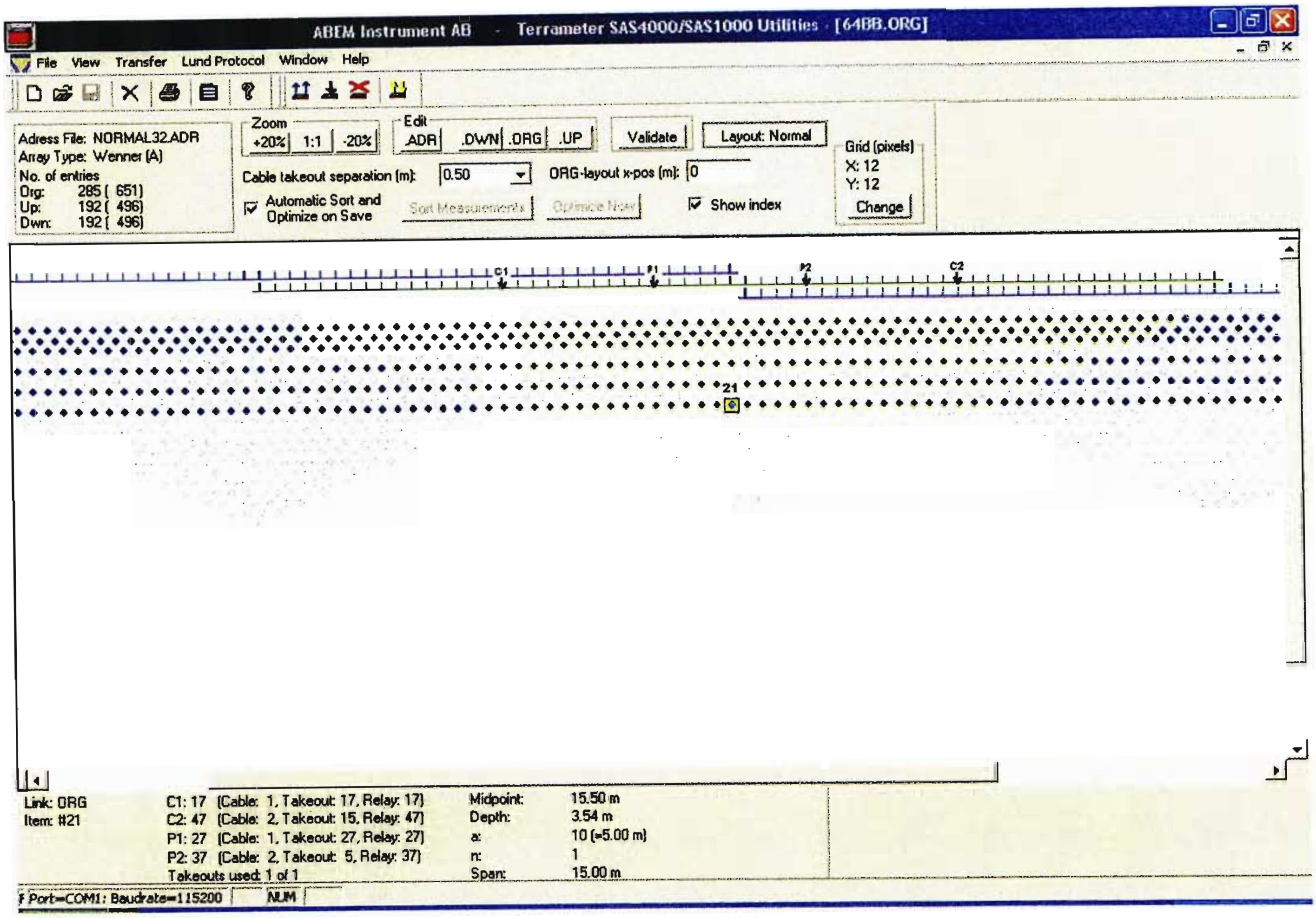
Link: ORG
Item: #11

C1: 11 (Cable: 1, Takeout: 11, Relay: 11)
C2: 53 (Cable: 2, Takeout: 21, Relay: 53)
P1: 25 (Cable: 1, Takeout: 25, Relay: 25)
P2: 39 (Cable: 2, Takeout: 7, Relay: 39)
Takeouts used: 1 of 1

Midpoint: 15.50 m
Depth: 4.95 m
a: 14 (=7.00 m)
n: 1
Span: 21.00 m

Port=COM1: Baudrate=115200

Original Wenner protocol used for the surveys in the KNP. Notice there are 280 data points and but less detail near the top of the profile.



Adress File: NORMAL32.ADR
Array Type: Wenner (A)
No. of entries
Org: 285 (651)
Up: 192 (496)
Dwn: 192 (496)

Cable takeout separation (m): 0.50
ORG-layout x-pos (m): 0
☑ Automatic Sort and Optimize on Save
☑ Show index
Grid (pixels)
X: 12
Y: 12

Link: ORG
Item: #21
C1: 17 (Cable: 1, Takeout: 17, Relay: 17)
C2: 47 (Cable: 2, Takeout: 15, Relay: 47)
P1: 27 (Cable: 1, Takeout: 27, Relay: 27)
P2: 37 (Cable: 2, Takeout: 5, Relay: 37)
Takeouts used: 1 of 1
Midpoint: 15.50 m
Depth: 3.54 m
a: 10 (=5.00 m)
n: 1
Span: 15.00 m
Port=COM1: Baudrate=115200 NUM

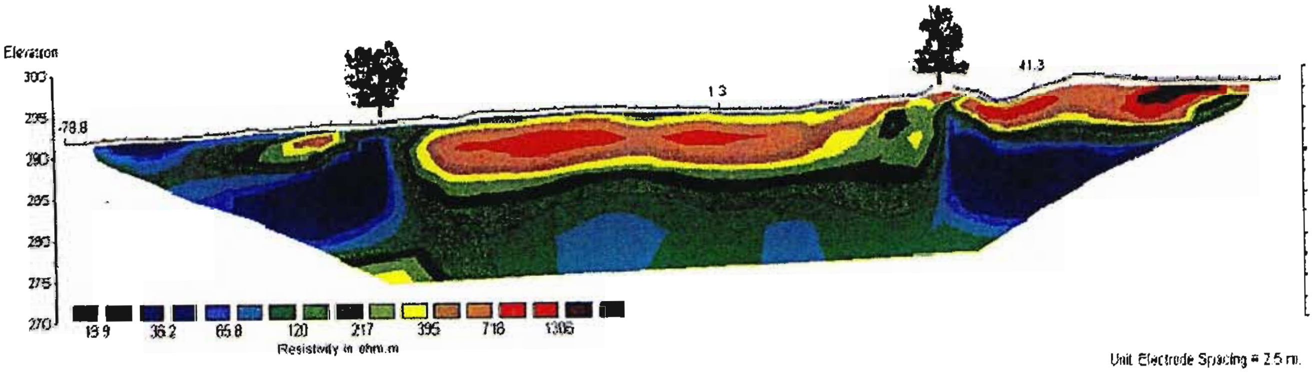
Modified Wenner protocol used for the surveys after instrument failure. Notice there are 285 data points with more detail near the top of the profile. The depth has also been reduced.

Editing and altering the standard protocols (Wenner, pole-pole, Schlumberger) to suit the user's requirements and preferences is termed writing of a protocol. There are numerous ways of doing this; however the approach used in the KNP study was the de-selection of possible data points or whole data rows. This is done selecting the Lund Protocol option once a standard protocol has been selected in the SAS4000 Utilities package, and then selecting the edit protocol option. At this stage of the editing process rows or points can be added or removed to the requirements of the user. The user needs to save any changes to ensure the protocol can be used. Protocol writing is a trial-and-error procedure and should be done before pursuing large projects to get an understanding of how the data capturing and modelling processes work in the ERT package.

APPENDIX B

Alternative uses of ERT instrumentation.

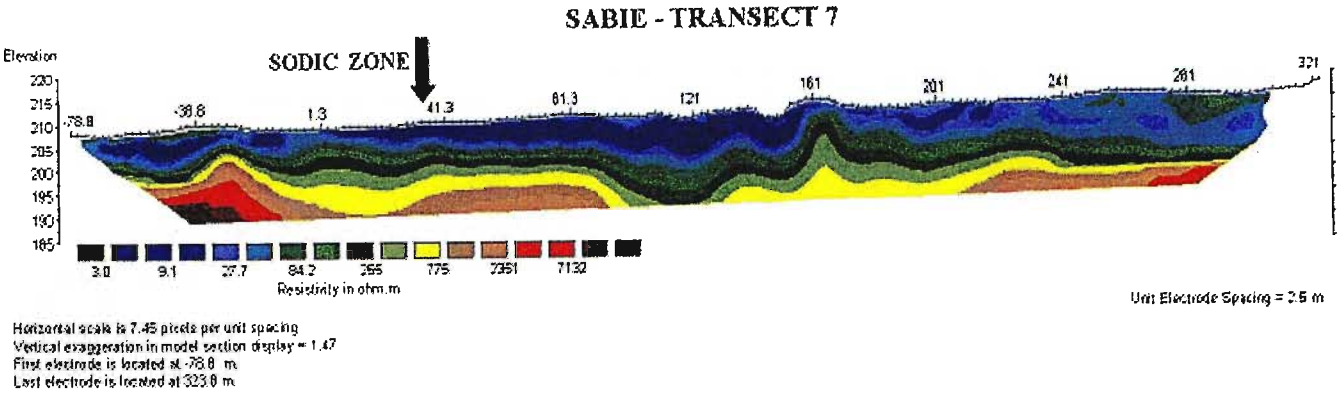
A strong point in using the ERT instrument is that it could be used as a quick simple once-off method of identifying areas for further study or areas of interest. An example of this is a study that has asked numerous questions of scientists in the KNP for many years now. In the northern part of the KNP along the Pungwane River, there are definite terraces on the riverbanks. This is a classic example where ERT could aid in the understanding of ecohydrology as a science. On the ridges of the terraces, there are long lines of large trees that run on top of the terrace crests. Scientists are continually questioning what and why there are definite lines of trees on the crests? Many different theories have been suggested, mostly regarding animal-plant interactions and competition, fires and soil water availability.



ERT survey of terraces along Pungwane River. Note the dolerite intrusion and the two aquifers on either side that the trees are sourcing water from. A quick survey was conducted perpendicular to the terraces and interestingly it is the geology that determines the distribution of the trees. There is a definite geological intrusion into the parent material and the trees are not able to extract water from the intrusive dyke. On both side of the dyke are accumulations of water; presumably aquifers and the trees are tapping into this source of water. The dyke runs parallel to the Pungwane River, hence the terraces and distribution of large trees. This is an example that has answered a question that has been studied and asked for some time by many institutions. A quick survey provided enough valuable insight to conclude the study. If any test boreholes were required the exact position could have been identified, thus saving drilling costs considerably. Once again there is a definitive link to ecohydrology and more importantly to the understanding of the soil water component of the hydrological cycle.

APPENDIX C

Roll along survey of transect 7, Nkuhlu Exclosures.



This is an example of a roll along survey of Transect 7 in the Nkuhlu exclosures. The survey was done in May 2005, with the help of Mr R Bester. The survey starts at point –78.8m at the Sabie River and stretches upslope to point 323.8m and consists of three roll along surveys. Topography has also been included in the survey. The bedrock is made up of granites and possibly gneiss with numerous deposits of alluvium, sand and scree. Many rounded boulders are present near and in the river. The darkish reds in the survey indicate bedrocks. The materials with the lower resistivity are the alluvial materials that were deposited in possible paleochannels near the present day river. The blueish colours do not necessarily indicate moisture but are probably moister than the surrounding materials and will probably contain a higher clay content than the surrounding materials, which could be attributed to the accumulation from fluvial actions or weathering of the granites (refer to the Sodic site). There is however a definite section at the top of the profile that indicates there is definite moisture in the profile and is possibly moving towards the river. The further you move away from the river the drier the profile gets, indicating the uniformity of the profile. There is a lot of metamorphics that has taken place in the area, hence the uneven bedrock, which would have encouraged the paleochannels formations. Around the 160m mark is an intrusion of the bedrock; this could be an intrusion such as a dyke or just an extremely resistant ledge in the bedrock and coincides with the rocky outcrops found near the Combretum site.

APPENDIX D

Topography data used in ERT studies.

Topography data can be included in the all pseudosections if the study area has been surveyed using a GPS instrument. It is advisable to GPS the survey as a habit whenever conducting resistivity surveys. The GPS data is imported into the "DAT" file (once converted to an "EXCEL" file) for the survey to reproduce pseudosections with topographic data. The "DAT" file is shown below and it is important to note the inclusion of the topographic data at the end of the file. The altered file is run through the modelling package and a pseudosection is produced with topographic data, making the survey more realistic.

```
Sabie4a.topo                               Name of file
  2.5                                      Electrode spacing
    1                                      Type of measurement 1= resistivity
  242                                      No. data points
    0                                      0= No. IP data
    0                                      0= No. Mid point
            -100    5        9.6893        First Electrode position; depth of reading; resistivity
             -95    5       30.8944        Electrode position; depth of reading; resistivity
       ......      ......  ......          ......
       ......      ......  ......          ......
       ......      ......  ......          ......
             -90    5       17.4481        Electrode position; depth of reading; resistivity
             -90   60      376.5826        Electrode position; depth of reading; resistivity
             -85   60      318.0204        Electrode position; depth of reading; resistivity
             -80   60      254.7876        Last Electrode position; depth of reading; resistivity
    2                                      2= If topography data present
   81                                      No. of topography points
 -100    205.172                           Horizontal and vertical co-ordinates of first point.
-97.5    205.359                           Horizontal and vertical co-ordinates of second point.
......   ......                            ......
......   ......                            ......
......   ......                            ......
 97.5    216.631                           .......
  100    216.538                           Horizontal and vertical co-ordinates of last point.
    0                                      Enter 4-5 0s at the end of the file
    0
    0
    0
    0
```

APPENDIX E

Soil Survey data for the Nkuhlu Exclosure

The soil surveys of the Nkuhlu Exclosures were conducted by Paterson and Steenekamp, in 2003

Map unit	Dominant soil form and series	Effective depth (mm)	Other soil forms and series	Soil characteristics
Gs	Glenrosa tsende (Gs 1211)	50-450	Mispah myhill (Ms1100) Cartref egolomi (Cf 1200)	Shallow; greyish-brown to yellowish-brown (occasionally pale grey), unstructured, gravelly loamy sand to sandy loam topsoil directly overlying weathering rock. Surface stone and rock outcrops occur in places in the map unit, especially in the watercourses.
Mu	Montagu esperanza (Mu 1120)	900-1200+	Valsrivier luckhoff (Va 1112) Augrabies giyani (Ag 1120)	Deep; greyish-brown, weakly structured, sandy loam topsoil on weakly (occasionally moderately) structured, calcareous, yellow-brown sandy clay loam subsoil, usually with signs of wetness (grey colours and mottling) deeper in the profile. Some loss of topsoil in places, especially close to the Sabie river in the north of the unit)
Oa	Oakleaf Ritchie (Oa 1110)	500-1500+	Oakleaf caledon (Oa 1220)	Mostly deep (shallower in south); greyish-brown, weakly structured, sand to sandy loam topsoil on brown to reddish-brown, weakly structured, sandy loam subsoil. Some rock outcrops occur in places, usually in the Sabie river bed (and on the river bank in the south of the unit).

APPENDIX F

Soil analyses results for the Nkuhlu Exclosure.

The soil surveys of the Nkuhlu Exclosures were conducted by Paterson and Steenekamp, in 2003

Full Exclosure							
Map Unit		**Mu**		**Oa**		**Gs**	
Depth (mm)		**0-400**	**400-900**	**0-350**	**350-900**	**0-250**	**250-700**
>2 mm		3.6	11.2	0.7	1.5	7.4	3.4
Sand	%	75.5	53.4	85.8	71.4	78.5	69.2
Silt		14.5	24.6	8.2	18.6	13.5	18.8
Clay		10	22	6	10	8	12
Na	C mol Kg^{-1}	0.62	24.77	0.43	0.46	0	0.93
K		0.8	0.22	1.33	0.13	0.66	1.83
Ca		4.33	7.26	2.57	5.96	2.64	7.25
Mg		1.25	4.26	1.15	2.8	0.64	2.18
CEC		6.37	12.55	5.12	9.07	4.98	11.71
pH (H$_2$O)		7.3	9	7.41	7.36	6.63	6.76
P (Bray 1)		1.65	10.53	1.15	3.41	6.97	2.02
BD		1.67	1.76	1.41	*-1.35*	*-1.35*	1.47
Total C	%	1.03	0.36	0.66	0.62	0.96	2.18
Total N		0.089	0.034	0.057	0.051	0.097	0.167
Total S		0.0772	0.1043	0.0743	0.1492	0.0839	0.2464

Notes:

CEC = Cation Exchange Capacity (LiCl method)

BD = Bulk density (measured in g cm$^{3\ -1}$); estimated bulk density values (see Section 3) in italics in brackets.

APPENDIX G

TDR data (VWC) from the three survey sites.

Riparian Lower

DATE	WC1	WC2	WC3	WC4
5	0.201	0.253	0.113	0.157
6	0.203	0.26	0.111	0.151
7	0.206	0.254	0.262	0.288
8	0.205	0.247	0.251	0.257
9	0.203	0.25	0.239	0.248
10	0.209	0.247	0.25	0.253
11				
12				
13	0.219	0.299	0.25	0.252
14	0.212	0.322	0.242	0.239
15	0.204	0.325	0.234	0.227
16	0.217	0.324	0.226	0.219
17	0.201	0.318	0.216	0.213
18	0.206	0.328	0.212	0.209
19	0.207	0.329	0.204	0.202
20	0.216	0.323	0.199	0.198
21	0.203	0.319	0.195	0.193
22	0.199	0.32	0.19	0.186

Combretum

DATE	WC1	WC2	WC3
5	0.043	0.028	0.002
6	0.043	0.029	0.001
7	0.135	0.028	0.002
8	0.135	0.03	0.003
9			
10	0.149	0.031	0.005
11			
12			
13	0.152	0.109	0.008
14	0.143	0.104	0.008
15	0.135	0.104	0.008
16	0.128	0.103	0.01
17	0.118	0.095	0.01
18	0.105	0.096	0.011
19	0.09	0.088	0.01
20	0.078	0.075	0.009
21	0.074	0.066	0.01
22	0.065	0.057	0.008

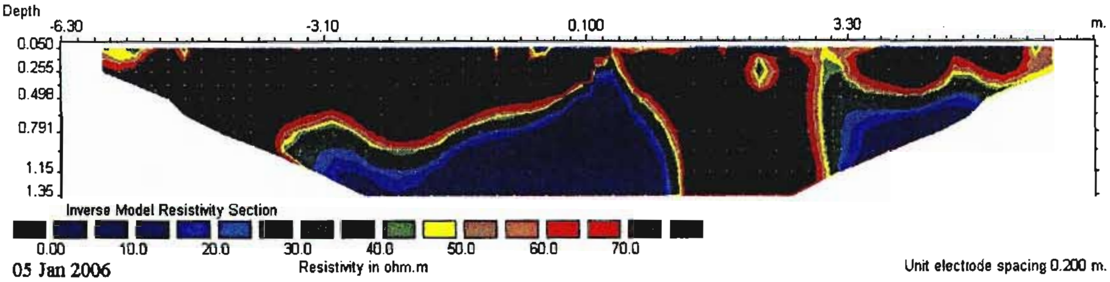
Sodic

DATE	WC1	WC2	WC3	WC4
5	0.249	0.263	0.26	0.19
6	0.251	0.267	0.258	0.186
7	0.249	0.286	0.325	0.382
8	0.264	0.335	0.339	0.38
9				
10	0.282	0.359	0.416	0.369
11				
12				
13	0.314	0.379	0.4	0.375
14	0.326	0.38	0.402	0.385
15	0.327	0.386	0.384	0.352
16	0.333	0.39	0.374	0.335
17	0.322	0.391	0.369	0.324
18	0.331	0.401	0.386	0.31
19	0.337	0.384	0.391	0.31
20	0.339	0.382	0.382	0.293
21	0.343	0.389	0.368	0.278
22	0.327	0.373	0.359	0.271

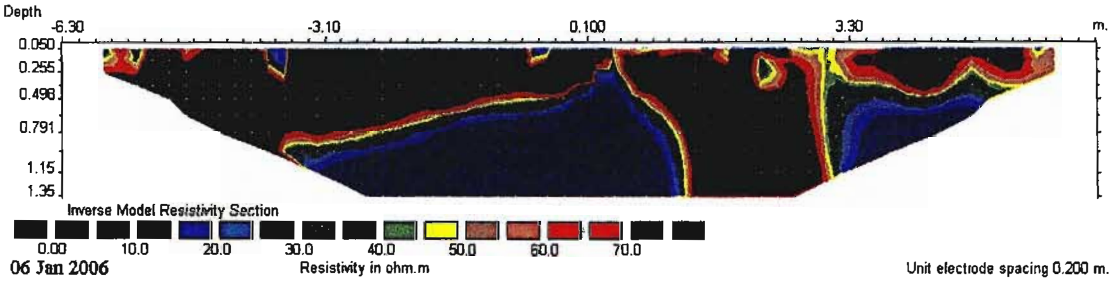
APPENDIX H

Riparian Lower site ERT data (Full set).

Riparian Lower (05 - 06 Jan 2006)

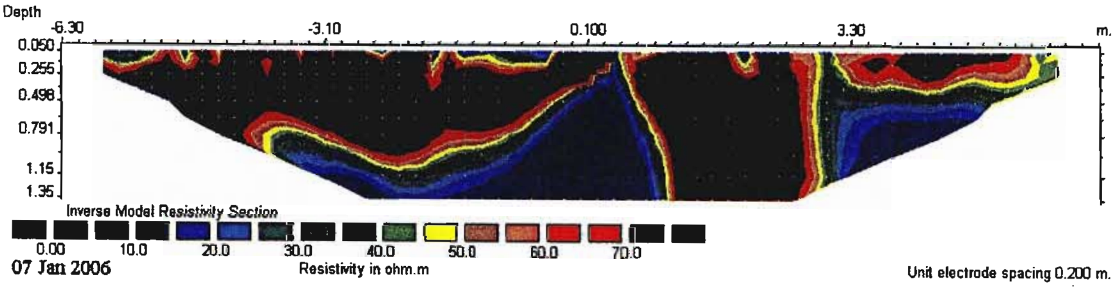


05 Jan 2006

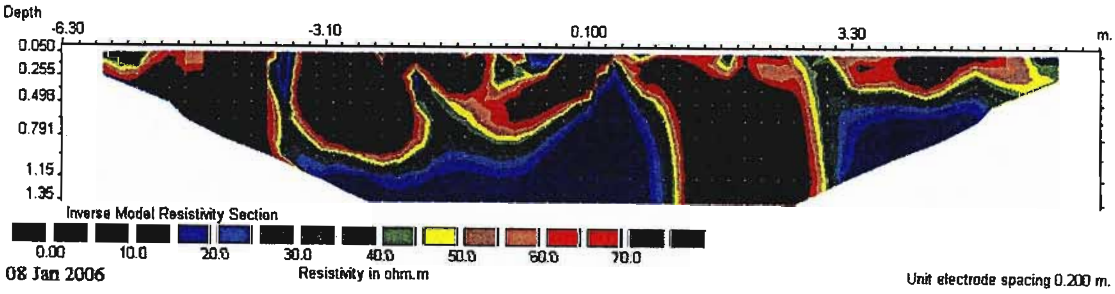


06 Jan 2006

Riparian Lower (07 - 08 Jan 2006)

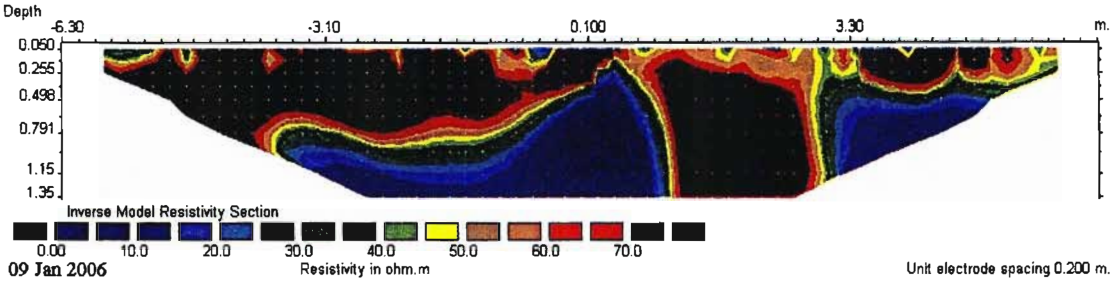


07 Jan 2006

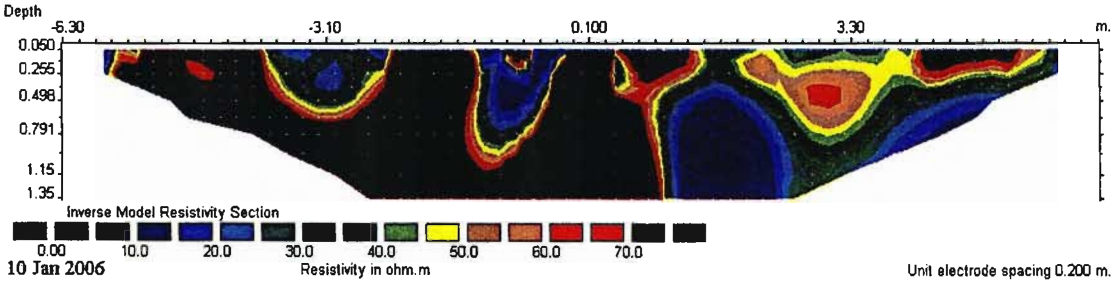


08 Jan 2006

Riparian Lower (09 - 10 Jan 2006)

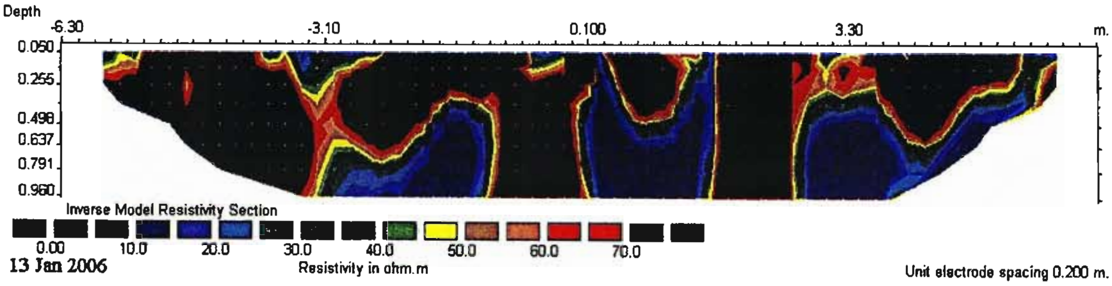


09 Jan 2006

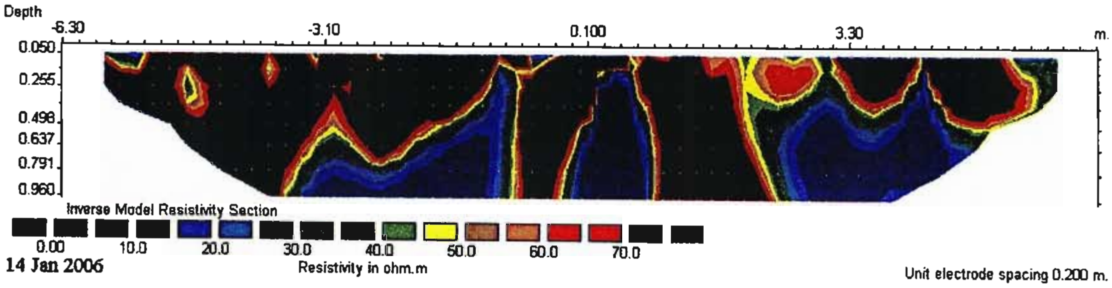


10 Jan 2006

Riparian Lower (13 -14 Jan 2006)

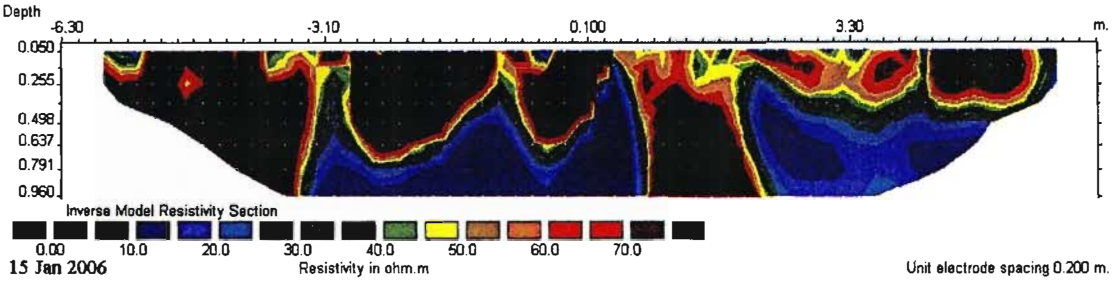


13 Jan 2006

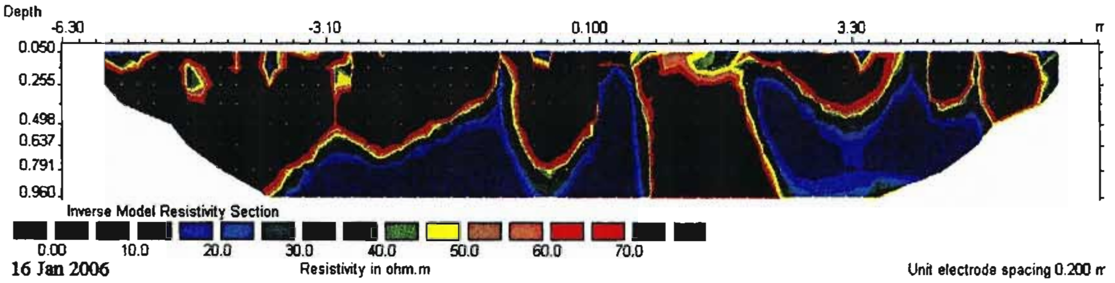


14 Jan 2006

Riparian Lower (15 -16 Jan 2006)

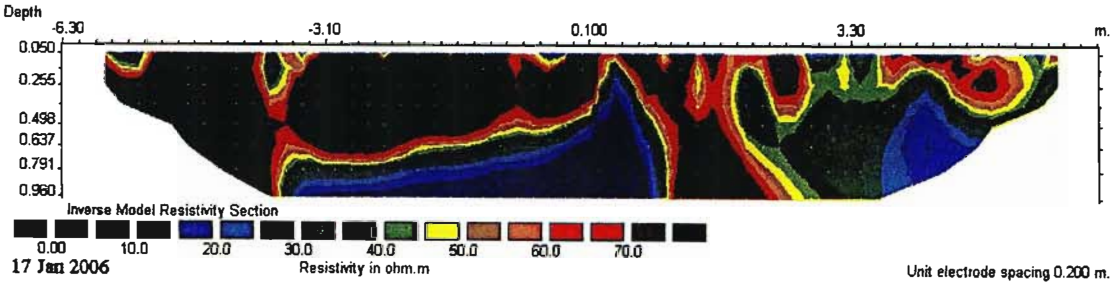


15 Jan 2006

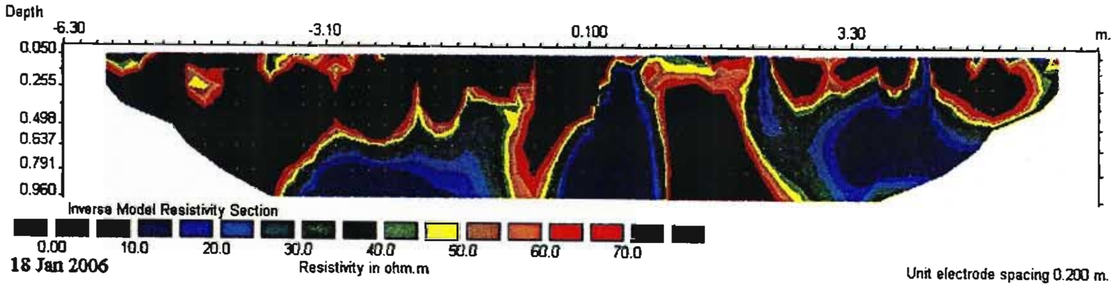


16 Jan 2006

Riparian Lower (17 - 18 Jan 2006)

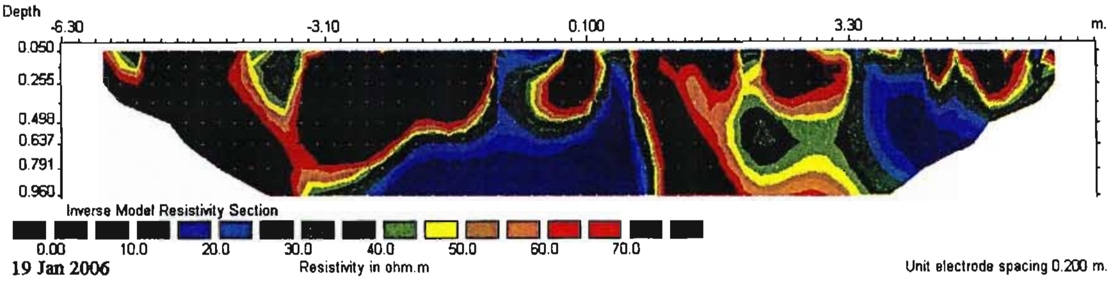


17 Jan 2006

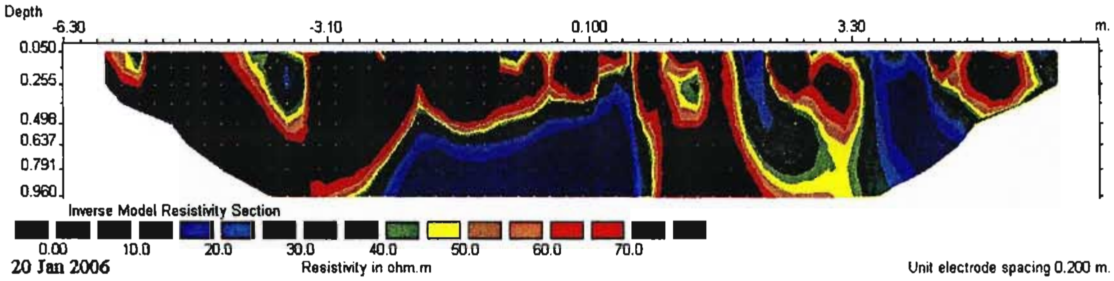


18 Jan 2006

Riparian Lower (19 - 20 Jan 2006)

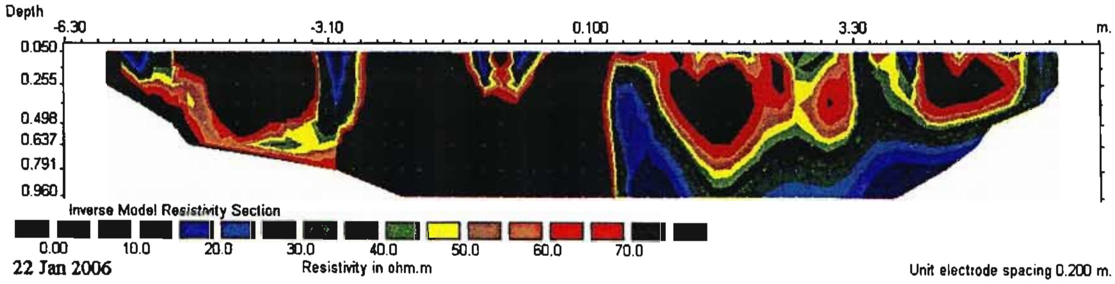


19 Jan 2006



20 Jan 2006

Riparian Lower (22 Jan 2006)

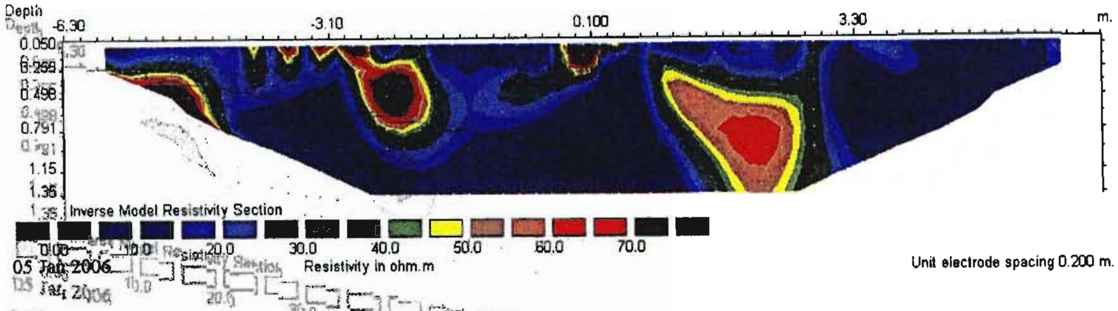


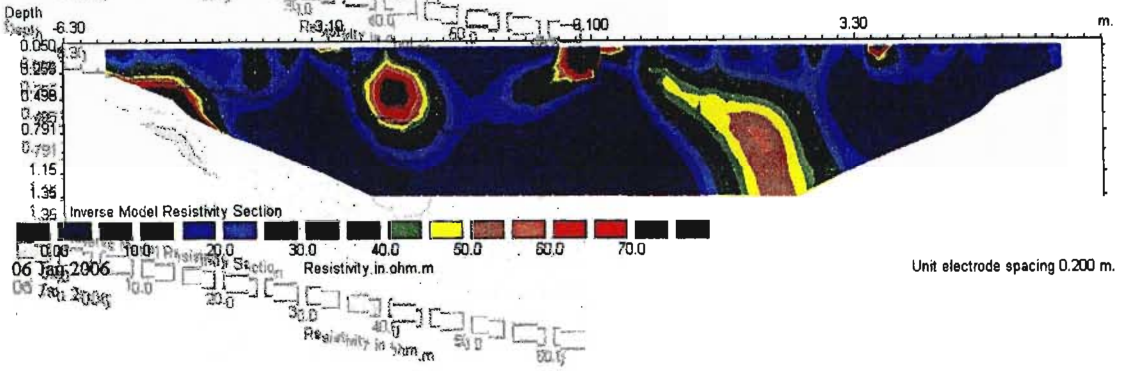
22 Jan 2006

APPENDIX I

Sodic site ERT data (Full set).

Sodic (05 - 06 Jan 2006)





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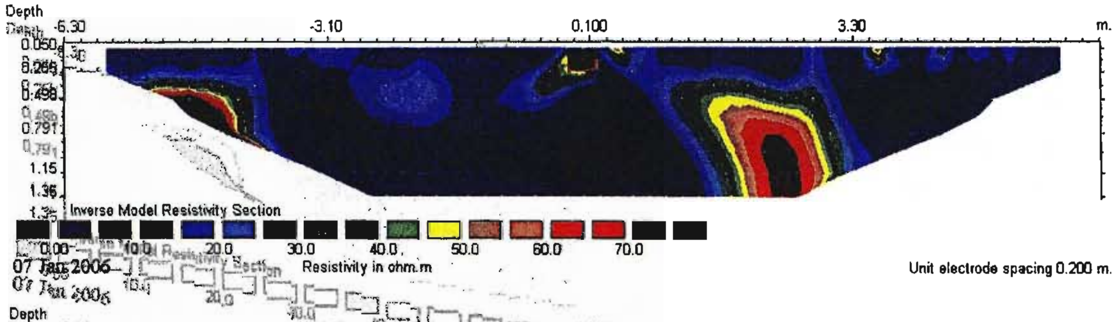

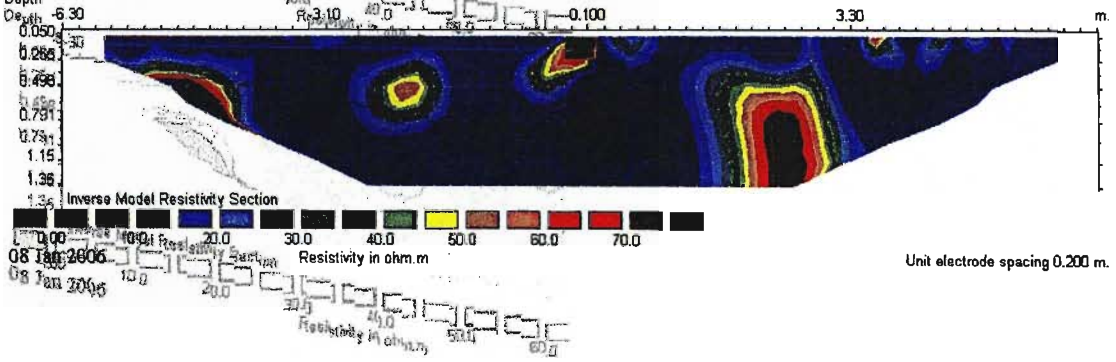

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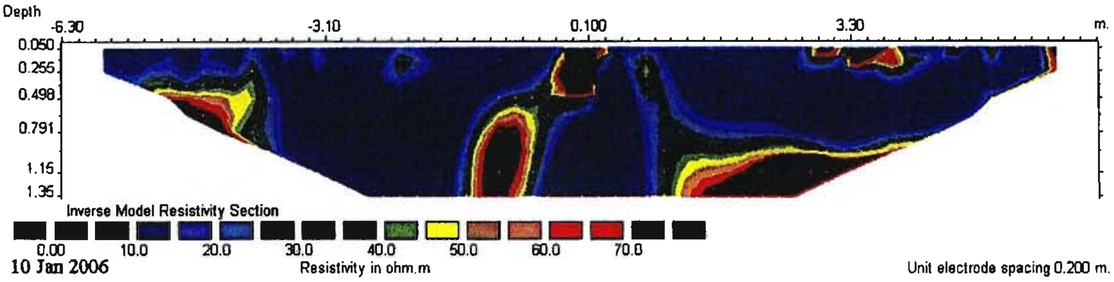

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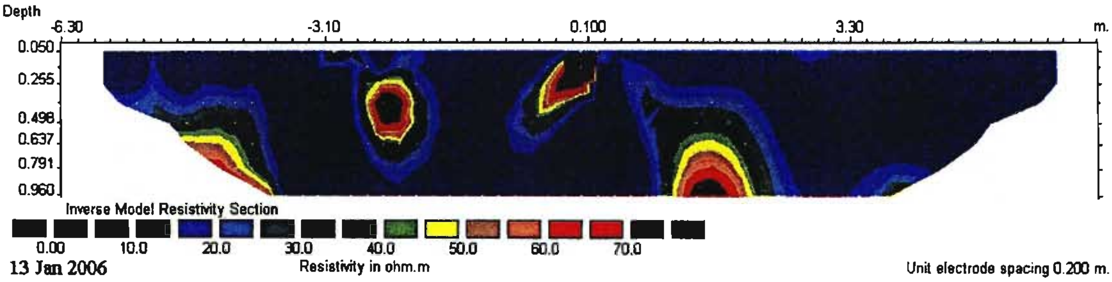

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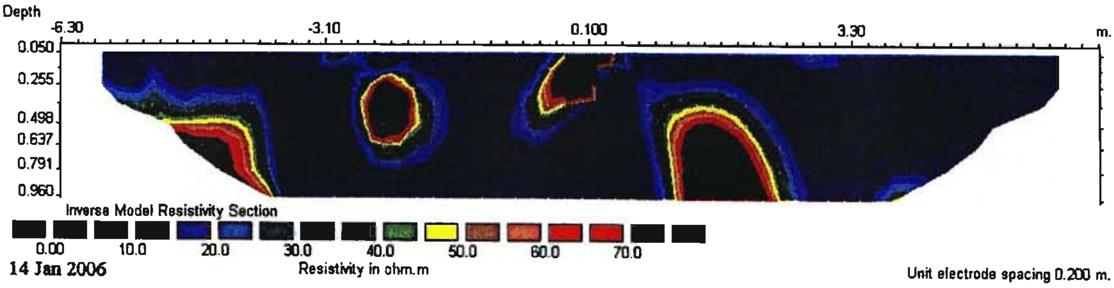

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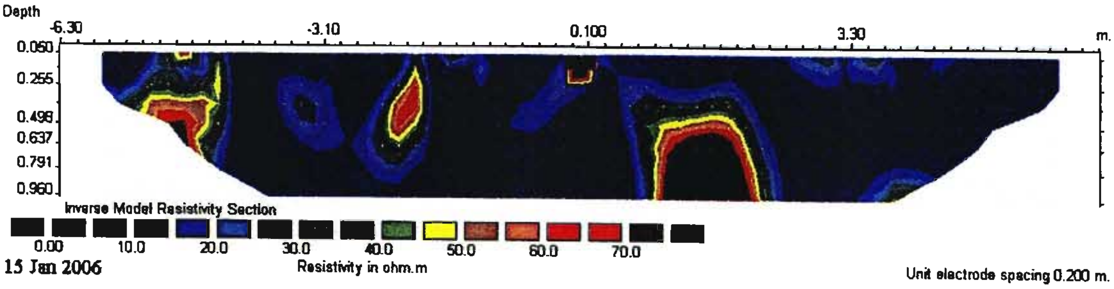

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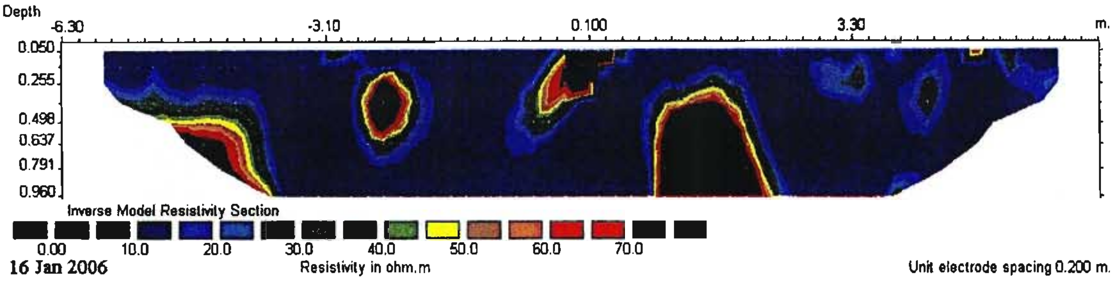

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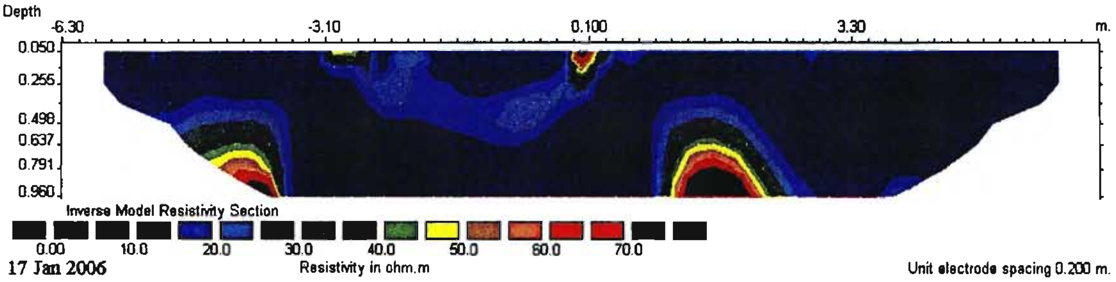

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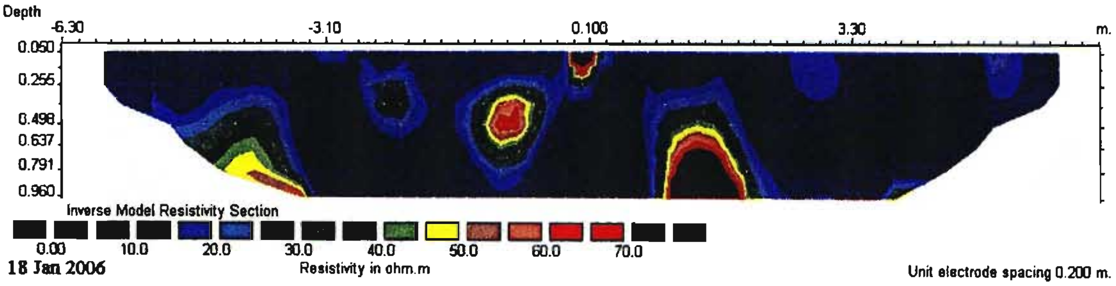

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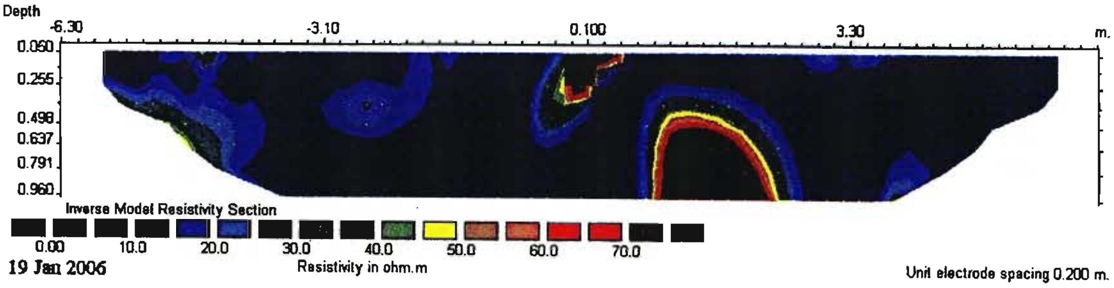

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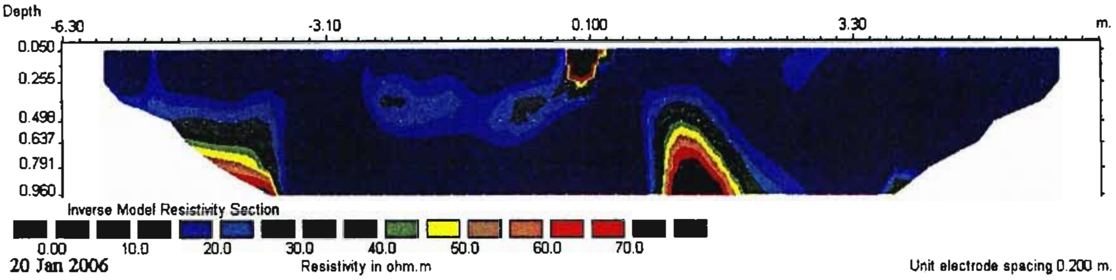

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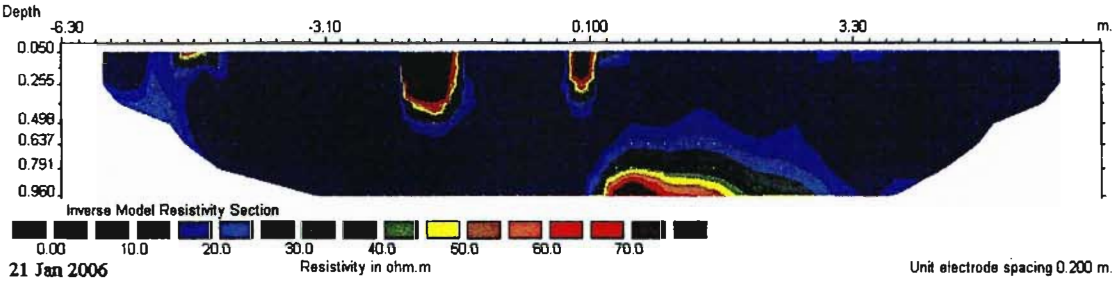

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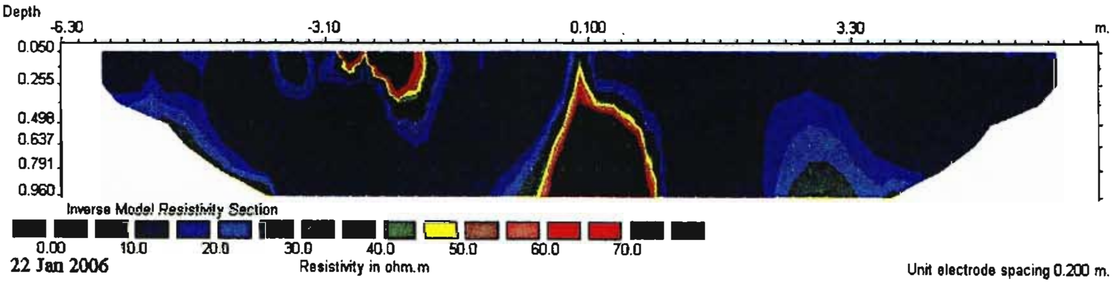

22 Jan 2006

APPENDIX J

Combretum site ERT data (Full set).

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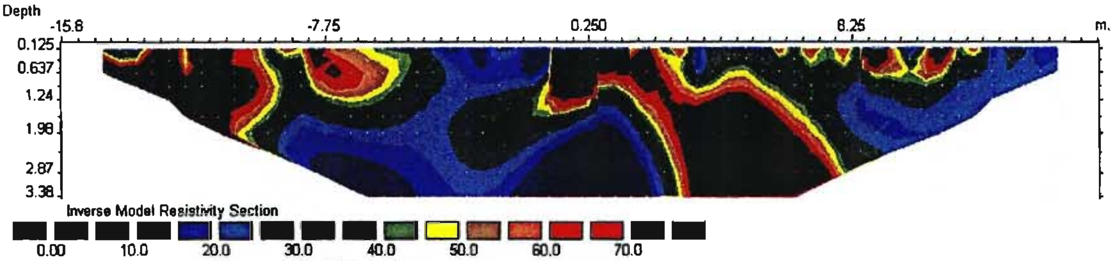

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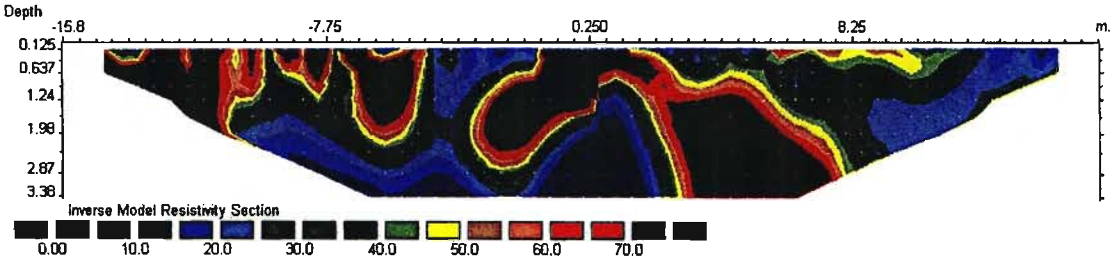

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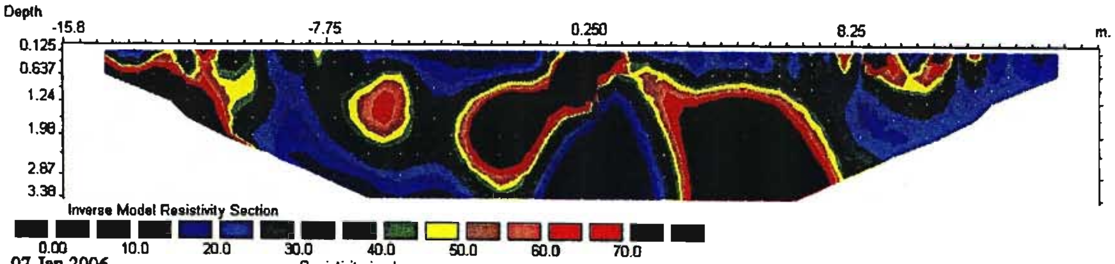

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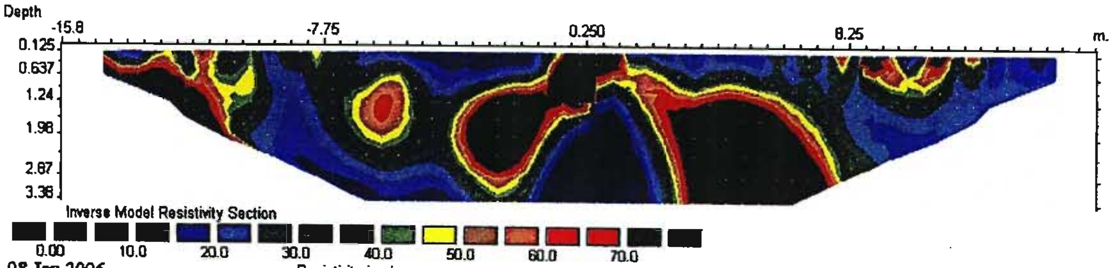

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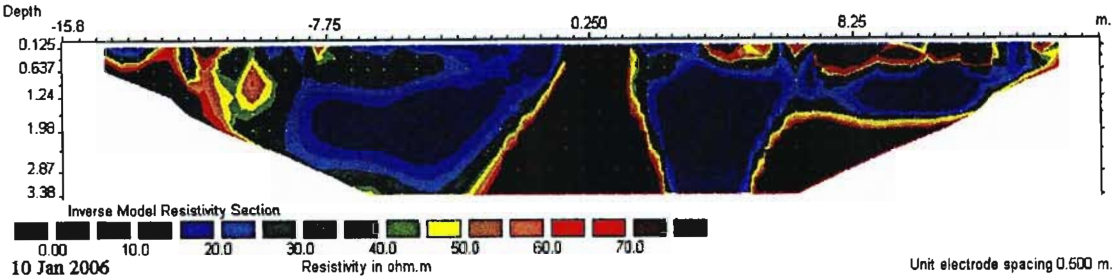

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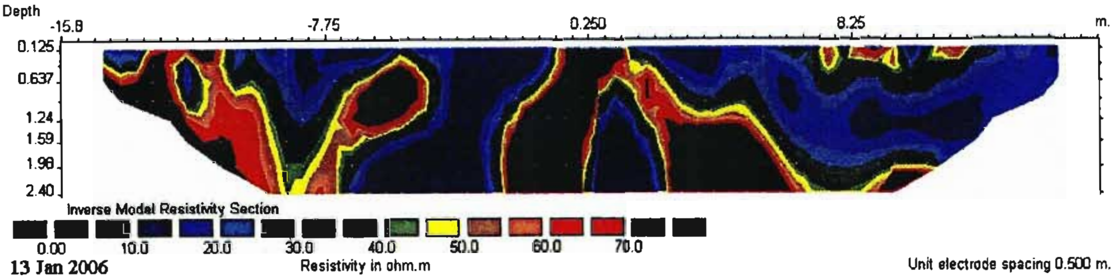

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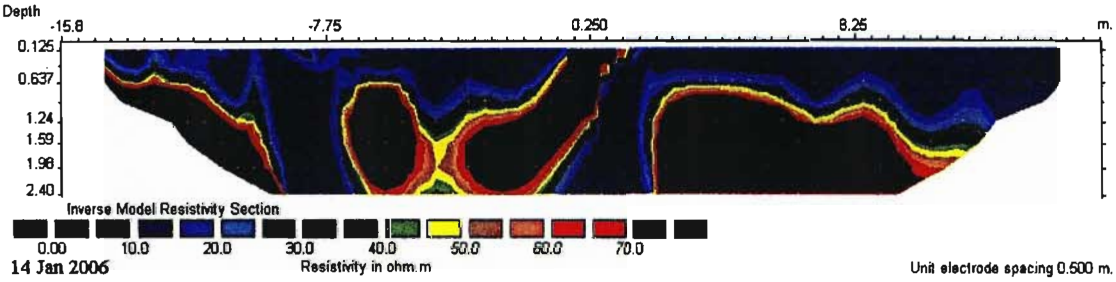

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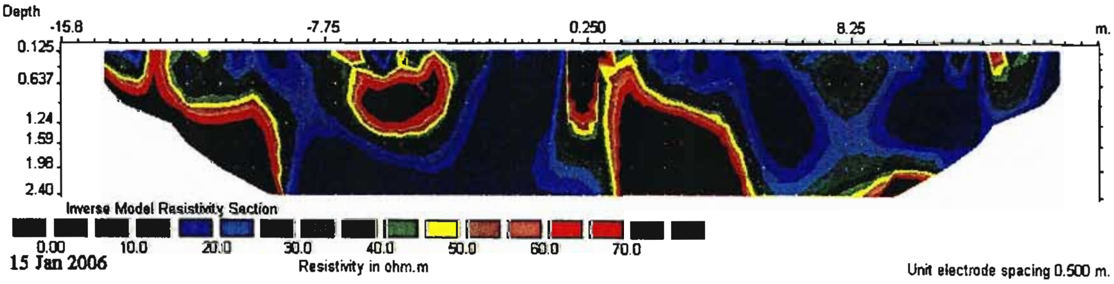

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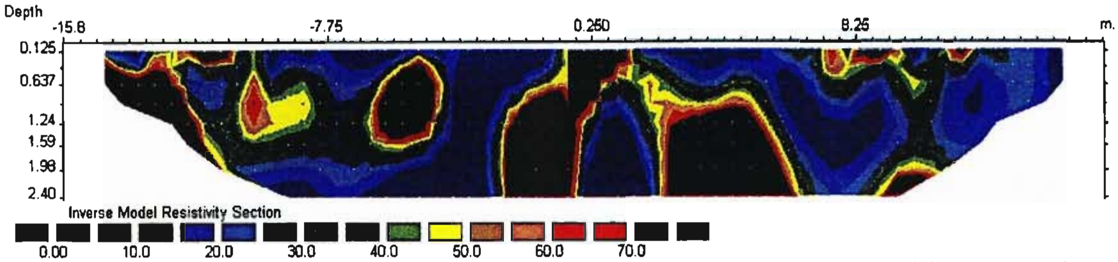

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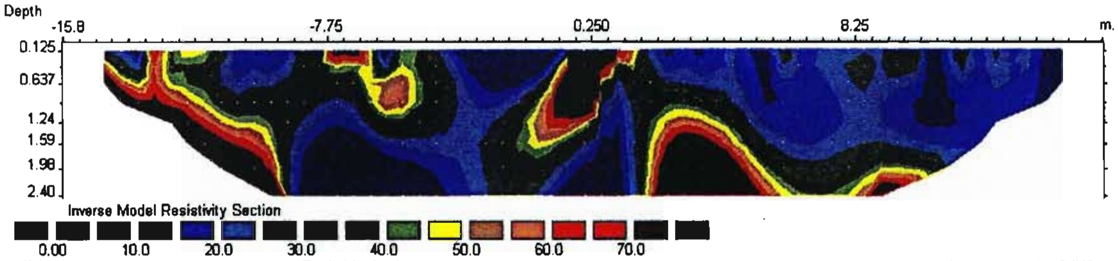

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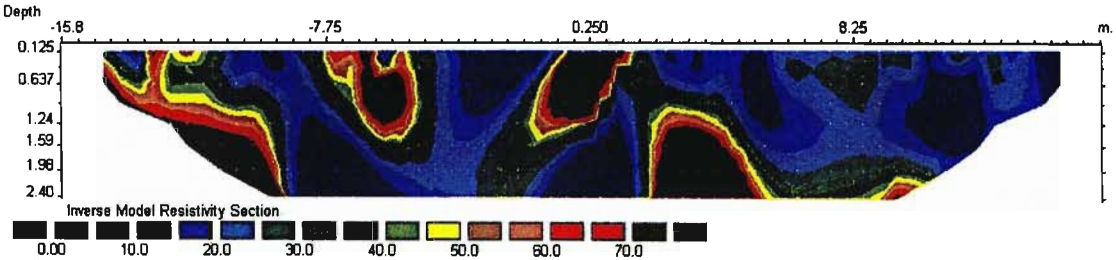

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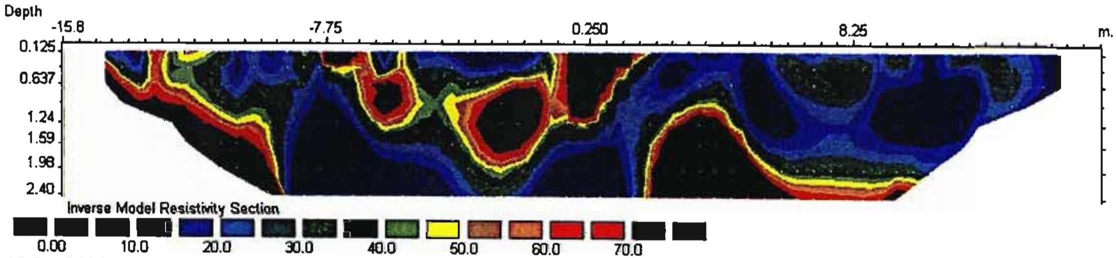

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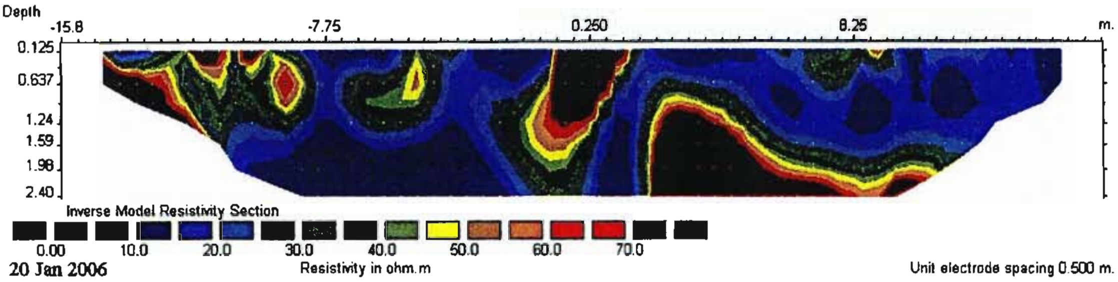

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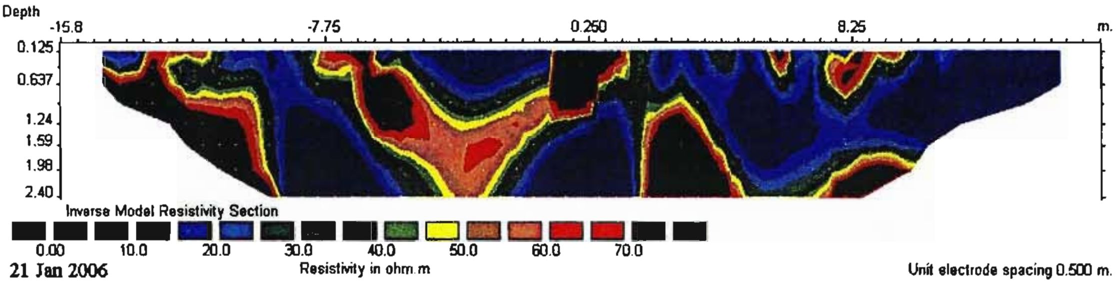

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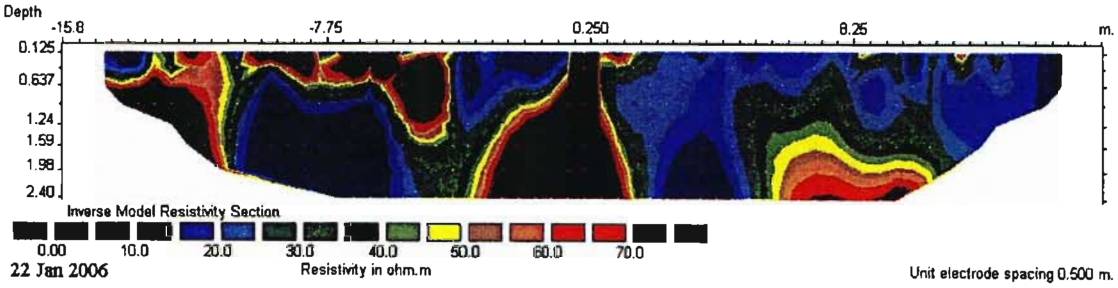

22 Jan 2006

APPENDIX K

OPERATION MANUAL
FOR THE ELECTRICAL RESISTIVITY TOMOGRAPHY METER.
ABEM TERRAMETER SYSTEM.

FIELDWORK AND MODELLING COMPONENTS INCLUDED.

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University of KwaZulu-Natal
Pietermaritzburg
2005

TABLE OF CONTENTS

1. INTRODUCTION

The purpose of electrical resistivity is to determine the subsurface resistivity distribution by making measurements on the ground surface. From these measurements, the true resistivity of the subsurface can be estimated. The ground resistivity is related to various geological parameters such as the minerals and fluid content, porosity, degree of water saturation in the rock and dissolved ions in the water. Resistivity investigations can thus be used to identify zones with different electrical properties, which can thus be referred to different geologic strata (Abem, 2005).

We have seen the greatest limitation of the resistivity sounding method is that it does not take into account horizontal changes in the subsurface resistivity. A more accurate model of the subsurface is a two-dimensional (2-D) model where the resistivity changes in the vertical direction, as well as in the horizontal direction along the survey line. In this case, it is assumed that resistivity does not change in the direction that is perpendicular to the survey line. In many situations, particularly for surveys over elongated geological bodies, this is a reasonable assumption. In many geological situations, 2-D electrical imaging surveys can give useful results that are complementary to the information obtained by other geophysical method. For example, seismic methods can map undulating interfaces well, but will have difficulty (without using advanced data processing techniques) in mapping discrete bodies such as boulders, cavities and pollution plumes. Ground radar surveys can provide more detailed pictures but have very limited depth penetration in areas with conductive unconsolidated sediments, such as clayey soils. Two-dimensional electrical surveys should be used in conjunction with seismic or ground radar surveys as they provide complementary information about the subsurface.

1.1 The basics of resistivity

Electrical resistivity surveys have been used for many decades in hydro-geological, mining and geotechnical investigations. More recently, it has been used for environmental surveys. The resistivity measurements are normally conducted by injecting current into the ground through two current electrodes (C in Figure 1.1), and measuring the resulting voltage difference at two potential electrodes (P). From the current (I) and voltage (V) values, an apparent resistivity (p_a) value is calculated.

$$p_a = \mathrm{k\,V / I} \qquad \text{Equation ...1.1}$$

Where k is the geometric factor, which depends on the arrangement of the four electrodes.

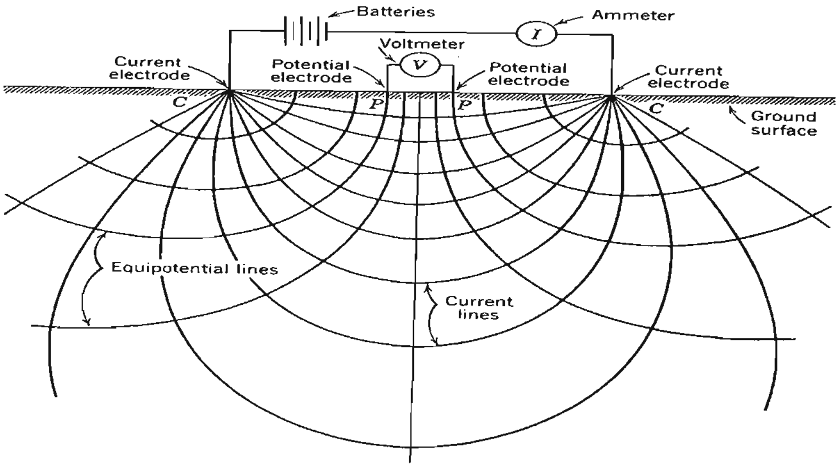

Figure 1.1. Basic electrical circuit for resistivity determination and field for homogeneous subsurface stratum (after Todd, 1980).

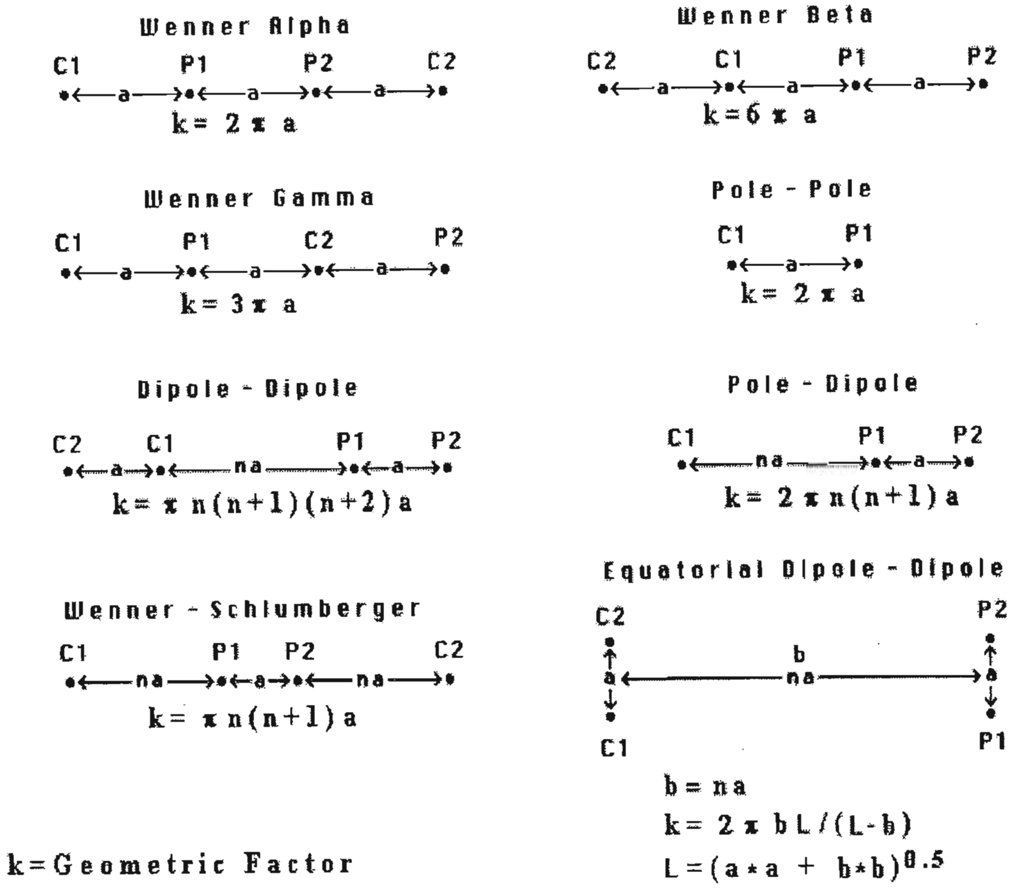

Figure 1.2. Common arrays used in resistivity surveys and their geometric factors (after Loke, 1999)

Figure 1.2 shows the common arrays used in resistivity surveys together with their geometric factors. Resistivity meters normally give a resistance value, R = V/I, so in practice the apparent resistivity value is calculated by

$$p_a = \mathrm{k\,R} \qquad \text{Equation ....1.2}$$

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

1.2 The relationship between geology and resistivity

Before dealing with the 2-D and 3-D resistivity surveys, we will briefly look at the resistivity values of some common rocks, soils and other materials. Resistivity surveys give a picture of the subsurface resistivity distribution. To convert the resistivity picture into a geological picture, some knowledge of typical resistivity values for different types of subsurface materials and the geology of the area surveyed, is important. The resistivity of these rocks is normally a function of the amount and quality of water in pore spaces and fractures. The degree of connection between the cavities is also important. Consequently, the resistivity of a type of rock or soil may vary widely. (Abem, 2005). The amount of water in a material depends on the porosity, which may be divided into primary and secondary porosity. Primary porosity consists of pore spaces between the mineral particles, and occurs in soils and sedimentary rocks. Secondary porosity consists of fractures and weathered zones, and this is the most important porosity in crystalline rock such as granite and gneiss. Secondary porosity may also be important in sedimentary rocks, such as limestone. Even if porosity is low, the electrical conduction taking place through water filled pore spaces may reduce the resistivity of the material dramatically. The degree of water saturation will of course affect the resistivity, and the resistivity above the groundwater will be higher than below if the material is the same. Refer to Table 1.1 for the electrical resistivity ranges in natural waters. However, if the content of fine-grained material is significant, the water content above the groundwater surface, held by capillary forces, may be large enough to dominate the electrical behaviour of the material. The resistivity of the pore water is determined by the concentration of ions in solution, the type of ions and the temperature.

The resistivity of ground water varies from 10 to 100 ohm•m. depending on the concentration of dissolved salts. Note the low resistivity (approx. 0.2 ohm•m) of seawater in Table 1.1 due to the relatively high salt content. This makes the resistivity method an ideal technique for mapping the saline and fresh water interface in coastal areas.

Type of Water	**Resistivity / [Ω m]**
Precipitation	30-1000
Surface water, in areas of igneous rock	30-500
Surface water, in areas of sedimentary rock	10-100
Groundwater, in areas of igneous rock	30-150
Groundwater, in areas of sedimentary rock	>1
Sea water	approx. 0.2
Drinking water (max. salt content 0.25%)	>1.8
Water for irrigation and stock watering (max. salt content 0.25%)	>0.65

Table 1.1. Electric resistivity of some types of natural waters (after Kollert, 1969).

However, the variations may be limited within a confined geological area, and variations in resistivity within a certain soil or rock type will reflect variations in physical properties. Fresh crystalline rock is highly resistive, apart from certain ore minerals, but weathering commonly produces highly conductive clay-rich saprolite. Refer to Table 1.2 for the common resistivity values of igneous and metamorphic rocks. Igneous and metamorphic rocks typically have high resistivity values while sedimentary rocks, which usually are more porous and have higher water content, normally have lower resistivity values. Wet soils and fresh ground water have even lower resistivity values. Clayey soil normally has a lower resistivity value than sandy soil. The presence of clay minerals strongly affects the resistivity of sediments and weathered rock (Dahlin and Loke 1998). The clay minerals may be regarded as electrically conductive particles, which can absorb and release ions and water molecules on its surface through an ion exchange process. As the variation in temperature of the ground is generally very small, the temperature influence is normally negligible.

Common Rocks/Materials	**Resistivity (ohm meters)**	**Ore Minerals**	**Resistivity (ohm meters)**
Clay	1 – 100	Pyrrhotite	0.001 – 0.01
Graphitic Schist	10 – 500	Galena	0.001 – 100
Topsoil	50 – 100	Cassiterite	0.001 – 10,000
Gravel	100 – 600	Chalcopyrite	0.005 – 0.1
Weathered Bedrock	100 – 1000	Pyrite	0.01 – 100
Gabbro	100 – 500,000	Magnetite	0.01 – 1,000
Sandstone	200 – 8,000	Hematite	0.01 – 1,000,000
Granite	200 – 100,000	Sphalerite	1000 – 1,000,000
Basalt	200 – 100,000		
Limestone	500 – 10,000		
Slate	500 – 500,000		
Quartzite	500 – 800,000		
Greenstone	500 – 200,000		

Table 1.2. Resistivities of common rocks/materials and selected ore minerals (Delta Mine Training Centre, 2005).

Note the overlap in the resistivity values of the different classes of rocks. This is because the resistivity of a particular rock or soil sample depends on a number of factors mentioned above such as the porosity, the degree of water saturation and the concentration of dissolved salts.

Metals, such as iron, have extremely low resistivity values. Resistivity values have a much larger range compared to other physical quantities mapped by other geophysical methods. The resistivity of rocks and soils in a survey area can vary by several orders of magnitude. In comparison, density values used by gravity surveys usually change by less than a factor of 2, and seismic velocities usually do not change by more than a factor of 10. This makes the resistivity and other electrical or electromagnetic based methods very versatile geophysical techniques.

2. FIELD WORK COMPONENT

This part of the manual purely refers to the field work component of the survey. Note various instruments may have different setup options and user preferences may vary. This is a basic guideline that is advisable to follow for efficient and accurate results. Users are encouraged to refer to the ABEM manual provided, which is housed in the orange box, for additional assistance with the fieldwork component.

2.1 Cable setup

- Depending on the electrode spacing: lay out the green rope on the survey line to determine the 2.5m spacing of electrodes. The rope is marked with the centre point of the survey and the joins of the cables. If 5m spacing is required, use electrode spacing on the cables.
- Un-roll the cables starting at the bottom of the survey, this is point 1 on the first cable. Each cable (4) comprises 21 electrodes.
- TOTAL ELECTRODES = 81
- Pull cables out from the reels with care; pull between electrode spacings and end plugs to minimize cable damage.
- The basic layout of the cable is to have two cables on either side of the instrument but the electrode numbers must follow in sequence (1-21, followed by 1-21 of the second cable, as so on).
- There are two white adapters that are extremely easy to loose and are vital for the survey. These adapters are to connect the first 2 cables and the last 2 at the 21-1 electrodes respectively. There is a notch in the adapters at one the end; the side with the notch must always be closest to the instrument. NB!!!!!
- Clip the caps into each other to prevent dirt entering the plugs. Keep plugs dry and free of dirt at all times.
- Electrodes 21 and 1 share the same electrode so there is an overlap at the joins. This is why there are not 84 electrodes and only 81.

- The instrument will act as the adapter between cable 2 and cable 3, but point 21 on cable 2 and point 1 on cable 3 will share the electrode.
- Hammer in electrodes to at least a depth of 250mm. (10mm diameter, 500mm, 81 long stainless steel electrodes)
- Connect terminal wires to electrodes with the crocodile clamps. Ensure good contact between electrodes and cable. Be careful not to loose any terminal wires. **Remember** 3 electrodes will have 2 terminal clamps attached to them because of the overlap of the electrodes.
- Pour water (100mm) round all electrodes to ensure better conductivity.
- Connect Terrameter to Electrode Selector Unit, ensure cable is well connected.
- Connecting cable is attached to the Terrameter plug on the Electrode selector unit.
- Connect electrode cables to Electrode Selector unit, ensure cables are well connected and cable sequence is in correct order. **NB**: The first two cables are connected to conn 1 and cable 3 and 4 are connected to conn 2.
- Connect unit to external power source (12 volt battery).
- Ensure you have a spare battery for the surveys.

2.2 Control unit setup

- Turn Control Unit on. Push two black powers buttons simultaneously as indicated on the panel.
- To change resolution on the LCD (display), push two vertical black buttons simultaneously either left or right.
- "SAS 1000 Application" Screen
    - Select : LUND Imaging System (for 2D surveys)
    - Use black button, vertical top (tick option), to accept page.
- "Record Manager" Screen
    - The following settings are recommended settings but can be adjusted if required by the user.
    - Mode: Resistivity.
    - Record: Record name to be entered by user.
    - Select options by ticking with the top black button after scrolling with the bottom black button with the arrow markings.
    - Scroll to OK option and tick to accept.

- "Resistivity" Screen. Series of screens will appear to adjust in this section. Select options by scrolling down to option with bottom arrow button and if user wants to change settings, use tick button to tick. Use vertical black button to move through various options. Tick to accept change.

- SCREEN 1
    - Output: 200mH
    - Mode: Auto
    - Acq. delay: 0.3 sec
    - Acq. time: 0.5 sec
    - Total cycle time: 3.8 sec
    - Use horizontal black button to move between screens in this section.

- SCREEN 2
    - Min stacks: 1
    - Max stacks: 4
    - Error limit: 1.0%
    - Norm: Median (Mean)
    - View app. Res.: Yes (No)
    - Data buffer size: 20
- SCREEN 3
    - Ignore errors: Yes (No)
    - Tx setup mode: Smart (Safe)

- SCREEN 4
    - Ignore negative Res: Yes (No)
    - Skip on errors1-5: Yes (No)
    - Wait between protocols: Yes (No)
    - Use external alarm: No (Yes)

- SCREEN 5
    - Type in operator name.

- SCREEN 6
    - Ch: 1
    - Start at sample: 1
    - No. of samples: 100

Use top black button to go back a step at any stage of the setup. Click to the left to go back a step and to the right to accept or move to next page.

2.3 Measuring

Click RED button DOWN to start measuring.

Click RED button again to activate the measuring screen.

The user will be asked if it is a file that is already in use if he/she wants to link (roll-along) and in which direction. This is only if the file is already in use!!!

- SCREEN 1- MEASURING

This screen will give the option to test the cables and electrodes individually.

- Electrodes test: Yes (No)
- Min output: 20mA
- Midpoint X.....
  Y.....

Scroll down to start option

- Tick to accept test, using tick button (black top, right tick)

- SCREEN 2 – MEASURING

The instrument will perform a quick test on the electrodes and cables. Any faults will be listed at this stage. The cable identified as cable 1 (below instrument) will become the negative numbers on this screen and the cable 2 (above instrument) will become the positive numbers. The user is to check the contact of the electrodes and the cables and if necessary, pour more water around the electrodes. Once the above steps are completed, proceed;

- Select electrodes that failed and re-test, once user has conducted above process.
- Select appropriate option and tick with top black button.

When user is satisfied with the test;

- scroll down to the start testing option and select

At this point the Resistivity testing will commence.

2.4 IMPORTANT CHECKS WHILE TESTING

- CHECK RESISTIVITY LEVELS WHILE TESTING, TRY TO DETERMINE IF THE READINGS ARE IN AN ACCEPTABLE RANGE.

- CHECK THE STANDARD DEVIATION, ENSURE THE % DOES NOT GET TOO HIGH. THIS WILL SHOW UP IN THE SOFTWARE AS PROBLEM AREAS.

- KEEP AN EYE ON THE INSTRUMENT AT ALL TIMES TO DETECT ANY MALFUNCTIONS.

- KEEP A SPARE 12V BATTERY NEARBY IN CASE OF POWER SHORTAGE.

2.5 Completion of field survey

On completion of the 258 tests done the user is to switch off the instrument by moving back through the screens to the starting screen or rolling along with the same survey.

- The user will be prompted to select if he/she wants to perform a roll-along option and in which direction. If this is required select the correct option and switch off the instrument.
- The user then moves the first cable (cable 1 of 4) to the top of the survey line if moving in the up direction. The opposite if moving in the down direction. Be careful not to loose the adapters and now move the instrument to the new centre point after setting up the new electrode positions of the moved cable. The adapters still need to be positioned correctly to face the instrument.
- Once all is set up and electrode contact is good, switch on the instrument again.
- Instead of opening a new file, select the file you were working on and the roll along survey will be incorporated into the file. The resistivity readings will be reduced as most of the survey has already been conducted.
- You can do as many roll-along surveys as required: be careful not to confuse yourself!!!
- If no roll-along is required, complete the process.
- Use the top back button, pushing to the left.
- Once at the start screen, push the two (middle and lower black buttons) power buttons simultaneously, and tick to accept the power off option by using the top black button.

If at anytime, there is a problem with the test, and the instrument is switched off. The instrument automatically saves the tests completed. The user switches instrument back on and scrolls to the files he/she was working on, to continue with the test.

2.6 GENERAL IMPORTANT POINTS

- When working with instrument, keep out of direct sunlight.
- Working near electric fences, underground piping, and other sources of electricity affect results. Switch off nearby electric fences etc.
- Do not use Resistivity meter during electrical storms.
- Do not touch electrodes while testing, could be harmful.
- Refer to Owners Manual for more assistance if needed.
- Take notes on the surroundings, geology, rocky outcrops etc., they will become important in the modelling and interpretation phase of the survey.

3. MODELLING COMPONENT

This part of the manual purely refers to the computer modelling component of the survey. Note various computers may have different setup options and user preferences may vary. This is a basic guideline that is advisable to follow for efficient and accurate results. Users are encouraged to refer to the ABEM manual provided, which is housed in the orange box, for additional assistance with the modelling component.

3.1 Computer setup

- Don't use DELL PC's
- Install ABEM software and then install GEOTOMO software as well as the green dongle provided in the small brown file. ABEM cd is with the INSTRUCTION MANUAL in the orange box. The GEOTOMO cd and dongle are in the brown file also located in the box.

3.2 Instrument setup

- Connect Terrameter to the computer with the cable provided in the orange box.
- Install the green dongle in the USB port.
- Connect the Terrameter to the external power source.
- Open the SAS4000 Utilities program
- Select File: open new LUND PROTOCOL PROJECT: ok
- Select File: Save as: Select your project name to save with (*.lup extension).
- Switch on the Terrameter.
- Select RS232 Communication and tick. Take note of the transfer rate (baudrate) in bps. The rate must be the same on the Terrameter and the PC. If you want to change the rate, scroll to the setup option on the first screen and select the Serial I/O option. In the SAS4000 program this rate can be altered by clicking on the "program properties" icon. From there go to transfer settings and change the rate if needed.
- Click on the "import" icon and highlight the files you want to import. Note you must import all three files for each survey.

- When files imported successfully, click ok and close the importing window.
- Open all files to find the imported file, and select.
- Click on the green addition sign to add this file to the project.
- Click on the reddish exclamation sign to convert this file. This is vital!!!
- Convert the file and close the windows.
- Save the changes you made and then minimize the program.

3.3 Modelling process

- Open the RES2DINV program.
- Select file - Read data file – Open the file (should have DAT ext.).
- Program will read the file, click ok.
- Go to inversion – Least squares inversion and select.
- The file will now be selected and saved with an INV ext. , click save to start the inversion process.
- Three pictures will appear on the screen. They will change continually while the model is running. The bottom picture is the inverse model resistivity picture that is important.
- One of two windows may pop up while the program is running, the will warm you that the ranges in the resistivity are great and would you like to continue and the other will tell you it has been through X amount of iterations, and would you like to add more and continue or would you like to stop the modelling process. The greater the number of iterations modelled, the lower the RMS error will become until a point where no improvement will occur.
- At this point no data has been altered at all.
- Click on the display option – show inversion results – ok.
- This is the basic results that occur in the picture you have just seen.
- Click on edit data – RMS error stats
- At this point you will see the data in a bar graph formation with a green line at the bottom end of the graph. Move this line by using the arrow keys to remove poor/suspect data. Notice the number of records you will be removing by looking at the bottom of the graph.

- Click on exit to exit and you will be prompted to save this file because you have removed data. Save the new file so that you can use the altered file to re-run the inversion process. Note that the picture should appear better because some bad data points were removed.
- Click on exit – quit display window.
- Click on file, this is to read the file you have just saved so that the inversion process can be repeated on the new file. Repeat the inversion process as discussed earlier.
- If you are not yet satisfied you can click on edit – exterminate bad data points - ok.
- This screen will be made up of a series if lines, with small crosses in the lines. The crosses represent the data points, and the lines represent the neatness of the data. If there are points that are visibly incorrect, these can be selected by clicking on them. They will now appear red in colour.
- When completed click on exit – quit edit window. You will once again be asked to save the changes, which will be used in the next modelling exercise.
- The program will automatically ask you if it can read the altered file to perform the inversion process. Select the appropriate file and read it. Repeat the inversion process as above once again. The results should be better. Note the RMS error!!
- If at this point the user is not yet satisfied with the results, click on change settings or the inversion options – there are numerous options available that will alter the modelling process slightly. Every user will change these settings as he/she requires. After the changes have been made re-run the model by clicking on the least squares option, to update the picture.
- During the modelling process, you will re-run the least squares option many times, and after a while you will notice that the RMS error won't improve much. At this point, the modelling is as good as its going to get without loosing too much data. It is easy to get the perfect picture by cutting out data but the picture will be worthless. Rather have all your data points and a picture that is not that great.
- Important to note is the range of the resistivity, blue does not necessarily mean water. Be aware of the ranges of the different materials and the scale used. This is a geological instrument!! When doing the field portion of the survey, take note of the surroundings, rocky outcrops etc. They will become important when interpreting the data.

3.4 Topography data

- Topography data can be included in the pictures (pseudosections) if the area has been surveyed using a GPS instrument.
- It is advisable to GPS the survey as a habit whenever conducting resistivity surveys.
- Convert the GPS data into an excel file.
- Open the last file modelled (*.DAT) in an excel package to view the file.
- Convert file as shown in example in Table3.1. Save as a DAT extension.

Sabie4a.topo				Name of file
2.5				Electrode spacing
1				Type of measurement 1= resistivity
242				no. data points
0				0= No. IP data
0				0= No. Mid point
	-100	5	9.6893	First Electrode position; depth of reading; resistivity
	-95	5	30.8944	Electrode position; depth of reading; resistivity
	......	......	......	......
	......	......	......	......
	......	......	......	......
	-90	5	17.4481	Electrode position; depth of reading; resistivity
	-90	60	376.5826	Electrode position; depth of reading; resistivity
	-85	60	318.0204	Electrode position; depth of reading; resistivity
	-80	60	254.7876	Last Electrode position; depth of reading; resistivity
2				2= If topography data present
81				No. of topography points
-100	205.172			Horizontal and vertical co-ordinates of first point.
-97.5	205.359			Horizontal and vertical co-ordinates of second point.
......	......			......
......	......			......
......	......			......
97.5	216.631			....
100	216.538			Horizontal and vertical co-ordinates of last point.
0				Enter 4-5 0s at the end of the file
0				
0				
0				
0				

Table 3.1. Example of the DAT file. Note the format setup.

- In RES2DINV open the modelled survey, click on topography options – display topography. This is to see if the topography makes sense or not.
- Go back to the main screen and click on show inversion results – ok.
- Re-run inversion process with most recent file.
- Click on display sections – include topography in model display. It will then ask you how many iterations you would like to use and what contour spacing you want to use. This is normally set on logarithmic contour intervals.
- You will get the pseudosection with the topography included.
- The user must save this and print it directly if wanted by using the print screen function.
- Click on exit – quit display window, to get out.
- Click on quit – quit program to get out of the program
- Exit the SAS4000 UTILITES by clicking exit.

3.5 IMPORTANT NOTES

The modelling component is probably the most time consuming component of the survey. Be careful not to remove too much data to obtain the "perfect picture".

Refer to geological maps, field visits and soils data for the interpretations of the pseudosections.

Refer manuals provided and housed in the orange box if problems arise.

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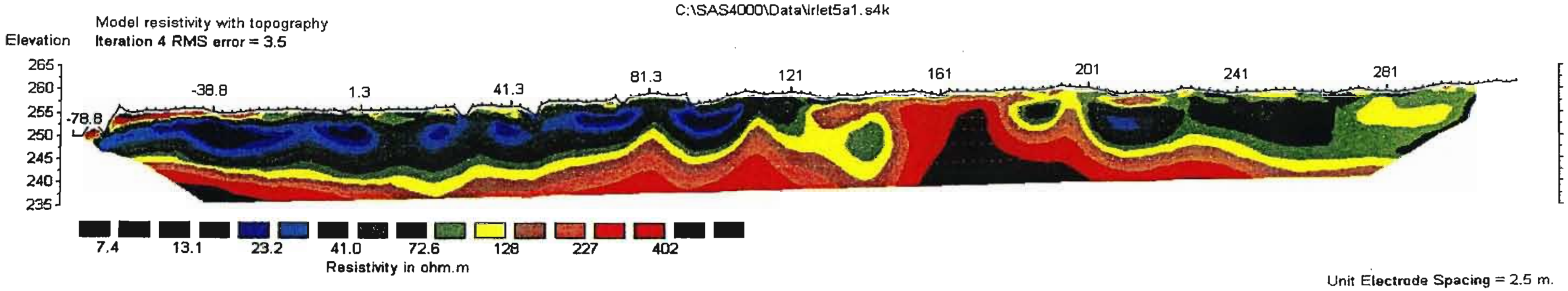
APPENDIX L

Letaba transect 5 interpretations.

The survey starts at point –78.8m at the Letaba River and stretches upslope to point 316.3m.

The bedrock is made up of granites and possibly gneiss with numerous deposits of alluvium, sand and scree. Many rounded boulders are present near and in the river. The darkish reds in the survey indict bedrocks. The reddish colours at the surface of the profile are rocky outcrops that are derived from the parent materials below but are at various stages of weathering. The materials with the lower resistivity are the alluvial materials that were deposited in possible paleochannels near the present day river. The blueish colours do not necessarily indicate moisture but are probably moister than the surrounding materials and will probably contain a higher clay content than the surrounding materials, which could be attributed to the accumulation from fluvial actions or weathering of the granites.

There are lot of metamorphics that has taken place in the area, hence the uneven bedrock and loose rocky materials at the surface, which would have encouraged the paleochannels formations. Notice how the moisture content increases as you get near the river, which could indicate a possible aquifer leaking into the river. Around the 160m areas, is an intrusion of the some parent material, this could be an intrusion such as a dolerite dyke or just an extremely resistant ledge in the parent material. Notice how the moister materials have formed to the upslope section of the intrusion. Around point 210m notice the possible accumulation of water. Also present are other possible accumulations illustrated by the green shades on either side of the intrusion.



Horizontal scale is 7.59 pixels per unit spacing
Vertical exaggeration in model section display = 1.47
First electrode is located at -78.8 m.
Last electrode is located at 316.3 m.

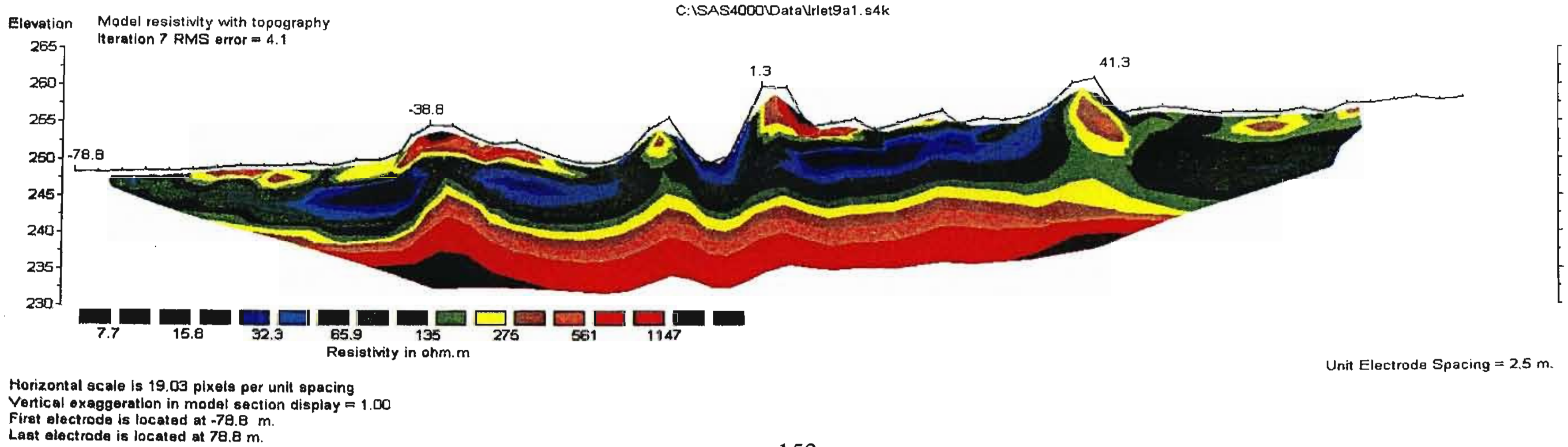
APPENDIX M

Letaba transect 9 interpretations.

The survey starts at point –78.8m at the Letaba River and stretches upslope to point 78.8m.

The bedrock is made up of granites and possibly gneiss with numerous deposits of alluvium, sand and scree. Many rounded boulders are present near and in the river. The darkish reds in the survey indict bedrocks. The reddish colours at the surface of the profile are rocky outcrops that are derived from the parent materials below but are at various stages of weathering. The materials with the lower resistivity are the alluvial materials that were deposited in possible paleochannels near the present day river. The blueish colours do not necessarily indicate moisture but are probably moister than the surrounding materials and will probably contain a higher clay content than the surrounding materials, which could be attributed to the accumulation from fluvial actions or weathering of the granites.

There are a lot of metamorphics that has taken place in the area, hence the uneven bedrock and loose rocky materials at the surface, which would have encouraged the paleochannels formations.



APPENDIX N

Craigieburn transect 1 interpretations.

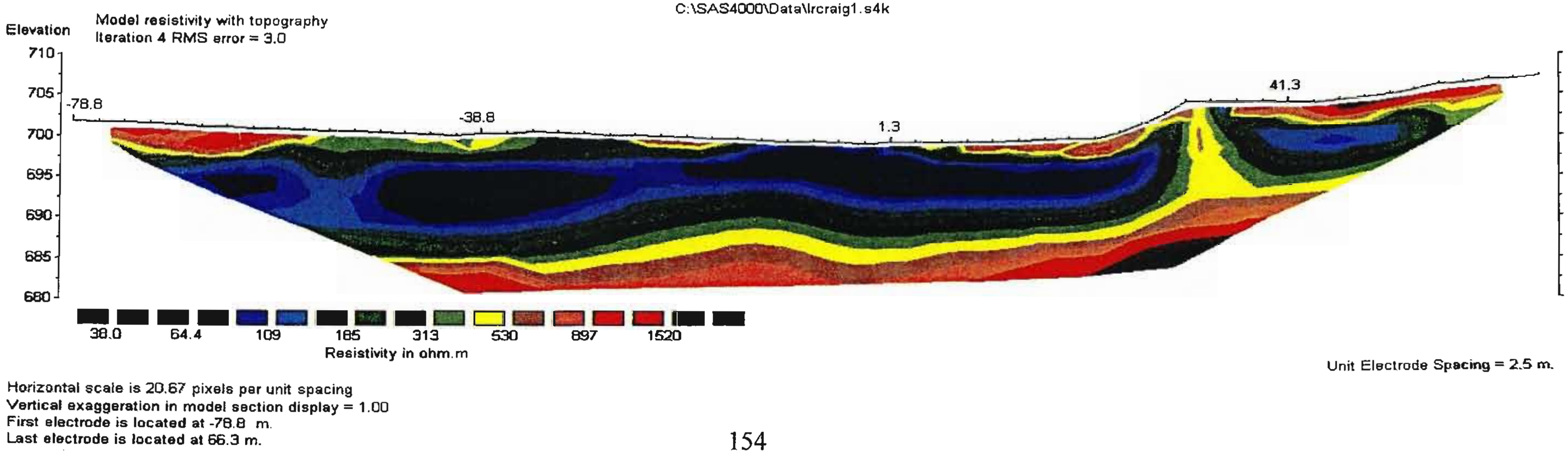
Craigieburn survey 1 taken upstream of the confluence and upslope of the donga. Survey direction being from northern side of donga through lands into valley bottom and up the steeper bank to the south. Ref = -78.8m – 66.3m

The general bedrock is granite and gneiss and is indicated in the survey by the darker reddish colours. In the vicinity of the 30m mark on the survey, there is a fault and it is up-thrown to the south. Notice the rock strata and the degree of upward movement (about 5m) on the southern side of the fault. This fault causes the rocky outcrops seen on the site.

The darker pigments near the surface of the profile could be loose poorly sorted sands and gravel accumulations or resistant accumulation of partly weathered granitic material.

Note, the water accumulations and moist sandy material below the surface near the centre of the survey. Bear in mind the survey crosses the two streams upstream of the confluence. There could be a possible accumulation of moister materials with the two channels clearly visible or clay overburdens. Notice the more saturated sands to the north of the survey (-70m) could possibly result from anthropogenic intervention in the cultivated field in the vicinity.

Note the water accumulation upslope of the fault to the south of the survey confirming the definite fault in the survey.



APPENDIX O

Craigieburn transect 3 interpretations.

This survey was done perpendicular to the first two but followed the path of the donga. The starting point was some 50m upslope of the start of the donga and crossed both streams near the confluence before following the donga down slope. Once again the starting point was at point –78.8m and ended at point 66.3m.

Notice the moist sand in the vicinity of the confluence and following the rivers streams underground.

Around the 18m point there is a sudden accumulation of moist material and this could be attributed to the additional dongas entering the main donga perpendicularly. This will also explain the accumulations of loose poorly sorted sands at the surface of the survey in the region of the inlet donga. Likewise there is an additional inlet donga down slope of the donga just discussed. Note the similarities.

Notice the sharp bedrock contact at the eastern base of the survey.