The use of magnetic susceptibility measurements to delineate wetlands in KwaZulu-Natal, South Africa.

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Abstract

The aim of this research was to investigate the possibility of using soil magnetic susceptibility to differentiate wetland soil from non-wetland soil, thereby enabling the identification of a wetland boundary. The initial methodology to test the viability of using magnetic susceptibility for wetland delineation was carried out at nine sites in three areas of Kwazulu-Natal, South Africa. Changes in vegetation were used to identify the permanently, seasonally and temporarily wet zones at each site to provide a quick indication of the various boundaries. At least one transect was studied at every site, extending from the outer edge of the temporary zone to the water's edge. Magnetic susceptibility readings, soil samples and/or elevations were taken in each zone. It was found that the magnetic susceptibility readings could be used to differentiate between the various wetland zones but boundaries were not identified due to the reconnaissance nature of the work, a specific protocol had yet to be developed. This methodology was a reconnaissance phase to assess the potential of using soil magnetic susceptibility.

A second methodology was designed specifically to identify a wetland boundary. The wetland zones were identified using vegetation indicators from the South African field procedure for delineating wetlands. Magnetic susceptibility readings were done on transects perpendicular to the suspected boundary and a critical value was identified. A magnetic susceptibility boundary was marked according to the critical value and verified by taking readings along transects parallel to it on both sides. The boundary was then identified using the South African field procedure according to soil indicators. The soil data showed a similar boundary to the magnetic susceptibility boundary but indicated a 'boundary zone' of approximately 12m in width rather than a specific line.

A final methodology was planned to improve the resolution of the magnetic susceptibility boundary. A grid was laid out over a strip through the wetland including the boundary area on both sides. This was to provide accurately spaced points at which to take magnetic susceptibility readings and elevations. The critical value, a value that separates wetland from non-wetland soil, was identified and verified using soil indicators. The field procedure was more difficult to carry out than using the magnetic susceptibility sensor, yet both methods identified the same boundary with a resolution of about 3m. This initial study demonstrates the potential for using magnetic susceptibility for wetland delineation. Although the results at the final site proved the method to be successful, it was not suitable for use at all sites and the results were often difficult to interpret. Limitations include factors such as plinthic horizons close to the soil surface and shallow, rocky soils. Thus further research is required before magnetic susceptibility can be used to delineate wetlands in KwaZulu-Natal, South Africa.

Preface

This work was carried out under the supervision of Dr Nevil Quinn and in consultation with Professor Jeff Hughes.

It represents original work by the author and has not otherwise been submitted in any form for any degree or diploma at any University. Where use has been made of the work of others it is duly acknowledged in the text.

This dissertation is dedicated to my parents :

Iain and Janet Watson

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CHAPTER 1

Overview

1.1 Introduction

Wetlands are an important resource necessary for functions such as flood control and water purification. Delineation of wetlands is necessary to enable careful management planning when wetlands fall within an area affected by human activities such as forestry or farming. In South Africa, wetlands are delineated using a field procedure based on soil morphology, vegetation and landscape position (Land-Use and Wetland/Riparian Habitat Working Group 1999). This procedure can be time consuming and is, to an extent, subjective due to the identification of colours by comparison with a Munsell colour chart and estimation of degree of mottling. An alternative, or supplementary method could possibly be provided by using a magnetic susceptibility (MS) meter to differentiate wetland soils from non-wetland soils.

All substances have magnetic properties (Smith 1999). Measurements can be made of the magnetic properties of almost any material, making them useful in a wide range of disciplines. They are particularly useful in the environmental disciplines since the measurements are rapid, simple and non-destructive and are often quicker and easier to carry out than conventional methods (Thompson *et al.* 1980). One of their applications is in soil science where magnetic susceptibility (MS) signatures can be related to soil type (Mullins 1977).

The aim of this research was to investigate the possibility of using soil MS as a way of differentiating between wetland soil and non-wetland soil, thereby enabling the identification of a wetland boundary. If the method could be developed, it would be a useful reconnaissance tool that would enable fairly quick wetland mapping over a large area as a supplement or alternative to conventional soil survey methods (Williams & Cooper 1990). The extent of its usefulness is currently unknown, little research into this particular application of MS has been done. Two studies have been undertaken, one by Williams and Cooper (1990) in Oklahoma and one by Grimley and Verpraskas (2000) in Illinois. These two approaches are described in full in Section 2.9.3. This research aimed to explore the possibility of designing a method that would be specific to the conditions in South Africa and in Kwazulu-Natal in particular.

1.2 Problem statement

Wetlands are an important natural resource. Wetland delineation is necessary to prevent activities such as agriculture and commercial forestry affecting their functioning. South Africa recognises the importance of protecting wetlands and has implemented the principles of the Ramsar Convention in various policy and legislative documents such as the Biodiversity Bill (1995), the National Environmental Management Act No.107 of 1998, the National Water Act No.16 of 1998 and the Marine Living Resources Act No.18 of 1998 (South African Wetlands Conservation Programme 2001). This legislation means that it is against the law to undertake any unauthorized activity that is likely to destroy or impede upon the functioning of a wetland.

Delineation is important for wetland conservation, as mentioned in the introduction, the current method used is time-consuming and subjective. Limited research has been done into the use of MS for identifying hydric (wetland) soils. It was suspected that this measurement can provide a quick alternative to soil survey but the extent of its usefulness, and the conditions under which it is likely to be successful, were unknown.

1.3 Aims and objectives

The aims of the research are to adapt and develop work already done on the use of MS measurements for hydric soil delineation for wetlands in South Africa and to develop a rapid reconnaissance method in order to save time when mapping wetlands over large areas.

The objectives are to :

- test whether magnetic susceptibility is a viable option or not.
- determine for which land types (geology, soils, climate, vegetation) the use of MS to delineate wetland soils may be appropriate
- if the results are successful, to design a quick, user-friendly field method; and
- provide recommendations for further research.

1.4 Methodology

In order to achieve the aims and objectives outlined above, the first step was to conduct a literature review considering MS, wetlands and their soil chemistry, current methods used to delineate wetlands and the possibility of using MS for this purpose. The second step was to design a methodology to test the idea. Much of the initial fieldwork involved trial and error to gain some understanding of how the MS meter operates and whether it was likely to work at all.

The third step involved assessment of the initial methodology and the design of a revised methodology to get more specific results. Further fieldwork was carried out to test the revised methodology. A final methodology used all the knowledge gained from the previous fieldwork and a study was carried out with the intention of proving conclusively that an MS boundary corresponded with a soil survey boundary. Chapter 3 gives a full description of the methods used.

1.5 Overview of the dissertation

Chapter 2 presents the findings of the literature review. Literature on MS, the MS of soils, wetlands, the chemistry and classification of hydric soils, wetland delineation in South Africa and the United States and the use of MS for wetland delineation was reviewed. Chapter 3 focuses on developing and refining a methodology. The methodology was developed in 3 phases as more knowledge was gained about the MS meter and its operation in different conditions.

Chapter 4 is a summary of the results from all the fieldwork, divided into the 3 phases mentioned above. The data are displayed mainly as graphs and tables with all the raw MS data presented in Appendix 2, the soil data included in Appendix 3. Chapter 5 consists of the overall discussion. Chapter 6 contains the final conclusions and recommendations for future research.

CHAPTER 2

Magnetic Susceptibility and Wetlands

2.1 Introduction

Magnetic measurements date back to 1831 when Faraday showed that the movement of a magnet could produce an electric current (Thompson *et al.* 1980). Modern electronics has made it possible to rapidly and easily measure magnetic parameters of weakly magnetic natural minerals by utilizing the connection between magnetism and electricity (Thompson *et al.* 1980). Measurements can be made of the magnetic properties of almost any material, making them useful in a wide range of disciplines. They are particularly useful in the environmental disciplines since the measurements are rapid, simple and non-destructive and are often quicker and easier to carry out than conventional methods (Mullins 1977; Thompson *et al.* 1980; Thompson & Oldfield 1986; Dearing 1999a; Dearing 1999b;).

Although this dissertation considers one application of magnetic measurements in soil science, i.e. in the use of magnetic susceptibility to characterise soil types, other environmental applications include problems in geophysics, meteorology, climatology, hydrology, limnology, oceanography, sedimentology, geomorphology, ecology and land-use studies (Thompson *et al.* 1980). The last two decades have seen a considerable increase in the use of natural magnetic tracers, the mineralogy of environmental materials is characterised and used to trace their movement through fluvial systems (e.g. Caitcheon 1993, 1998; de Jong *et al.* 1997; Hutchinson 1993). This technique is used in soil redistribution studies, linking slopes to channels, tracing bedload movements and reconstructing hydrological processes in sediment sequences (Dearing 2000). There is little recent literature on the application of magnetic measurements in soil science, the key article being a review by Mullins (1977). Thompson and Oldfield (1986) are also commonly referred to in the more recent literature with respect to magnetic measurements in soil science.

Magnetic susceptibility (MS) is not the only magnetic measurement that can be made. Saturation isothermal remanence magnetization (SIRM) and remanent coercivity are also useful environmental measurements; the ratio between these measurements are used to classify magnetic minerals (Thompson & Oldfield 1986). There are also different types of magnetic susceptibility measurements. This review will focus on magnetic susceptibility measurements of soils with the specific purpose of applying them to wetland delineation. This will involve a review of the current methods used to delineate wetlands and an assessment of whether magnetic susceptibility measurements would provide a suitable alternative, or a useful addition.

2.2 An introduction to the magnetic properties of solids

Materials are usually considered as either 'magnetic' if they are attracted to a magnet or 'non-magnetic' if they are not attracted by a magnet. The reality is that all substances have magnetic properties and those with very weak properties are perceived as non-magnetic (Thompson & Oldfield 1986). At the atomic level magnetic fields arise from the motion of electrons of which two types occur i.e. electrons move in an orbital rotation around the nucleus and they spin about their own axes. Both these motions produce currents which in turn produce magnetic fields (Mullins 1977; Thompson & Oldfield 1986). In the natural iron oxide minerals, the spin moments are the dominant generators of magnetic properties (Smith 1999). Table 2.1 describes various types of magnetism.

Table 2.1 The magnetic properties of solids (*after* Thompson & Oldfield 1986; Dearing 1999b; Smith 1999).

Type of magnetism	Description	Examples
Diamagnetism	Very weak. Arises from the interaction between the orbital motion of electrons (the spin electron moments do not contribute because they are paired and cancel each other out) and an applied magnetic field. Weak negative magnetization of the solid results, this is lost as soon as the magnetic field is removed. It is independent of temperature.	quartz, feldspar, calcite, water
Paramagnetism	Behave in the opposite way to diamagnetic minerals. The incompletely filled inner electron shells of Mn^{2+} , Fe^{2+} and Fe^{3+} ions are generally responsible for paramagnetism because they have unpaired electrons with free spin magnetic moments. When a magnetic field is applied to a paramagnetic substance the spin magnetic moments order themselves and orientate parallel to the applied field direction. This magnetic property is temperature dependent, thermal agitation constantly tries to break down the small magnetic energies that align the electrons. Once the magnetic field is removed the paramagnetic effect is lost. Paramagnetism is dominant over diamagnetism but is weaker than ferromagnetism.	biotite, pyrite
Ferromagnetism	The magnetic properties of these materials change dramatically at a critical temperature called the Curie temperature. Below this temperature these materials can have a remanent magnetisation (exists without the presence of a magnetic field) but above the Curie temperature they behave as paramagnets. This is due to the breakdown of the ferromagnetic ordering by thermal energy. Ferromagnetic effects are much greater than diamagnetic or paramagnetic effects.	pure iron
Ferrimagnetism	This is very similar to ferromagnetism. Ferrimagnetic behaviour depends on the crystal structure (usually iron oxides with a spinel structure). They contain two types of magnetic sites which have antiparallel magnetic moments of different magnitudes, the sum of the moments pointing in one direction exceeds that of the opposite direction (see Figure 2.1), leading to a net magnetisation. Ferrites have low electrical conductivities and are used in computer memories.	magnetite
Antiferromagnetism	These materials have a similar arrangement of magnetic sites to ferrimagnets but their magnetic moments are identical, resulting in zero bulk spontaneous magnetisation (Figure 2.1). Antiferromagnetic ordering is destroyed above the Curie temperature, making it temperature dependent. Imperfect antiferromegnetic properties are produced as a result of impurities or spin canting. Spin canting is when a slight modification of the antiferromagnetic anti-parallelism occurs.	haematite

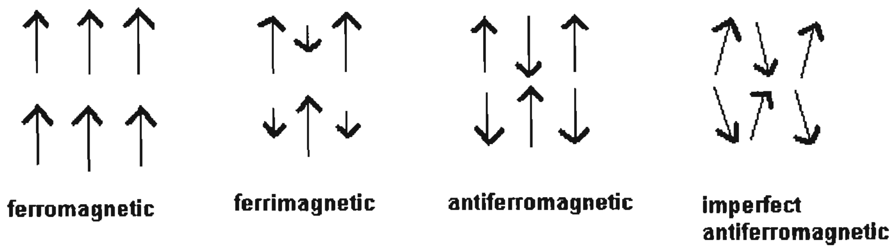


Figure 2.1 Arrangement of the magnetic moments in some magnetic properties of solids (*after* Thompson & Oldfield 1986; Smith 1999)

Hysteresis is another physical phenomenon that determines the magnetic properties of materials. When a magnetic field is applied to an unmagnetised iron bar its magnetisation increases slowly as a small field is applied. If the field is removed the magnetisation returns to zero. If a stronger field is applied, beyond a certain critical field, the magnetisation is not reversible on removal of the field, hysteresis occurs instead (Thompson & Oldfield 1986). Hysteresis describes the changes in magnetisation associated with removal of the field and how they differ from those that occurred during the preceding increase of the field. In summary, the changes now lag behind the field and upon complete removal of the field, the iron retains a remanent magnetisation (it does not become unmagnetised again) (Thompson & Oldfield 1986). Many simple magnetic properties used to characterise materials can be classified as hysteresis parameters. The interrelationships between these properties is best understood using hysteresis loops (Figure 2.2). A hysteresis loop is obtained by cycling the magnetic field from an extreme applied field in one direction to an extreme in the opposite direction and back again.

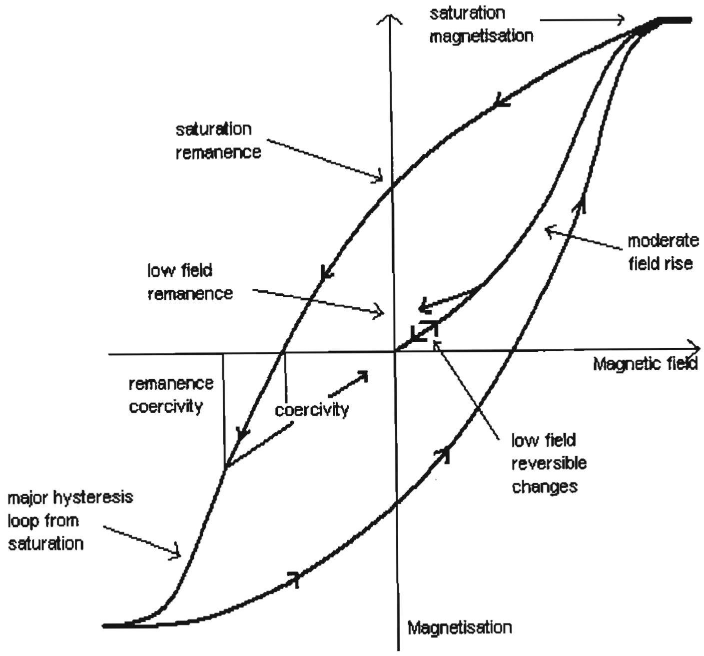


Figure 2. 2 Magnetic hysteresis loop and initial magnetization curve showing saturation magnetization, saturation remanence, coercivity, remanenence coercivity and low field magnetization changes (Thompson & Oldfield 1986).

Five of the most important hysteresis parameters that are often measured in environmental fields are given in Table 2.2.

Table 2.2 Five of the most important hysteresis parameters often measured in environmental fields (Thompson & Oldfield 1986).

Name of parameter	Symbol	Description
Saturation magnetisation	M_S	Magnetisation induced in the presence of a large magnetic field (>1T , T is the symbol for tesla, the SI unit of magnetic induction), when the field is removed the magnetisation does not reduce back to zero.
Saturation remanent magnetisation	M_{RS}	The remaining magnetisation after the field applied above (saturation magnetisation) is removed.
Saturation coercivity	$(B_O)_C$	A reverse field that is applied in order to reduce the magnetisation to zero.
Coercivity of remanence	$(B_O)_{CR}$	An even larger reverse field that is required to reduce the magnetisation to zero and leave no remanent magnetisation on withdrawal
Initial susceptibility	K	Represented by the gradient of the magnetisation curve at the origin of Figure 2.2 above.

Hysteresis is only one factor that affects the magnetic properties of solids. The crystal size, shape and structure are also important. The time dependence of magnetisation is another effect since changes in magnetisation with time are known as (especially important when geological time scales are involved) viscous changes. Grain interactions caused by magnetostatic interaction when magnetic grains lie close to each other can also modify the magnetic behaviour of a solid (Thompson & Oldfield 1986).

2.3 Magnetic susceptibility

2.3.1 Definitions and units

The most commonly and easily measured magnetic property of soils is the magnetic susceptibility (Mullins 1977). *Volume magnetic susceptibility*, K, is defined by the relation

$$\boldsymbol{K = M / H}$$

where M is the volume magnetisation (total magnetic field per unit volume) induced in a material of susceptibility, K, by an applied field (inducing magnetic field per unit volume) H. Volume susceptibility is therefore a dimensionless quantity (Mullins 1977; Thompson & Oldfield 1986; de Jong *et al.* 1998).

Specific susceptibility (or mass susceptibility) X, is defined as volume susceptibility divided by density:

$$\boldsymbol{X = K / \rho}$$

and has units $m^3.kg^{-1}$ (Dearing 1999; Mullins 1977; Thompson & Oldfield 1986). Susceptibility is generally measured in small fields, of strengths less than 1mT as it is found that susceptibility is reasonably independent of applied field intensity (the Earth's magnetic field) at these low fields (Thompson & Oldfield 1986).

When a substance is magnetised its internal magnetic field is less than the externally applied field. The intrinsic susceptibility, K_i, relates the induced magnetisation to the internal magnetic field. The extrinsic susceptibility, K_e, is what is actually observed and this relates the induced magnetisation to the externally applied field (Thompson & Oldfield 1986). The relationship between these two susceptibilities is given as : $K_e = K_i / (1 + NK_i)$ where N is the demagnetisation factor. This relationship is important because it can be used to relate the magnetic susceptibility of a sample and the concentration of ferrimagnetic grains present (Thompson & Oldfield 1986).

2.3.2 Measurement of susceptibility

The electronics revolution has led to considerable improvements in instrumentation for measuring magnetic susceptibility, largely due to a growing amateur metal detecting market. This has led to improved sensitivity, speed, portability and simplified measurement (Thompson & Oldfield 1986). There are a wide variety of methods available for measuring magnetic susceptibility but not all of them are suitable for soil measurements (Oades & Townsend 1963; Mullins 1977). Mullins (1977) suggested that the simplest and most reliable method of measuring the susceptibility of soils is to use "some type of weak alternating field bridge design". This has become the most commonly used method, known as the 'a.c'. method.

A balanced a.c. bridge circuit is widely used for the measurement of small changes in inductance, capacitance or resistance. In susceptibility bridges the magnetising field is produced by a current-carrying solenoid, flat coil or Helmholtz coil pair. The induced magnetisation is detected by a balanced coaxial pick-up coil. Inserting a sample into the coil system alters its inductive balance and produces an out-of-balance signal in the pick-up coil, which is proportional to the total susceptibility of the sample. Depending on the type of a.c. bridge and coil used, the signal can be amplified and measured in millivolts or rectified and measured in microamperes (Thompson & Oldfield 1986). Alternative approaches are also adopted in the 'a.c.' method e.g. balanced transformer circuits are used which work at different frequencies and can be used to measure samples of different sizes (Likhite *et al.* 1965 and Radhakrishnamurty *et al.* 1968, cited in Thompson & Oldfield 1986). The Bartington system detects a frequency change in a sharply tuned 'metal detector' oscillator circuit that is caused by the introduction of a sample (Thompson & Oldfield 1986). The Bartington *MS2* magnetic susceptibility system is commonly used for the measurement of magnetic susceptibility in the environmental sciences (Bartington Instruments 2001). The *MS2* meter is a portable instrument that can be used both in the laboratory and in the field. It has a range of individually calibrated sensors that can be used for different purposes. It has a high resolution and provides non-destructive, accurate measurements that are read in approximately 1 second. The system is versatile and is currently used in geomorphology, geophysics, archaeology and mineral exploration (Bartington Instruments 2001). The technical specifications are included in Appendix 1.

Bartington is not the only manufacturer of MS instruments e.g. Kappabridge and Molspin are also mentioned by Walden *et al.* (1999). They stress that comparability between equipment cannot be assumed because very few attempts have been made to compare results obtained with different equipment. The Bartington MS2 System is probably the most widely used in environmental research because it provides satisfactory sensitivity for many applications, portability for field surveys and a dual frequency option for single samples (Walden *et al.* 1999). The Bartington MS2 System consists of a meter and five sensors for laboratory and field use. Tables 2.3 and 2.4 describe the sensors and their use. This project focused primarily on soil field mapping using the MS2D sensor with a limited amount of work using the MS2F sensor.

Table 2.3 The Bartington MS2 Magnetic Susceptibilty System sensors (*after* Bartington 2001; Dearing 1999; Walden *et al.* 1999).

Name	Lab	Field	Description
MS2B	•		Dual frequency for accurate measurement of liquid or granular samples in sample pots or drill cores.
MS2B62	•		Single frequency, accepts a 250cc capacity sample container (largest sample possible), tolerant to inhomogeneity in granular samples.
MS2C	•	•	Designed for measurement of continuous sections of core.
MS2E/1	•		For measurements with high special resolution along split cores.
MS2E/2	•		For measurememts on small geological or industrial specimens.
MS2G	•		Used with a 1cc volume sample vial for powders or liquids, smallest sample size available.
MS2XT	•		Water jacketed sensor with a temperature compensated integral electronics unit permitting measurement of the temperature dependency of magnetic susceptibility.
MS2D		•	A search loop 185mm in diameter, depth of investigation approximately equal to its diameter.
MS2F		•	Narrow probe, tip diameter of 15mm with a similar depth of investigation.

Table 2.4 Bartington MS2 sensors and their use after Dearing (1999); Walden *et al.* (1999).

Use	Sensor
Geology	
Field mapping	D, E or F
Identifying rock type in exposure	E or F
Identifying erratics in drift deposits	E or F
Identifying mineral zones	D
Single samples	B or XT
Soils	
Field mapping	D or F
Field measurement of soil profiles	F
Identifying provenance of stones	E or F
Measurement of soil cores	C
Single samples	B or XT
Archaeology	
Location of former occupation sites	B, D or F
Stratigraphy studies	D, E or F
Tests for magnetometer 'surveyability'	B, D, E or F
Hydrology and Sedimentology	
Field survey of bedload	D, E or F
Field tracing of enhanced bedload	D, E or F
Single samples of stone, soil and vegetation	B or XT
Building materials	
Field surveys of hidden material	D
Geological source	B or XT
Infill permeability detection	B or XT

2.4 Magnetic susceptibility and soil science

2.4.1 The magnetic properties of soil minerals

The study of the magnetic properties of soils is a difficult field of study but Thompson & Oldfield (1986) point out that some characterisation of the magnetic properties of soils is vital since the weathering of rocks releases iron which is transformed into chemically stable magnetic oxides which may then persist in the soil, in the suspended load of rivers, in atmospheric dusts and in the historical record preserved in sediment, peat and ice cores. They suggested that if the magnetic properties of soil can be characterised, they can then be applied in almost any other environmental magnetism problem.

Soils contain a wide variety of minerals and their magnetic properties are a reflection of the particular combination of minerals present. The diamagnetic component of soils includes quartz, orthoclase, calcium carbonate, organic matter and water (Thompson & Oldfield 1986). These components do not contribute to the magnetic properties except in an extreme case such as pure silica sand. Many soil minerals, both primary (inherited from the parent rock) and secondary (formed by weathering processes), are paramagnetic. Ferrimagnetic minerals such as maghaemite and magnetite usually dominate but when they are absent paramagnetic minerals such as olivine and pyroxene contribute significantly to the magnetic susceptibility (Thompson & Oldfield 1986). Some clay minerals are iron-rich and have high susceptibilities.

Several antiferromagnetic minerals are found in soils with goethite and haematite being the most important (Dearing 1999). Goethite is more common in temperate climates while haematite is found in drier and more highly oxidising conditions. Lepidocrocite is also a canted antiferromagnetic mineral, largely confined to gleyed (waterlogged, reducing conditions) soils where it occurs as orange mottles (Thompson & Oldfield 1986). Magnetite and maghaemite are the most important ferrimagnetic oxides. Magnetite occurs as a primary mineral, inherited from basic igneous rocks, and as a secondary mineral, maghaemite is also a secondary mineral. Table 2.5 gives a summary of various parent materials, their mineral constituents and their magnetic behaviour.

Table 2.5 Parent materials, minerals and their magnetic behaviour (*after* Thompson & Oldfield 1986; Dearing 1999; Smith 1999).

Parent material	Minerals	Type of magnetism	Magnetic susceptibility
Igneous rocks (e.g. basalt, gabbro, granite).	Magnetite, maghaemite	Ferrimagnetic	Strong positive susceptibility
	Ilmenite, titanoheamatite, rutile	Canted antiferromagnetic	Moderate positive susceptibility
	Pseudobrookite	Paramagnetic	Weak positive susceptibility
Sedimentary rocks (e.g. red beds, limestones, ocean sediment).	Iron sulphides	Ferrimagnetic	Strong positive susceptibility
	Haematite and goethite, titanomagnetite	Canted antiferromagnetic	Moderate positive susceptibility
	Quartz and feldspars	Diamagnetic	Weak positive susceptibility
Metamorphic rocks (e.g. slate)	Haematite, ilmenite	Canted antiferromagnetic	Moderate positive susceptibility
	Pseudobrookite	Paramagnetic	Weak positive susceptibiliy

2.4.2 The magnetic enhancement of surface soils

Many researchers have noted that the magnetic susceptibility of soil is higher than that of the parent material, and that the susceptibility of the topsoil is usually higher than that of the subsoil (de Jong *et al.* 1998; Le Borgne 1955 cited in Mullins 1977; Tite & Linington 1975; Thompson & Oldfield 1986). Le Borgne (1955, 1960), cited in Tite & Linington (1975), has suggested that this enhanced susceptibility of the soil is due to the *in situ* conversion of the iron oxides from an antiferromagnetic form such as haematite (α Fe_2O_3) or goethite (α FeOOH) to the ferrimagnetic form, maghaemite (γFe_2O_3). Le Borgne also proposed two possible mechanisms involving reduction, followed by reoxidation to maghaemite. In the first process, he proposed that during wet conditions, anaerobic breakdown of soil organic matter leads to the reduction of iron and then during the subsequent dry period the iron is reoxidised to form maghaemite. A criticism of this idea is that organic matter breakdown is usually impeded by anaerobic conditions, but does not necessarily preclude what Le Borgne proposed (Kotze *et al.* 1996a). The second process is a heating mechanism whereby the burning of organic material produces the temperature increase and reducing conditions neccessary for the reduction to magnetite (Fe_3O_4) in a thin layer of soil underlying the fire and reoxidation occurs during the cooling down of the fires when air enters the system. These findings have been substantiated by subsequent researchers and form the basis of most work performed since then (Mullins 1977). Smith (1999) still refers to Le Borgne's (1960) work, stating that burning of surface vegetation cover and topsoil can promote a massive increase in MS. Smith also suggests that even if a soil is not burned directly, its upper horizons may contain a significant amount of dust as a result of fall-out from other burnt areas.

Mullins (1977) identifies four ways in which maghaemite is formed in soil and refers to them either as 'burning mechanisms' (as described above) or 'pedogenic mechanisms'. These pedogenic mechanisms include the same reduction-oxidation process described by Le Borgne, and the dehydration of lepidocrocite (γ FeOOH) to maghaemite. This process is restricted to local conditions where gleyed soils are either drained or subjected to high temperatures (a temperature above 275°C is required). Thompson and Oldfield (1986) have noted that soils near cities may have a higher susceptibility in the topsoil due to fallout from the atmosphere of magnetic particles derived from fossil-fuel combustion. This will not always be the case but should be considered when selecting sites for magnetic susceptibility studies.

Another area of research has involved studying the variation of susceptibility down a profile and relating it to soil type. Vadyunina and Babanin (1972), cited in Mullins (1977), reviewed Russian work that suggested that magnetic susceptibility measurements can be used as evidence of soil processes such as gleying. Maher (1984, 1986) has undertaken research on the mineral magnetic properties of contemporary and fossil soils with a view to relating them to soil forming processes (Thompson & Oldfield 1986).

2.5 An introduction to wetlands and their importance

Wetlands comprise approximately 6 per cent of the world's surface and in the past were considered to be wasteland and worthless (Williams 1990). More recently, wetlands have been recognised for their hydrological, chemical, biological and socio-economic benefits and demands for their conservation are now widespread (Williams 1990). According to the South African National Water Act No. 36 of 1998, a wetland is defined as :

> 'land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil'.

There are different types of wetlands that occur from the top to the bottom of catchments, these include springs and seeps, marshes, flood plains, swamp forests, mangrove swamps and estuaries (Braack *et al.* 2000). An area is considered to be a wetland if the soil is saturated for long enough for anaerobic conditions to develop, if the conditions favour the growth of water-loving plants (hydrophytes) and if a high water table results in saturated soil conditions. All three of these criteria must be met (Braack *et al.* 2000). Figure 2.3 shows a cross-section through a typical wetland.

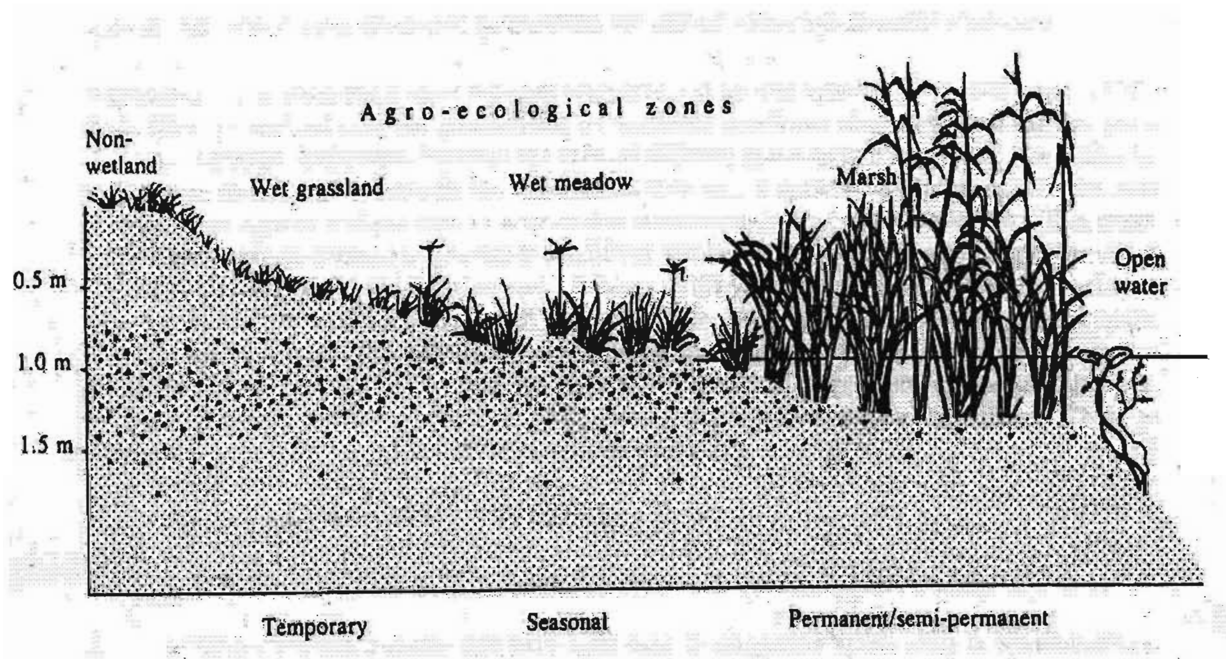


Figure 2.3 A cross-section through a wetland (Kotze *et al.* 1996a)

Wetlands are usually found in flat areas where topography or geology slows down the movement of water through the catchment. This causes the surface soil layers to become temporarily, seasonally or permanently waterlogged (Braack *et al.* 2000). Hydrophytes become established and the wetland area performs a number of important functions that are important for preserving and purifying water.
Some functions of wetlands include flood reduction and streamflow regulation, groundwater recharge and discharge, water purification, erosion control by wetland vegetation, chemical cycling, shoreline stabilisation and storm protection, and biodiversity conservation (Braack *et al.* 2000; Hails 2000). Wetlands are also a valuable source of water, an economically efficient way of treating wastewater, they provide grazing for livestock, fibre for construction and handcraft production, valuable fisheries, hunting waterfowl and other wildlife, valuable land for cultivation and are aesthetically important (Mitsch & Gosselink 1993; Braack *et al.* 2000). All these functions and values are very good reasons to protect and conserve wetlands yet many are being, or have been, destroyed by human activities.

Wetlands are negatively affected by drainage for crop cultivation, poorly managed burning, poorly managed grazing, timber production, road building, irresponsible damming, mowing and harvesting of plants, alien plants, purification of wastewater and non-sustainable fishing and hunting (Braack *et al.* 2000). Wetlands can be utilised but it is important not to destroy their basic functioning in order to benefit from their many functions and values. By destroying wetlands we interfere with the movement of water through whole catchments, creating the potential for increased flooding and erosion and reduced water quality (Hails 2000). It is therefore important to identify wetlands and ensure that human activities do not detrimentally affect their functioning.

The first step in wetland protection is identification and delineation of the wetland boundaries (Lyon 1993; Land-Use and Wetland/Riparian Habitat Working Group 1999). Unless the area is clearly mapped it is difficult to advise foresters as to how wide a buffer zone should be or developers as to how close to a wetland a structure can be built. Wetlands exhibit particular soil types due to their permanent and seasonal areas of waterlogging (Kotze *et al.* 1996a) These distinctive soil types are useful for distinguishing between wetland and non-wetland soils when a wetland is being delineated. Section 2.6 will consist of a discussion on the chemical processes that occur in wetland soils and Section 2.7 will look at how these soils are classified.

2.6 The soil chemistry of wetlands

When soil is saturated with water for long periods, the oxygen supply is depleted. This is due to its consumption by aerobic microbes and a low solubility of 8µg/ml (McBride 1994). When all the oxygen is used up, anaerobic microbes oxidize remaining organic matter so producing hydrogen ions and electrons (Kotze *et al.* 1996a). Oxidised ions such as Mn^{3+}, Fe^{3+}, NO_3^- and SO_4^{2-} are reduced as they accept these electrons. These conditions are referred to as redox (reduction-oxidation) conditions, defined as the potential of an atom of any given element to react depends on the affinity of its nucleus for electrons and the tendency of the atom to gain maximum stability by filling its outer electroshell or comply with the octet rule (an atom must have eight electrons in its outer shell or outermost energy level) (Evangelou 1998). An ion is only able to be reduced if an electron is provided by oxidation of another ion, for a redox reaction to proceed oxidation and reduction have to be coupled (Evangelou 1998). Two half reactions (the oxidation and reduction steps) are required for a change of redox status in a particular element. Redox chemistry affects mineral solubility, pH, mineral surface chemistry, the availability of certain chemical species, the toxicity of certain species e.g. As(III) has a high toxicity but As(V) has a low toxicity, salt content of solutions and volatility of chemical species (Evangelou 1998).

The reduced form of the ions are more soluble than when oxidised and most of them are lost, or moved downwards in the profile, due to leaching (McBride 1994; Kotze *et al.* 1996a). Leaching is the downward movement with water. The brown and red colours in soil are largely due to ferric oxide minerals (the oxidised forms of iron), the reduced forms of iron (Fe^{2+}) appear green or blue with the soil matrix appearing grey due to the lack of iron. Thus waterlogged soils that have lost much of their iron through leaching appear grey, sometimes with blue or green. This process is referred to as gleying. Prolonged waterlogged conditions, such as would be found in the permanently wet zone, causes sulfides to precipitate with Fe^{2+}, to form insoluble sulfide minerals such as pyrite (FeS_2).

Periodic saturation leads to alternate anaerobic (when wet) and aerobic (when dry) conditions. As waterlogged soil dries out, oxygen is able to enter and react with any reduced iron that is still present. The iron is re-precipitated in localised areas of the profile as yellow, orange or red mottles in the grey matrix. The colour of the mottles is determined by the mineral that is formed, these are commonly iron oxides such as haematite (Fe_2O_3, red) or iron oxyhydroxides for example goethite ($FeOOH$, yellow). Thus soils that are permanently waterlogged appear uniformly grey throughout the saturated area. Soils that are saturated for long periods are predominantly grey with yellow and red mottles and soils saturated for short periods are predominantly brown with grey mottles (Kotze *et al.* 1996a). Plate 2.1 shows an example of a gleyed subsoil. Not all gleyed soils have the same appearance, Plate 2.1 shows a predominantly grey soil. Gley conditions can also be dominated by red or yellow (or both) mottling.

Plate 2.1 An example of the South African Willowbrook soil form. The B horizon shows the typical grey matrix of a gleyed soil (Soil Classification Working Group 1991).

2.7 The classification of hydric soils

What gives wetland soils their unique characteristics is periodic wetting and drying cycles or permanent saturation. Wetland soils can firstly be divided into two broad categories, organic soils and mineral soils. When soil is waterlogged for long periods of time, or permanently, anaerobic conditions prevail and the breakdown of organic matter is impeded (Kotze *et al.* 1996a). The organic matter accumulates in the soil. These soils are typically identified by their organic or humus rich topsoils and are most prevalent in cool climates since biological activity decreases as temperature decreases. In South Africa, the minimum organic carbon limit is 10% and the minimum thickness of organic material within the upper 800mm of the soil profile is 200mm for a soil to be classified as organic (Kotze *et al.* 1996b). Soils that contain less organic carbon than that required for this classification are termed mineral soils. Hydric mineral soils are usually gleyed (grey in colour, sometimes also blue and green) and contain mottles of iron and manganese oxides and hydrates which can be yellow, orange, red, brown or black (Kotze *et al.* 1996a).

2.7.1 The United States of America

The United States of America has the most widely known and widely used soil classification system in the world. The current American definition of a hydric soil is provided by the United States Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) Wetland Science Institute and Soil Survey Division

> 'A *hydric soil* is a soil that formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part.' (USDA-NRCS 2001).

Hydric soils are specifically classified in Soil Taxonomy, the American soil classification system, according to the following four criteria (USDA-NRCS 2001) :

1. All Histels except Folistels and Histosols except Folists, or
2. Soils in Aquic suborders, great groups, or subgroups, Albolls suborder, Historthels great group, Histoturbels great group, Pachic subgroups, or Cumulic subgroups that are :
   a. Somewhat poorly drained with a water table at the surface during the growing season, or
   b. Poorly drained or very poorly drained and have either :
      (1) water table at the surface during the growing season if textures are course sand, sand, or fine sand in all layers within 20 inches (in) (50.8cm),
      or for other soils,
      (2) water table at less than or equal to 0.5ft (0.15m)from the surface during the growing season if permeability is equal to or greater than 6.0in (15.2cm)/hour (h) in all layers within 20in (50.8cm), or
      (3) water table at less than or equal to 1.0ft (0.3m) from the surface during the growing season if permeability is less than 6.0in/hr in any layer within 20in (50.8cm), or
3. Soils that are frequently ponded for long duration or very long duration during the growing season, or
4. Soils that are frequently flooded for long duration or very long duration during the

growing season.

The USDA-NRCS also provides a glossary of terms (definitions of terms such as water table, ponded and frequently flooded) used in defining hydric soils, making it possible to easily classify, and distinguish between, hydric and non-hydric soils.

2.7.2 South Africa

The South African soil classification system (Soil Classification Working Group 1991) is a simple system that uses two levels of classes i.e. an upper more general level of soil forms and a lower more specific level containing soil families (Kotze *et al.* 1996a). Each form is identified by a unique sequence of diagnostic horizons. Nowhere in the South African soil classification system is the soil moisture regime required for the classification of soils, unlike in the American system (Kotze *et al.* 1996a). There is also no standard procedure for describing soil drainage classes and no system has been developed for categorising soil water regimes. Instead it is possible to infer this information from the nature and sequence of the diagnostic horizons in the individual soil forms (Kotze *et al.* 1996a). For example, according to Scotney and Wilbey (1983), cited in Kotze *et al.* (1996a), soil forms common to wetlands in Kwazulu-Natal include Champagne, Katspruit, Willowbrook and Rensburg. Kotze *et al.* (1996a) remarked that :

> 'The Taxonomic Classification System for South Africa (Soil Classification Working Group 1991) may be adequate for categorising wetland soils at a broad regional level, it is certainly not adequate for categorizing wetlands for management and farm planning purposes in the humid regions.'

The same group of researchers (Kotze *et al.* 1996b) did further work in the classification of hydric soils. It was suggested that, as a long-term objective, *Soil Taxonomy* (The American soil classification system) should be used in South Africa since it is widely used and it accounts for depth of waterlogging. These authors developed a provisional three-class system for determining the degree of wetness of wetland soils based on soil morphology that is outlined in Table 2.6.

Table 2.6 A provisional three-class system for determining the degree of wetness of wetland soils (Kotze *et al.* 1996b).

Soil depth (mm)	**Degree of wetness**		
	Temporary	Seasonal	Permanent/semi-permanent
0-100	Matrix chroma 0-3 Mottles few/nil Low/intermediate OC[1]	Matrix chroma: 0-2 Mottles common Intermediate OC	Matrix chroma: 0-1 Mottles nil/few High OC
300-400	Mottles few Matrix chroma: 0-2	Mottles common/many Matrix chroma: 0-1	Mottles nil/few Matrix chroma: 0-1

[1] High OC : soil organic carbon levels are greater than 5%, often exceeding 10%
Low OC : soil organic carbon levels are less than 2%

Kotze *et al.* (1996b) stress that this is a provisional system that has not been extensively tested and that ongoing research is required in this field of study in order to update the South African Soil Classification to specifically include wetland soils. *Soil Taxonomy* is somewhat more complicated than the South African system and is unfamiliar to most South African soil classification users. Simpler methods of identifying hydric soils in South Africa would therefore be useful in wetland identification and delineation.

2.8 The importance of wetland delineation

As discussed in Section 2.5, wetlands perform important functions and need to be protected from any activity (mostly human) that will detrimentally affect their functioning. Wetlands that are used for grazing, harvesting or fishing also need to be managed correctly to avoid over-exploitation (Braak *et al.* 2000). Part of these protection or management plans involves mapping the wetland so that it is clear where the wetland ends and dryland begins. This is particularly important in commercial activites such as forestry or crop farming. If trees or crops are planted too close to the wetland they use up much of the water and this interferes with the functioning of the wetland. By undertaking a wetland survey and accurately delineating a boundary, human activities such as forestry can still be practised but any wetlands within the forest area can still function correctly and provide areas for biodiversity conservation (Hails 2000).

2.8.1 Current methods used for delineation

As with their hydric soil classification, the Americans are the current leaders in wetland delineation methods (Lyon 1993; Faulkner *et al.* 1995). The USDA-NRCS has published a substantial document entitled 'Field Indicators of Hydric Soils in the United States', the latest version to date being version 4, March 1998 (USDA-NRCS 2001). This document has been developed by soil scientists of the Natural Resources Conservation Service (NRCS) in cooperation with the US Fish and Wildlife Service (FWS), the US Army Corps of Engineers (COE), the Environmental Protection Agency (EPA), various regional, state and local agencies, universities and the private sector. It is a comprehensive guide to help identify and delineate hydric soils in the field.

Since the promulgation of the National Water Act No.36 of 1998 in South Africa, much work has been done on developing a field method for delineating wetlands. Prior to 1998 there was little incentive to delineate and protect wetlands but now it is illegal to disturb or destroy a wetland. A study was carried out in September 1999 as part of the initial stage of the development of a protocol for determining the Ecological Reserve for Wetlands, the aim being to develop a set of guidelines that could be used nationally to delineate wetlands (Marnewecke & Kotze 1999). This document was used, together with a series of 3 workshops involving government departments, the private sector, the University of Natal and non-government organisations, to develop a document entitled 'Wetland / Riparian Habitats : Practical Field Procedure for Identification and Delineation'. The procedure involves classification and delineation according to soil, terrain and vegetation criteria. According to the authors, the procedure has proved to be simple, effective and affordable and can be used by non-specialists who have aquired some elementary training and experience (Land-Use and Wetland/Riparian Habitat Working Group 1999).

2.9 Using soil magnetic susceptibility measurements for wetland delineation.

2.9.1 The effects of gleying on susceptibility

It has been observed that gley soils have low susceptibility values (Thompson & Oldfield 1986). Under gleyed conditions, a reducing environment prevails and both primary and secondary forms of ferrimagnetic minerals are dissolved. They can remain in solution and are often leached out of the profile (Section 2.6). These results seem in conflict with the persistence of ferrimagnetic oxides in stream, lake and marine sediments (Thompson & Oldfield 1986) but gleyed conditions differ in that their oxygen supply is used up by organic matter oxidation (breakdown) and is not replaced as rapidly as it is used up. A variety of bacteria are present that can operate in anaerobic conditions, reducing iron oxides to non-crystalline forms which are removed from the profile.

2.9.2 The persistence of magnetic oxides

Iron compounds are very sensitive to changes in soil conditions and this is clearly evident by the changes in soil colour due to the presence or absence of certain iron minerals observed by pedologists. It seems unlikely then that magnetic oxides would retain their characteristics during transport, deposition, or changing soil processes but evidence is available that is strongly in favour of a degree of persistence of magnetic oxides in soils and sediments (Thompson & Oldfield 1986). Magnetic archaeological studies have shown that iron oxides can persist for very long periods, provided that gleying has not occurred or the pedogenic regime (long-term conditions under which the soil is formed) has not changed drastically (Thompson & Oldfield 1986).

2.9.3 Basis of the approach.

Magnetic minerals consist largely of iron oxides. The magnetic susceptibility of soils is directly related to the concentration of magnetic minerals present, as well as their grain size and shape. Most magnetic susceptibility changes are due to variations in the concentrations and grain sizes of magnetite and maghaemite (Grimley & Vepraskas 2000) (Section 2.4). Waterlogged soils tend to have a lower iron mineral concentration since ferrimagnetic minerals are reduced and leached out of the profile (Section 2.6). Theoretically then, hydric soils should exhibit lower magnetic susceptibilities than non-hydric soils where the ferrimagnetic minerals are in the oxidised state and less soluble.

Grimley and Verpraskas's (2000) objective was the same as the objective presented in this project : to compare changes in MS values across wetland/hydric soil boundaries to changes in the hydric soil field indicators. If the MS values can be correlated with hydric soil field indicators, then MS would have potential in delineating hydric soils in the field. Grimley and Verpraskas (2000) also wanted to develop a method that could be used when field indicators are difficult to identify, such as when an organic topsoil is present. These researchers selected 6 study sites with different parent materials namely loess, lake plain and till, glacial outwash and till and coastal plain sediment. Most of the sites were located in Illinois in the United States. At the first five sites, hydric soil field indicators were identified and volumetric MS measurements made along transects that included the wetland centre, edge and upland. At each plot along the transect a pit was dug (40cm depth). The soil profile was described and if hydric soil indicators were present it was labelled 'hydric', if not, then 'non-hydric'. Triplicate MS measurements were done at depths 0-15cm and 15-30cm using the Bartington MS2F probe. Analysis of variance was used to determine whether the hydric soil values were significantly different to the non-hydric MS values. Significant differences ($P<0.01$) in MS (magnetic susceptibility) were found between hydric and non-hydric soils when sites were grouped by parent material and the two depths were analysed seperately (Grimley & Verpraskas 2000).

The sixth site was used to test the possibility of measuring MS at the surface only. A site was selected where there were small changes in topography and field indicators were difficult to identify. Two transects were used to determine the critical value and then this value was used to identify the boundary on another transect. The results showed that the MS method was accurate in delineating the boundary. Figure 2.4 shows how, in this example, a critical value of 30 x 10^{-5} SI would be used to separate hydric and non-hydric soils. Grimley and Verpraskas (2000) found that magnetic susceptibility measurements can be used in the same way as field indicators along transects, as long as the critical value that separates hydric soils from non-hydric soils is known. These critical values have to be determined on site by comparisons between magnetic susceptibility readings and field indicators. Grimley & Vepraskas (2000) also computed this value statistically, using a histogram, and although this method is very accurate it is unlikely to be necessary in most delineation exercises.

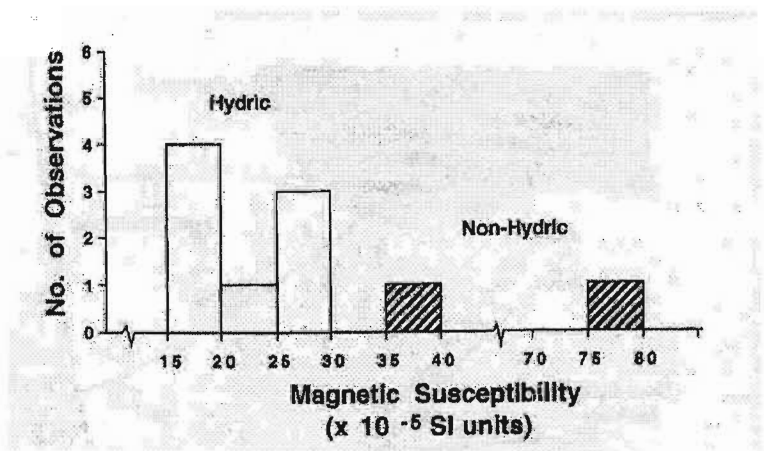


Figure 2.4 Distribution of MS values for hydric and and non-hydric soils collected at the surface of plots in transects I and II of site 6 studied by Grimley and Verpraskas (2000).

Williams and Cooper (1990) proposed that soil drainage (partly related to soil texture) may be the primary factor controlling the MS distribution across the landscape. They came to this conclusion after conducting a study on the use of MS for the delineation of any soil boundary, not only hydric soils. A transect through an ephemeral drainageway was selected and topsoil samples were taken at 1m intervals. Soil boundaries were mapped along the transect by the Soil Conservation Service. Various soil analyses were done, including specific mass magnetic susceptibility. The data were analysed using semivariograms and plots of semivariance versus distance. The following quote summarises the findings of this study :

> 'The results presented here demonstrate that magnetic susceptibility clearly defines the boundaries among the soils identified along the transect. Further, the results indicate that magnetic susceptibility is related to texture (particularly sand content), parent material, and drainage characteristics. Generally magnetic susceptibility values decreased with decreased elevation and were smaller on the more poorly drained soil.' (Williams & Cooper 1990)

The results of these two studies show that the method does work. It was not therefore necessary to repeat any of the work already undertaken; the aim of this project was to build on it and also adapt it for South African conditions. In designing the methodology it was decided that, although Williams and Cooper (1990) found that MS readings in poorly drained soils were generally lower, Grimley and Verpraskas's (2000) work would be a more useful base for the study planned for Kwazulu-Natal since the focus was specifically on wetland soils.

Since no work had been done in this field in South Africa prior to this study, it was difficult to plan a rigorous methodology without having some knowledge of how to operate the MS meter, what type of readings to expect and how the various sensors react. A preliminary methodology was designed around that of Grimley and Verpraskas (2000) which was then modified twice before a final method was designed. The aim of this project was to use the American researchers' experience to test the method in South Africa and also to develop a quick, user-friendly field method to delineate wetlands. The quickest MS method to use is the MS2D loop sensor at the surface and so this method was adopted rather than the MS2F sensor used by Grimley and Verpraskas (2000). A similar site selection process was followed to that of Grimley and Verpraskas (2000), where areas with different parent materials were selected in order to assess where the method was likely to be most successful. As mentioned by Grimley and Verpraskas (2000), site variations make it impossible to form general conclusions about particular areas without a large amount of data. A recommendation was to build up enough data to determine general critical values for parent materials.

2.9.4 Advantages of developing an MS method

The method would be useful for wetland conservation since wetlands can be quickly and accurately mapped. A database of maps of all the wetlands in a particular area could be created easily and quickly. Magnetic susceptibility measurements could be used as preliminary survey tools, perhaps together with other tools such as air photos for a quick reconnisance survey, that would still be fairly accurate, to be carried out when time and money is short i.e. too short to conduct a full field survey using the current, somewhat subjective, procedure (Section 2.8).

Another situation where the method could be useful is when altered wetlands need to be delineated, for example when the original vegetation has been removed and replaced by pasture. It could also be useful when hydric soil indicators are difficult to identify, such as in the case of humic, melanic or vertic horizons (Grimley & Verpraskas 2000).

2.9.5 Problems and disadvantages

It is difficult to assess the extent of the disadvantages of this method since very little practical work has been done. Thompson and Oldfield (1986) suggest that since the parent materials of soils consist of different rocks and other materials. Therse rocks and materials are composed of different minerals in different quantities and this affects the composition of the magnetic minerals in soils even if they are formed under the same weathering processes. It is therefore important to note the geology of an area before undertaking magnetic susceptibility measurements since any differences might be influenced by parent rock type rather than chemical and physical conditions for example the water regime.

CHAPTER 3

The development of a methodology for wetland delineation using magnetic susceptibility

3.1 Introduction

Since the technique being investigated is still in its formative stages, the methodology was developed as the field work progressed. The methodology was divided into 3 main phases, the first being the reconnaissance work, the second a more detailed transect method and the third a grid method. A description of the methodology undertaken at each site is followed, in Chapter 4, by a sequential representation of the results. This provides the best explanation of how the various methods were developed, based on the results at each stage.

3.2 MS Instrument

The Bartington Instruments Magnetic Susceptibility System (MS2 Meter, MS2D Sensor, MS2F Probe) was used. The MS2D sensor was used the most since it enables quick surface measurements although some work was done with the MS2F sensor for comparison. The MS2F sensor is more sensitive and takes longer to give readings. Since the equipment was on loan in the initial stages of the study, the MS2F sensor was only available for the reconnaissance phase of the fieldwork. As mentioned in Chapter 1, the technical specifications for the Bartington Susceptibility System are included in Appendix 1. Plate 3.1 shows how the instrument was used with the meter carried in a shoulder bag and attached to the sensor using a cable.

Table 3.1 gives the resolution and sensitivity of the D loop and F probe. These two sensors work on the same principle, a magnetic field produced around the tip of the probe or the circular part of the loop detects the magnetizability of the material within the field (Dearing 1999). The strength of the magnetic field and hence the sensitivity of the sensor diminishes exponentially with distance away from the sensor. For example, in a well-mixed soil either sensor will detect 90-100% of the susceptibility of material within the uppermost 2-3mm (Dearing 1999).

Table 3.1 Resolution and sensitivity of the D loop and F probe (Dearing 1999).

Sensor	Surface area	Sensitivity at different distances from the surface			
		90%	75%	50%	10%
D loop	268.7cm^2	2mm	5mm	15mm	60mm
F probe	1.8cm^2	2mm	2-3mm	3mm	6mm

Example : 50% of the signal comes from within the uppermost 15mm under the surface with the D loop, but only from within the uppermost 3mm and 1mm in the cases of the F probe.

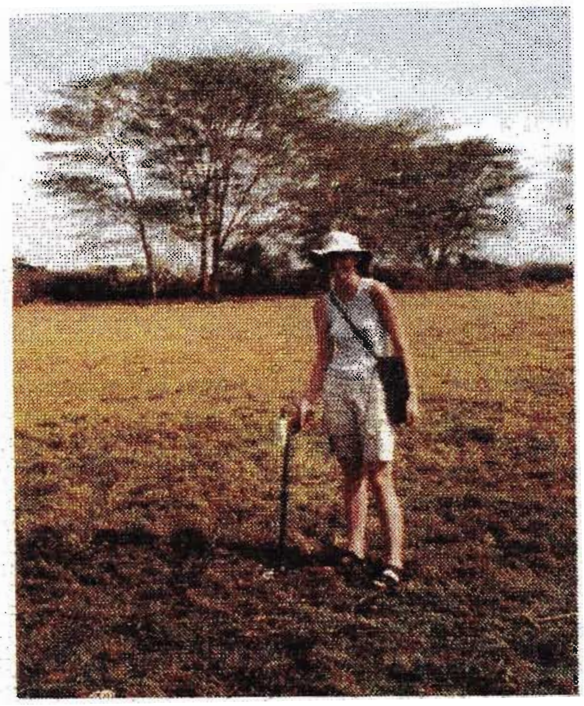


Plate 3.1 A demonstration of how the MS meter is carried in the field.

3.3 Initial methodology to test viability

3.3.1 Study sites

The broad study area consisted of the province of KwaZulu-Natal, South Africa. The geology of the province consists of a combination of sedimentary, igneous and metamorphic rocks providing a varied range of parent materials. Commonly occurring parent materials and their dominant mineral compositions are as follows : shale (quartz, micas), granite (feldspars, quartz), coastal plain sediment (quartz, calcite), sandstone (quartz), basalt (feldspars, pyroxene), dolerite (feldspar, pyroxene), tillite (quartz, feldspar, other rock fragments) and crystalline schist (mica, chlorite) (Holmes 1978; King 1972).

KwaZulu-Natal has been divided into land types (Department of Agriculture and Water Supply 1998) based on terrain units, defined as 'any part of the land surface with homogenous form and slope', pedosystems, defined as 'land over which terrain form and soil pattern each display a marked degree of uniformity' and climate zones. Data have been collected for each land type based on the geology and soils. A study has also been done by Fitzpatrick (1978) entitled 'Occurrence and properties of iron and titanium oxides in soils along the Eastern Seaboard of South Africa'. Since iron oxides are important contributors to the magnetic properties of soils, this study provides much insight as to where MS measurements are likely to be more successful in the province.

Based on the information mentioned above, as well as a generalised soil map for the region, at least three sites were selected, differing in parent material and soil type. A description of the three sites follows :

Coastal wetland

The sites in this region were situated along the Nothern KwaZulu-Natal coast, in the vicinity of St Lucia / Sodwana Bay. The geology in the area consists of Cainozoic and Recent sediments (sea-bed sandstones and mudstones, limestones, loose sand) and Cretaceous sediments (also sandstones, some enriched with minerals brought downstream by rejuvenated rivers) (King 1972). Fitzpatrick's generalized soil map (1978) shows that the soil types in this area consist of grey and red sands. The red sands developed when fresh feldspar was brought to the coast from the 'granite belt' by rivers. Weathering converted the feldspar into kaolin clay, dissolved the lime, oxidized the iron-bearing minerals to haematite which now coats the silica grains, giving them a red colour (King 1972). The study sites consisted of grey sands that are very low in iron. Fitzpatrick (1978) compiled a map showing the distribution and abundance of maghaemitic concretions in KwaZulu-Natal (Figure 3.1). Since maghaemite is one of the major contributors to the magnetic component of soils, this map gives an indication of the magnetic-mineral content of the soil. This map indicates that the distribution and abundance of maghaemitic concretions in this Northern coastal region is absent to very few.

Floodplain wetland, silt deposit (Pongola river floodplain)

The parent material in this area is made up of the Ecca, Beaufort and Dwyka Series and consist of shale, sandstone, granites, gneisses, mica and kyanite schists, lavas, hornfels and quartzite. It forms a sedimentary mixture deposited by ancient glaciers (King 1972). The soils are mainly weakly developed (lithocutanic B horizons), plinthic and some red and black clays and duplex soils (Fitzpatrick 1978). As the river gets closer to the sea, it flows through black clays, red structured clays and duplex soils (Fitzpatrick 1978). The distribution and abundance of maghaemite concretions is described as few (1-3%) and absent to very few (Fitzpatrick 1978).

Inland site (Natal Midlands / Drakensberg)

The Ecca and Beaufort series dominate in this area with the predominant geology consisting of shale, sandstone and dolerite intrusions (King 1972). The soil types are red apedal, mesotrophic clays to yellow apedal loams; yellow and red apedal, freely drained, dystrophic soils; yellow and grey hydromorphic, mesotrophic sands and loams; some red clays and duplex soils (Fitzpatrick 1978). The maghaemite abundance map shows that concretions are common (>5%).

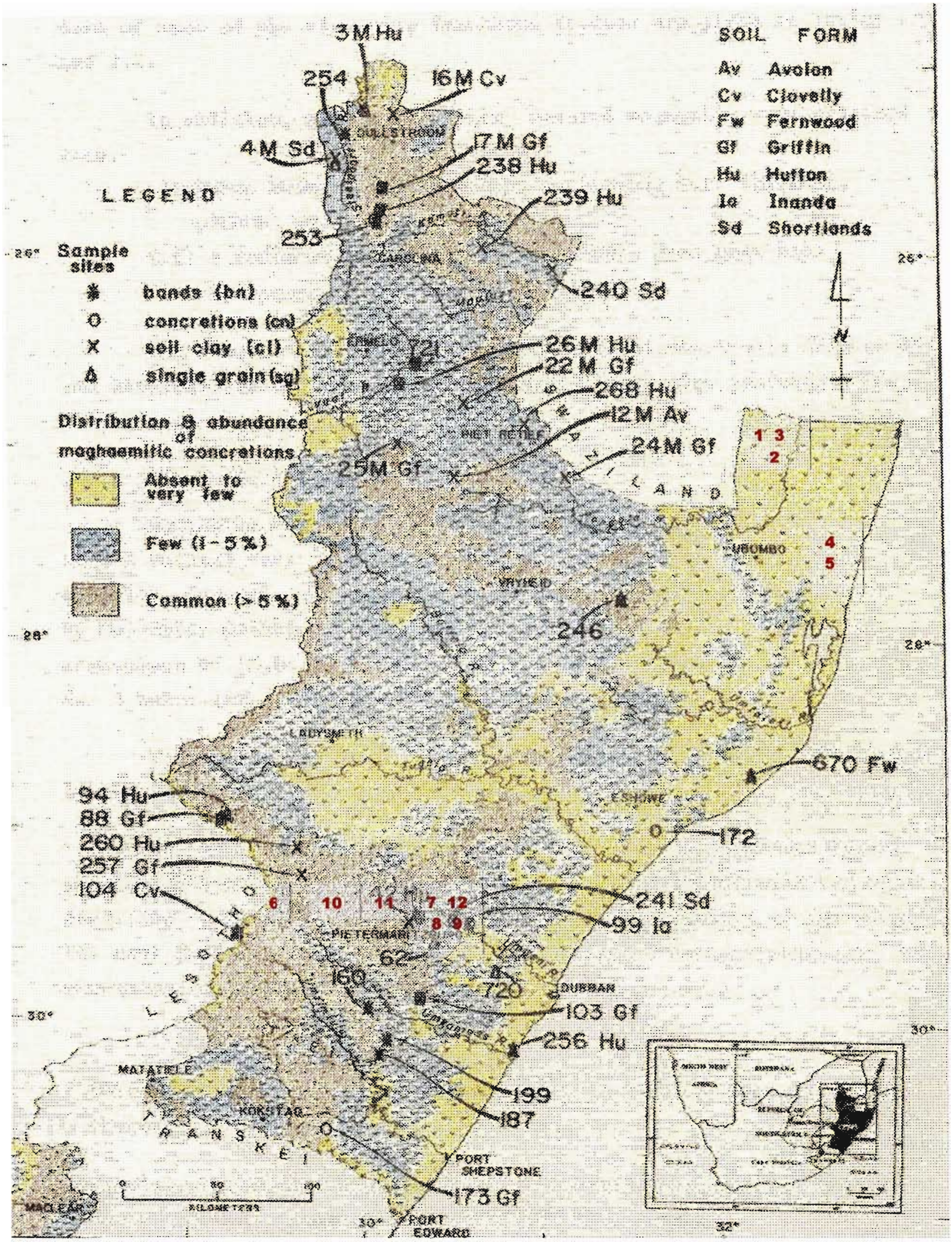


Figure 3.1 A map of KwaZulu-Natal showing sampling sites of various magnetic minerals, distribution and abundance of maghaemite concretions (*after* Fitzpatrick 1978). The red numbers are the approximate site locations indicated in Table 3.2, 10, 11 and 12 are the Mooi River, Midmar and Oribi grid sites respectively.

3.3.2 Methods used at each site

Table 3.2 below gives a summary of all the study sites and methods that were used and a more detailed description of the methods follows :

Table 3.2 Reconnaissance field work in Pongola, Sodwana and the Natal Midlands.

Area	Site No.	Site Name	Location	Site Type	Parent Material	MS[1] only	Samples[2], MS	Level[3], MS, No samples	Level, MS, Samples
Pongola	1	Bubhe	S26°59.812' E32°18.041'	Floodplain	Silt deposit, sedimentary mixture	1 (one bank) (MS2F)	1[4]	0	0
	2	Sokhunti	S27°01.447' E32°17.845'	Floodplain	Silt, sand	2 (opp banks)	2	0	0
	3	Nomaneni	S26°59.218' E32°16.662'	Floodplain	Silt, rhyolite ridge	none	2	0	0
Sodwana	4	Mkuze	S27°35.061' E32°28.512'	Coastal	Regic sand	1 (one side)	2	1	0
	5	Yengweni	S27°37.913' E32°25.924'	Coastal	Regic sand	1	1 (two tongues)	0	0
Natal Midlands	6	Highmoor	S29°19.352' E29°36.904'	Inland	Basalt Basalt	1 1	0 0	0 0	0 0
	7	Oribi	S29°39.122' E30°24.340'	Inland	Shale	none	2	0	0
	8	Hesketh	S29°39.166' E30°24.323'	Inland	Shale	none	1	0	0
	9	Shafton	S29°27.129' E30°14.768'	Inland	Dolerite	none	1	0	1

[1] MS refers to magnetic susceptibility readings taken along a transect perpendicular to the water's edge

[2] Soil samples were taken along the similar transects, often the same transects, to correspond with MS readings in the various wetland zones.

[3] A dumpy level was used to obtain elevation readings at 1m intervals on certain transects.

[4] The numbers indicate the number of transects sampled in the same way at each site.

Site 1, Bubhe Pan, Pongola

The MS meter was used for the first time at this site. The site was fairly flat with a zone of reeds at the water's edge was followed by a zone of short grass and then a line of Fever trees. Plate 3.2 shows the site and the transect line from the Fever trees (*Acacia xanthophloea*) to the water's edge.

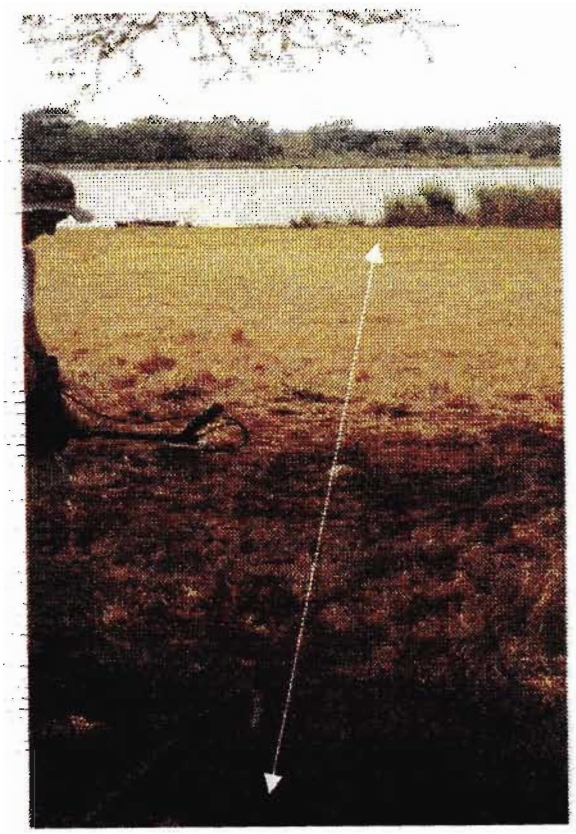


Plate 3.2 Bubhe Pan showing the transect line from the Fever trees to the water's edge.

A transect running from the water's edge up into a fenced tomato field was chosen and readings were taken at 1m intervals to get an idea of how the meter operates (using the MS2D loop sensor) and the range of values that could be expected for that area. A '*Cynodon spp* test' was carried out to determine if the MS readings are affected by a layer of grass. Readings were taken over the grass cover and again on the same site with the grass cleared i.e. in direct contact with the soil surface. It was decided that the grass would be cleared to reveal a bare soil surface for each reading since the sensitivity of the meter decreases with distance from the soil. (Table 3.1). It was also decided that three readings should be averaged for each point due to variation in readings for the same point. The same transect was then walked again but each point was cleared of grass and triplicate readings were taken. Soil samples were taken at five of the points, according to which vegetation zone they fell in and where the MS readings increased/decreased. An auger was used to extract a sample from the top 20cm and a sample from a depth of 20-40cm. The MS2F sensor was used to take readings at the same points along the same transect in order to compare the values. The MS data for all the sites is included in Appendix 2.

Based on the MS2F data and the visual vegetation zones, a 'zone investigation' was done. Approximate MS boundaries were estimated by subjectively grouping the MS values between limits for each wetland zone e.g. MS readings below 35 for the permanent zone. These limits were then tested by selecting ten points in each vegetation zone. The ten points were averaged and graphed to get an idea of the range of MS values that can be expected in each zone.

Site 2, Sokhunti Pan, Pongola

Two areas were selected at this site, on opposite sides of the pan. Transect 1 (Plate 3.3) extended from the water's edge up a slope into dense *Acacia spp* bush. The second transect (Plate 3.4) was a flat transect extending from the water through a zone of small *Acacias* and into a thicket of trees.

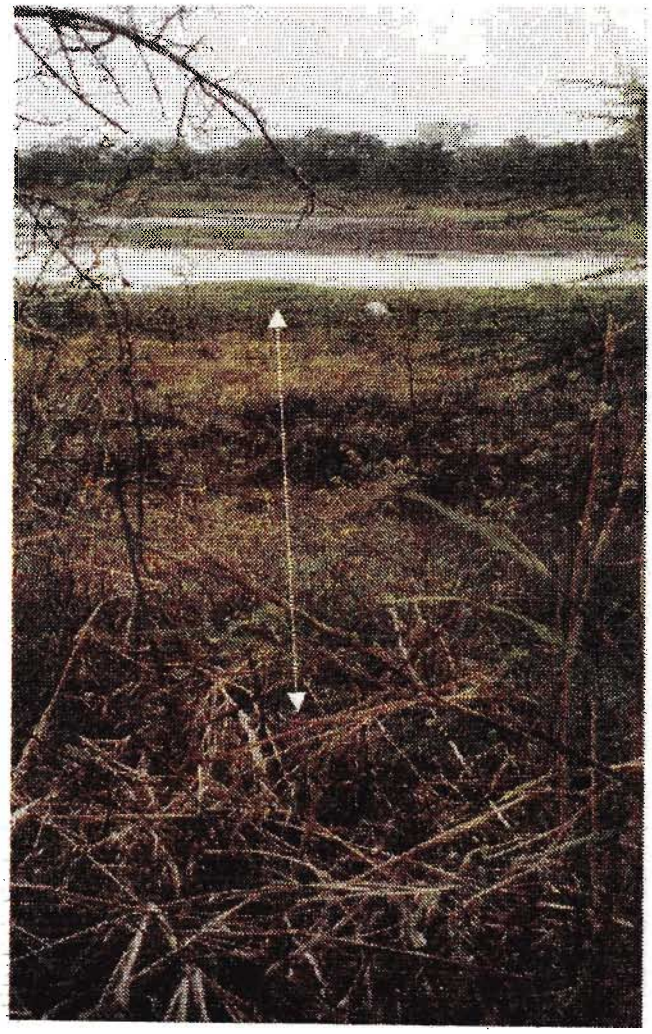


Plate 3.3 Sokhunti Pan. The line shows transect 1and the photograph was taken from the top of the slope.

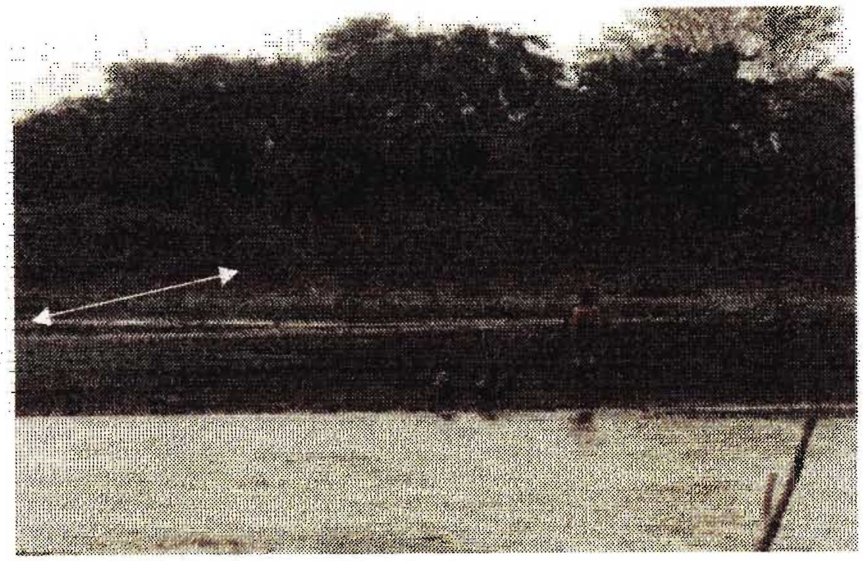


Plate 3.4 Sokhunti Pan showing transect 2.

The sites showed some disturbance as cattle were being grazed and fences had been erected in the wet mud near the water. Fishing nets and small boats were also visible. Zones were identified by vegetation changes and the MS2D loop sensor was used to take 10 readings in each zone. The readings were averaged and graphed. Transect lines were then identified at each site and readings and soil samples were taken (all readings and samples were taken in the same manner as described for Bubhe pan) at intervals between the water and the tree zones.

Site 3, Nomaneni Pan, Pongola

No reconnaissance work was done at this pan. Two sites were selected and transects were identified immediately. The first site, transect 1, (Plate 3.5) extended from the water's edge along a flat grass zone and then up a steep slope. The slope was identified as a rhyolite ridge. The second site was away from the ridge and was flat, extending from the water into a band of Fever trees. Soil samples and MS readings were taken in each zone along a transect.

Plate 3.5 Nomaneni Pan showing transect 1 taken from the water's edge and facing the rhyolite ridge.

Site 4, Mkuze Wetland, Sodwana

The section of Mkuze wetland studied is shown in Plate 3.6 below. It was a narrow strip of wetland situated in a small valley and it had been recently burnt.

Plate 3.6 Mkuze wetland, the white line shows the study transect.

A transect was done through the wetland from the one side of the small valley and up the slope on the opposite side. Firstly, MS readings were taken at 1m intervals in order to identify the MS boundaries ('reconnaissance' transect) Two 'detailed' transects were then done, also through the wetland to include both banks. Magnetic susceptibility readings and soil samples were taken in each vegetation zone, triplicate MS readings using the loop, as well as a level reading, were taken at 1m intervals. This was to give an indication of how the MS values corresponded with slope position. The vegetation zones were identified by observing changes in vegetation, usually from grasses and reeds at the water's edge to small trees and then to a zone of tall trees further away from the wetland.

Site 5, Yengweni Wetland, Sodwana

Two sites were selected at Yengweni Wetland, one extended across two tongues of wetland with a section of dry land between them; the other site was a flat bank leading to the edge of a pan. A transect was done through the two tongues and soil samples and MS readings were taken in the changing vegetation zones. The transect up to the edge of the pan involved MS readings only.

Site 6, Highmoor, Natal Midlands

This site, Highmoor nature reserve, is situated in the Drakensberg mountain range and the parent material is basalt. As mentioned in section 3.3.1, this parent material has a high iron content when compared with the Pongola floodplain and the coastal sediments. This site was chosen as a comparative study (high iron mineral content compared with the lower iron mineral contents of Pongola and the Northern KwaZulu-Natal coast). Two sites were selected, one was a seep on the side of a slope (Plate 3.7) and the other was a wetland at the edge of a dam (Plate 3.8). A tape measure was used to mark transects through the wetlands and MS readings were taken at points along the tape. No soil samples were taken at either site because of the protected status of the area. It was not possible to obtain permission to take samples since the officer in charge was away. Time was limited so only MS work was done.

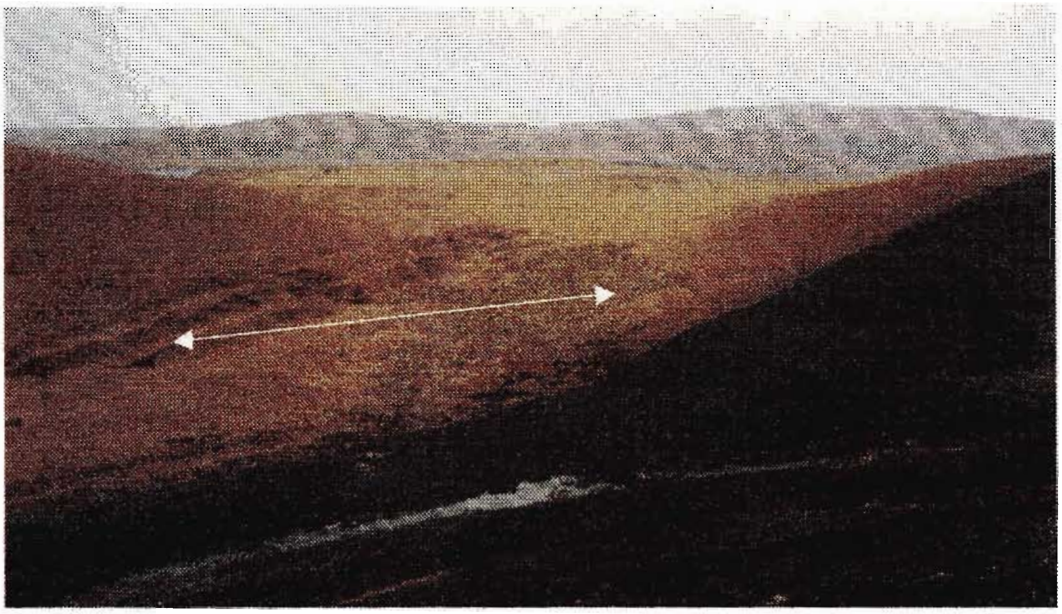


Plate 3.7 The seep site at Highmoor, the line shows where the transect was positioned.

Plate 3.8 A transect, marked by the tape measure, through the dry wetland adjacent to the dam at Highmoor.

Site 7, Oribi Wetland, Natal Midlands

This wetland (Plate 3.9) is situated near the Oribi Airport in Pietermaritzburg and the parent material is shale.

Plate 3.9 Transect 2 through the recently burnt site at Oribi.

Two transects were marked through the wetland using a tape measure and triplicate MS readings and soil samples for depths 0-20cm and 20-40cm were taken in each vegetation zone. This site had also been recently burnt.

Site 8, Hesketh Wetland, Natal Midlands

This wetland is situated in a conservancy in the residential suburb of Hayfields in Pietermaritzburg. The parent material is shale (Plate 3.10). One transect was marked from the edge of the water up to a road that ran alongside the conservancy. Magnetic susceptibility readings and samples were taken at intervals along the transect between vegetation changes. The vegetation was used as an indicator to identify the permanently, seasonally and temporarily wet zones.

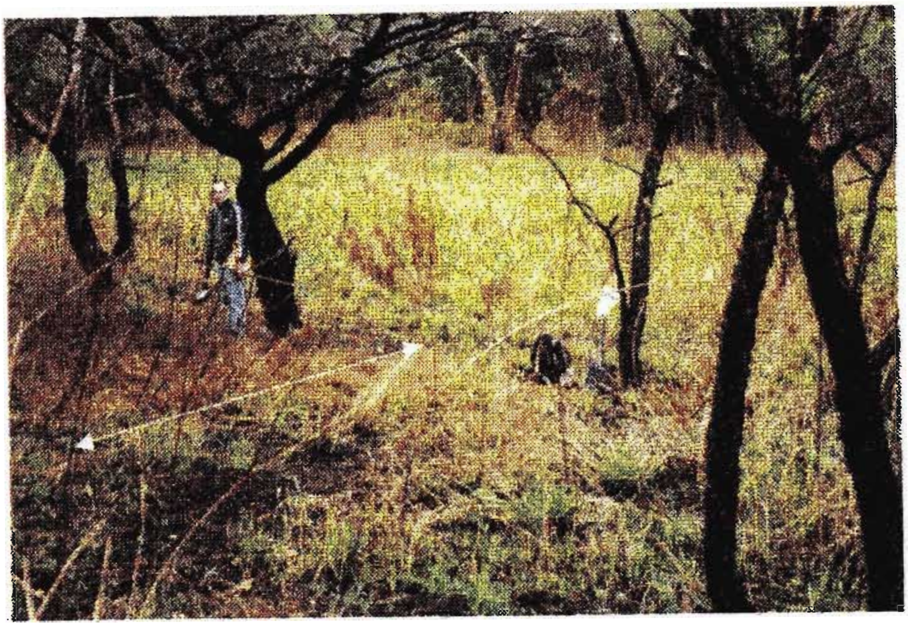


Plate 3.10 The wetland at Hesketh Conservancy showing the transect line.

Site 9, Shafton Wetland, Natal Midlands

This wetland was situated in a forestry plantation near Howick in the Natal Midlands. The parent material was dolerite. Two transects were marked, both from the edge of the water up a slope into recently harvested trees (Plate 3.11). A road ran through both transects.

Plate 3.11 The wetland at Shafton plantation.

Magnetic susceptibility readings readings were taken at 1m intervals along the first transect and soil samples were taken in each zone visually identified by vegetation changes. The second transect was done in the same way but level readings were also taken at 1m intervals. As at Mkuze wetland, this was done to give an indication of how the MS readings related to slope position.

3.3.3 Soil Analysis

The soil samples collected in phase 1 of the field work were all stored in plastic bags in their moist state. Upon return from the field, the colour of each sample was recorded using a Munsell colour book. The presence of mottles was also noted, as well as their chroma (high or low). The soil form was identified if possible according to the South African Soil Classification System (Soil Classification Working Group 1991). The colour in the wet state was also recorded. Each sample was then air dried and the colour in the dry state recorded. The soil data were summarized for each study site and are included in Appendix 3. Shafton and Hesketh were excluded altogether, as well as the dry colours for Bubhe and Sokhunti pans since a new methodology had been developed while the soil analysis was being done. The remaining samples were not analysed since the results would not have been useful for the new method.

3.4 Revised transect methodology

3.4.1 Introduction and study site

Based on the results from the initial field work, a second more detailed methodology was planned. This formed the next phase in the investigation, hopefully to develop a specific method for using MS to identify wetland boundaries. It involved a closer analysis of the boundary area only, rather than all the wetland zones. The fieldwork was carried out on a farm, near Mooi River in the Natal Midlands. The wetland studied was upstream of a dam (Plate 3.12).

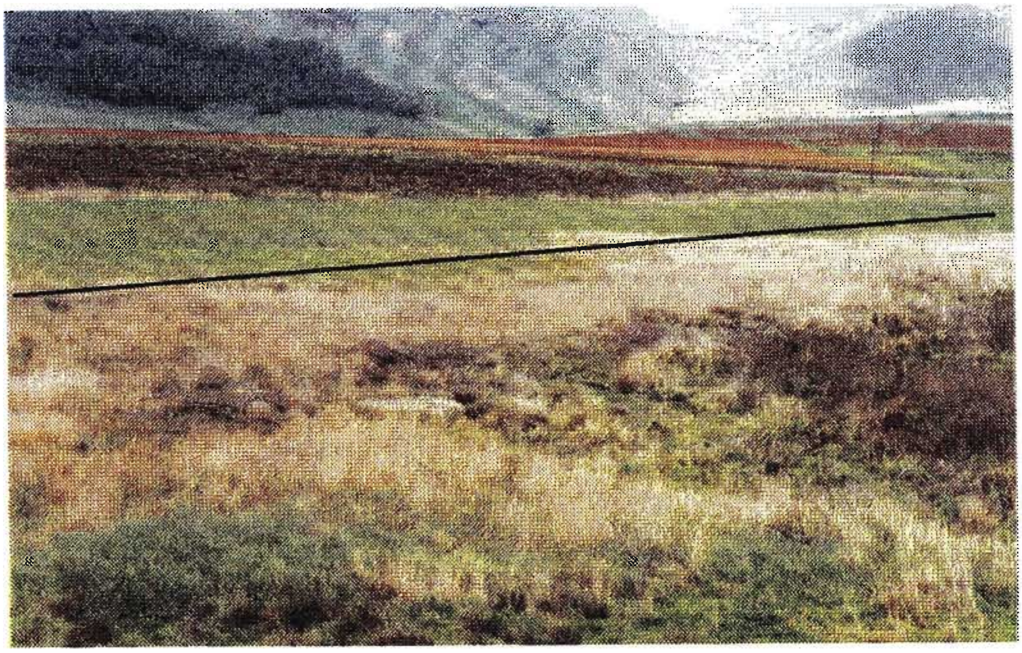


Plate 3.12 The wetland site near Mooi River in the Natal Midlands, the black line shows the edge of the permanently wet zone.

3.4.2 Transects

The first step involved a study of the slope and grasses. It was noted that the wetland was situated in the catchment of a dam on a small floodplain bounded by gentle slopes. The upper part of the slopes were under forestry and the trees had been recently harvested. The wetland zones were identified by looking at changes in vegetation and specific grass species (Land-Use and Wetland/Riparian Habitat Working Group 1999). Sedges predominated in the permanent/seasonal zone, *Eragrostis plana, Aristida junctiformis* and *Imperata cylindrica* were identified in the temporary zone.

The MS boundary was located using transects as follows. Four transects (Figure 3.2 T1-T4) were done from the non-wetland area across the temporary zone into the seasonal zone to try and identify if / where the MS readings decreased to below a certain level (the critical value). A tape measure was used to mark the transects (approximately 35m each) and MS readings were done at 1m intervals. On completion of each transect, a point on the tape was identified where the boundary was thought to be (where the readings dropped suddenly and remained low). A marker was left at the spot. Completing the four transects left four markers along the suspected boundary (curved line). These four markers were then joined using the measuring tape to make an 80m marker along the suspected boundary.

Two more MS transects (T5 and T6) were then done parallel to the tape (suspected boundary where the readings dropped), on either side at a distance of approximately 2m from the tape to verify it's position (all the values along the transect on the non-wetland side needed to be above the critical value and all the readings on the wetland side needed to be below the critical value). Soil analysis was then done at 6 points, three on either side of the boundary (Figure 3.3, points 1-6). Criteria used to identify whether the soil could be classified as hydric or not included soil form, soil colour and soil wetness factor according to the Field Guide for Wetland Identification and Delineation (Land-Use and Wetland/Riparian Habitat Working Group 1999). The soil data is summarized in the results chapter.

Problems were experienced with this method, mainly due to the variability in readings given by the MS meter. This is described fully in the results and discussion chapters. A final, even more detailed method was therefore planned to try and improve the resolution of the MS boundary.

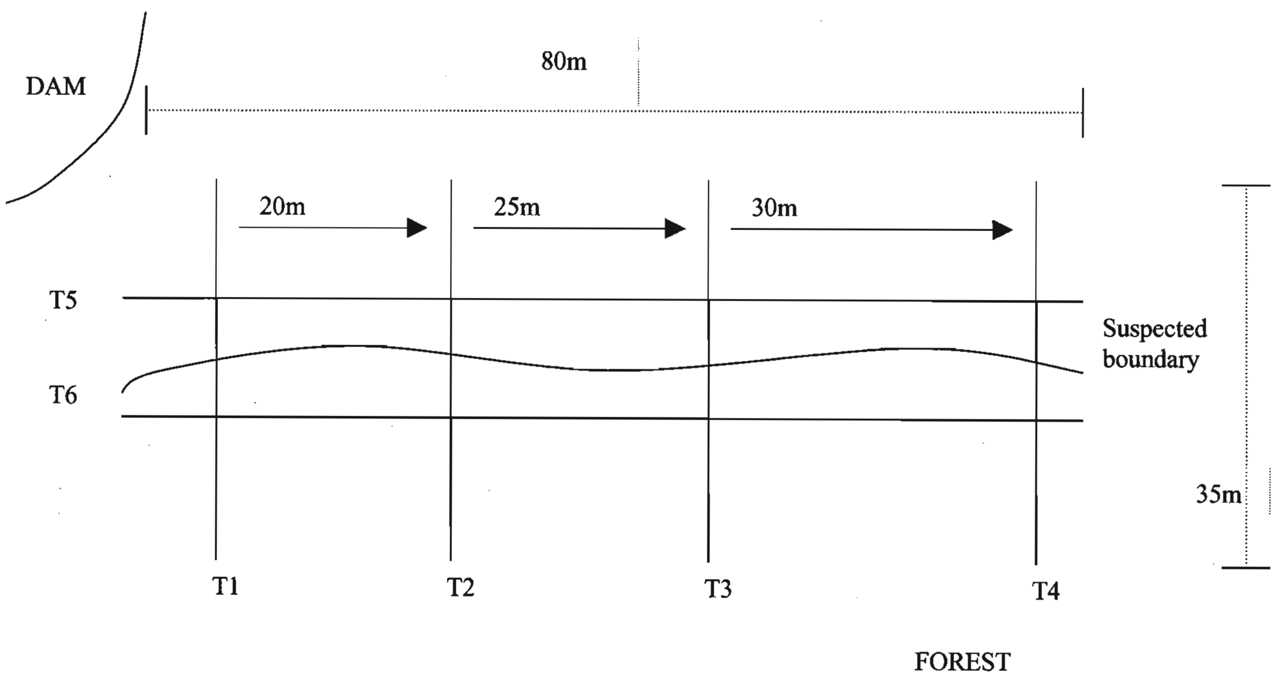


Figure 3.2 Transects studied near Mooi River, revised methodology.

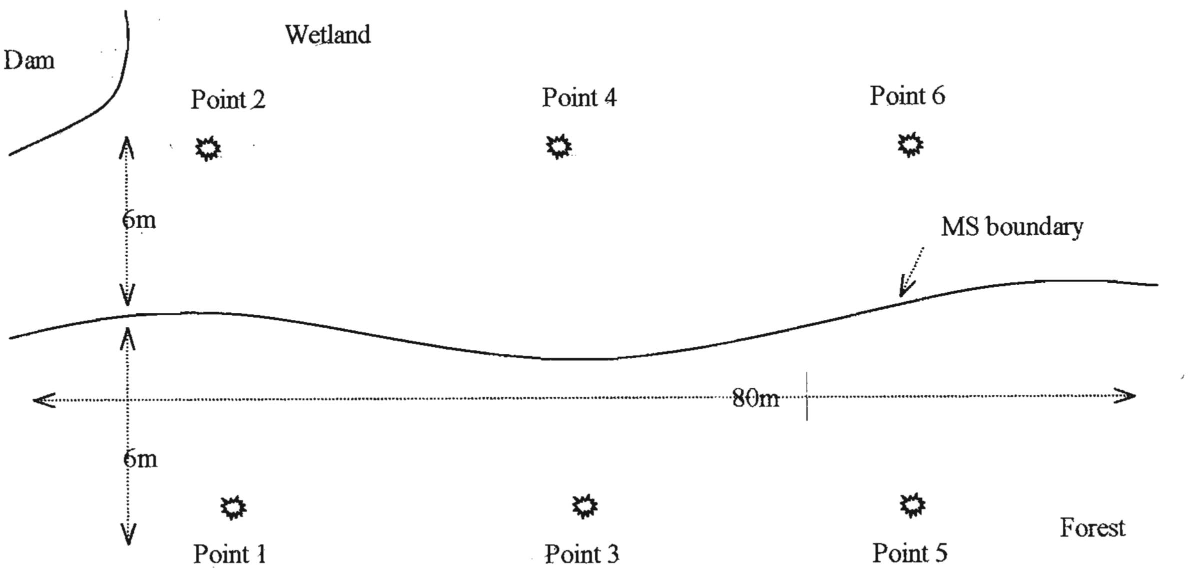


Figure 3.3 Points where field soil analysis was done to verify the MS boundary.

3.5 Grid methodology

Using all the experience and information gained about the MS meter in the first two methodologies, a final methodology was planned. It was aimed at describing the variation that occurs between readings in more detail. It was decided that a grid was needed to map the MS readings of a wetland at constant intervals. An undisturbed site at Midmar Dam in the Natal Midlands was selected (Plate 3.13).

Plate 3.13 The wetland site and grid at Midmar Dam.

As seen in Plate 3.13, sisal string was used to construct a 2m square grid, the grid ran 100m parallel with the boundary zone and was 50m wide. 100m and 50m tape measures were used to mark the frame, the string was secured into the soil using large nails, ensuring that the nails extended at least 30cm beyond the edge of the grid to avoid interference with the MS readings. Spray paint was used to mark the frame string at 2m intervals. The marks were then joined to form the grid. MS readings were taken at the intersections of the string i.e., at each corner of the squares, as shown in Figure 3.4.

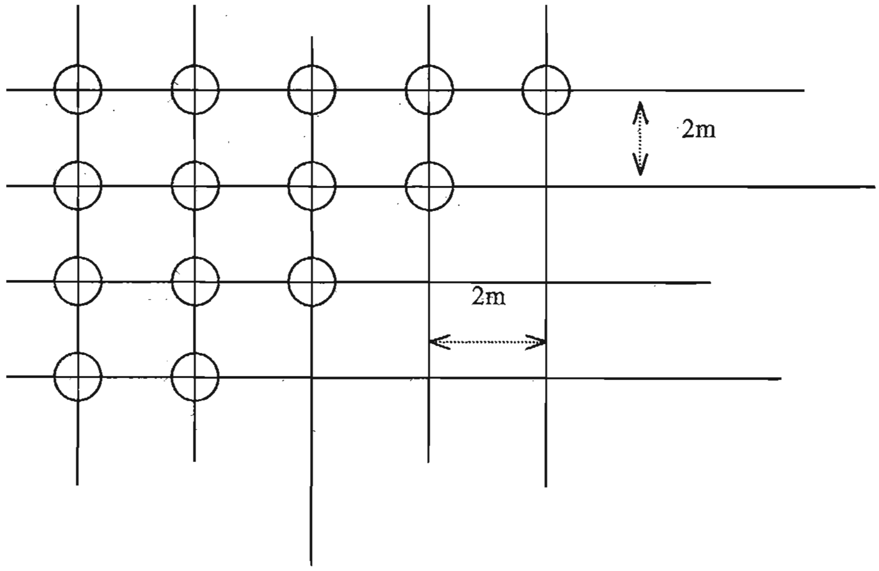


Figure 3.4 A section of the grid showing where the MS readings were taken (marked by circles).

The intention was also to do a level reading (a relative height using a dumpy level) at each point, and soil analysis to verify the boundary, but due to the poor MS results (related to the parent material, explained in Chapter 4), a new site was selected at Oribi airfield in Pietermaritzburg (Plate 3.14).

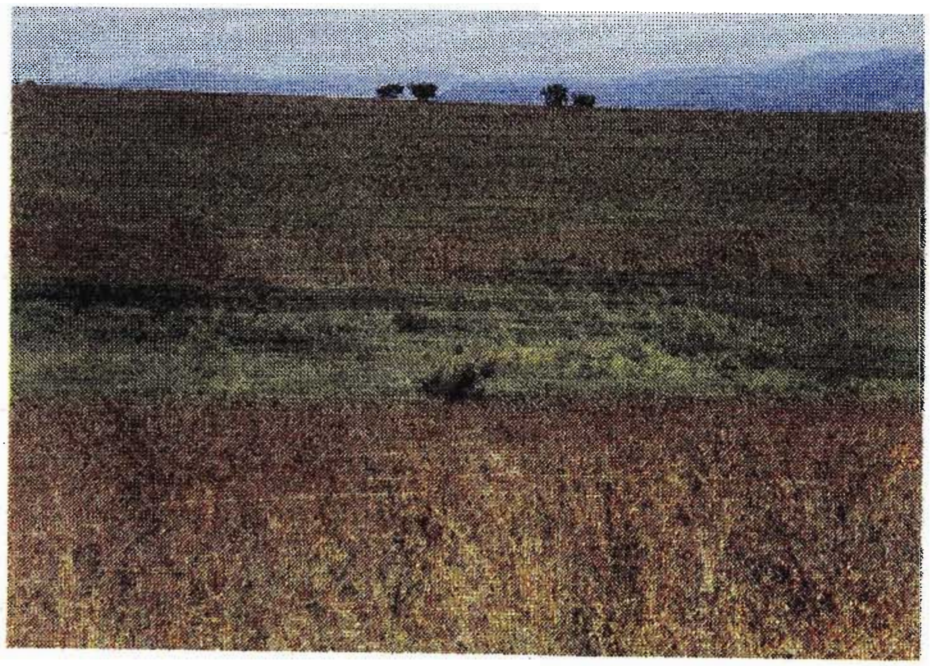


Plate 3.14 The final site at Oribi airfield showing the sisal string grid.

This was a smaller wetland so a long narrower grid was constructed right through it, to include the boundaries on both sides. The grid was constructed in the same way as the Midmar one, it measured 84m in length and 16m across. MS and level readings were taken at the points indicated in Figure 3.4. The MS grid was studied to locate the suspected wetland boundaries which were then marked on the ground. The field procedure was followed to identify whether the MS boundary coincided with the soil indicators. Six auger points were taken, three on each side of each boundary within the first block away from it i.e., within a range of 2m either side of the MS boundary. The grass species were also noted.

CHAPTER 4

Results

4.1 Initial reconnaissance work

As indicated in Table 3.2, the study sites were situated in three areas. Each site is discussed separately with general comments about the area at the end. Only the most relevant/representative MS data are presented. The MS readings and soil data for all the sites can be found in Appendix 2 and Appendix 3 respectively.

4.1.1 Pongola River Floodplain

Site 1 : Bubhe Pan

Table 4.1 gives the results from the '*Cynodon spp* test'. Taking readings over the grass results in lower, less consistent readings than if the grass is cleared. This is due to the fact that the sensor loses sensitivity with distance from its surface, if the area is largely taken up by grass and air the MS reading is reduced (Table 3.1). As mentioned in Chapter 3, the conclusion was therefore to always clear the soil surface of any debris to obtain the best contact between the sensor and the soil as possible.

Table 4.1 The effect of clearing the soil surface before taking an MS reading. Triplicate readings were taken at one point before and after grass removal.

MS readings without grass removal	mean	SD	MS readings with surface clearing	mean	SD
15.4	17.2	2.1	42.6	46.4	3.0
20.2			46.7		
16.0			49.9		

Figure 4.1 shows perhaps three rough MS zones i.e. a peak at the water's edge, a plateau an MS value of 50 as far as about 20m from the water and then an increase. These three zones corresponded with the three vegetation zones visible in Plate 3.2, namely the reed zone, the *Cynodon spp* meadow and the Fever tree zone. All the soil samples taken were within the wetland zones and classified as

wetland soils according to the field procedure (Land-Use and Wetland/Riparian Habitat Working Group 1999) (See Appendix 3). Figure 4.2 shows the results of using the MS2F probe sensor. This sensor generally gave lower readings than the loop and has a much lower depth of response but it also gives readings of a higher resolution (Appendix 1). The MS2F sensor was only used at Bubhe Pan, all the other readings were taken using the MS2D since the MS2D gives quicker readings and senses a larger soil area. Three MS zones were identified from Figure 4.2 : Permanent zone : MS below 35; seasonal/temporary zone : MS 35-100; non-wetland soil : MS above 100. These zones are specific to Bubhe Pan when using the MS2F sensor and were determined by correlating the observed vegetation with the MS readings obtained in that zone.

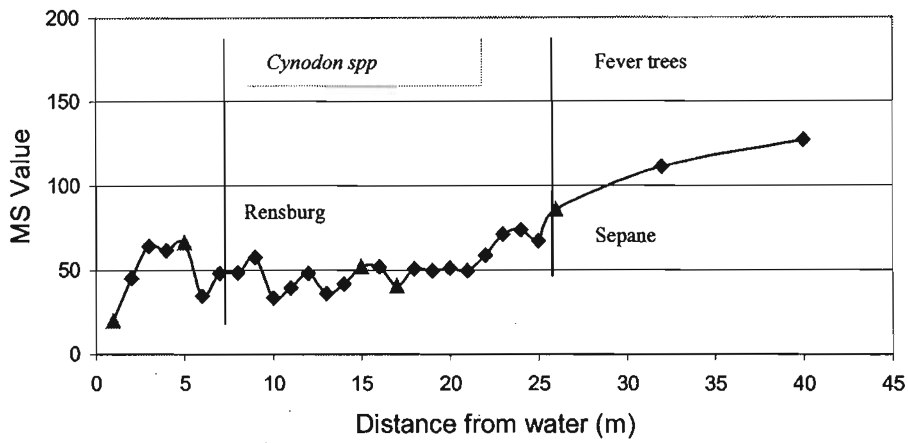


Figure 4.1 Bubhe Pan transect from the water's edge through the wetland zones using the MS2D (loop) sensor. The triangle points indicate where soil samples were taken, Rensburg and Sepane are the soil form names, both are considered to be wetland soils (Land-Use and Riparian Habitat Working Group 1999).

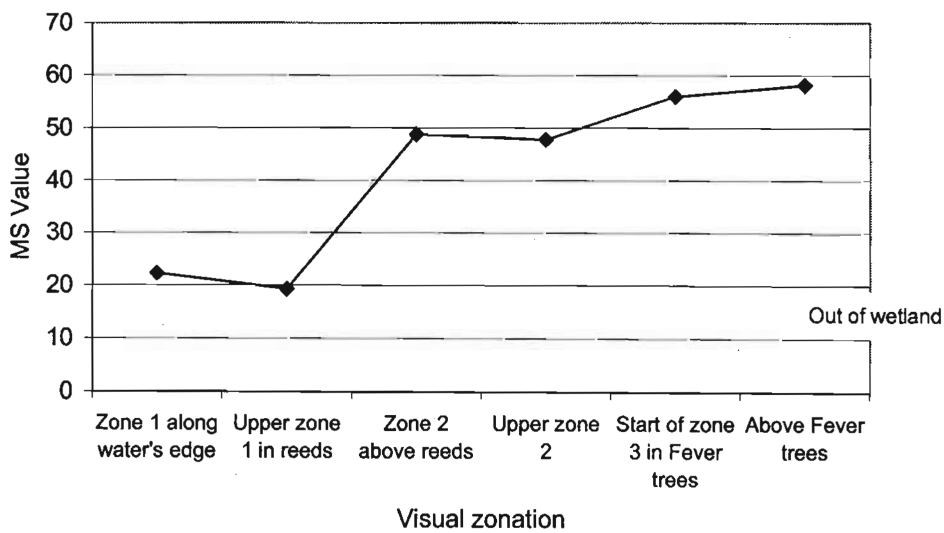


Figure 4.2 Bubhe Pan zone investigation using the MS2F (probe) sensor.

Site 2 : Sokhunti Pan

Figure 4.3 and Figure 4.4 below show the results of two MS transects. Zones were selected according to vegetation changes as at Bubhe pan, but only the MS2D or loop sensor was used at this site. An average of 10 readings taken in each zone was used to generate the points on the graph. In Figure 4.4, a peak at the water's edge showed an average MS higher than the readings at the top of the slope, out of the wetland. The peak at the water's edge is difficult to explain. Exploration with the auger showed red mottles and streaks. It was suspected that, due to the steep slope adjacent to the pan, soluble iron leaching out of the sandy soil further upslope accumulated at the base. The drop in MS values at the top of the slope (Figure 4.4) was explained by the fact that the soil changed from being clay-rich to sandy, lower in iron.

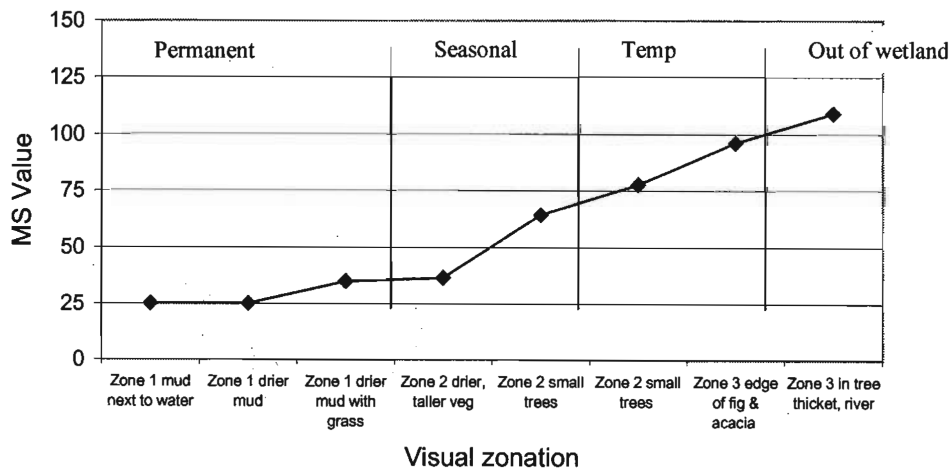


Figure 4.3 Sokhunti Pan reconaissance transect 1. The transect was approximately 60m in length.

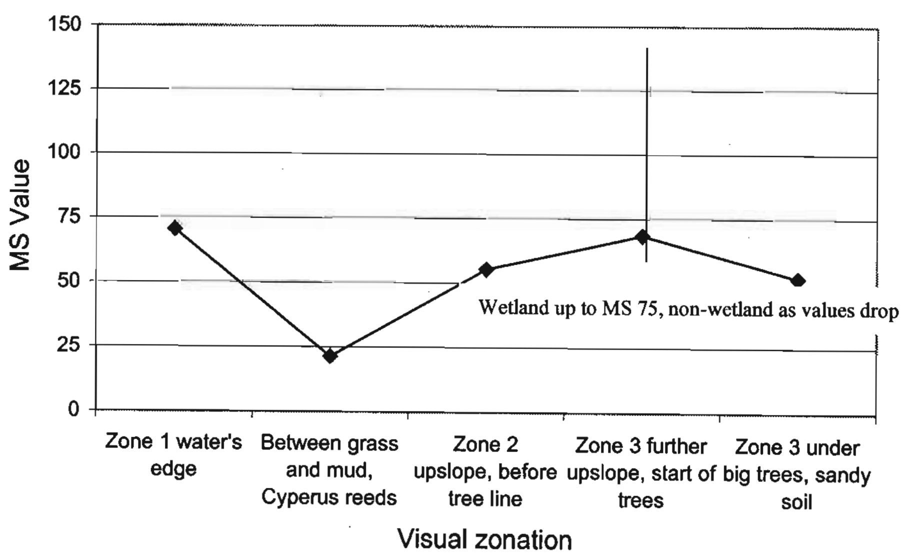


Figure 4.4 Sokhunte Pan reconnaissance transect 2

Site 3 : Nomaneni Pan

As indicated in Figure 4.5, the MS readings at this site were generally higher than the readings at the other Pongola sites. This was due to the fact that the transect extended from the water's edge up to a rhyolite ridge. Weathering of this iron-rich parent material and the movement downslope influenced the MS readings, even at the water's edge where red streaks were evident.

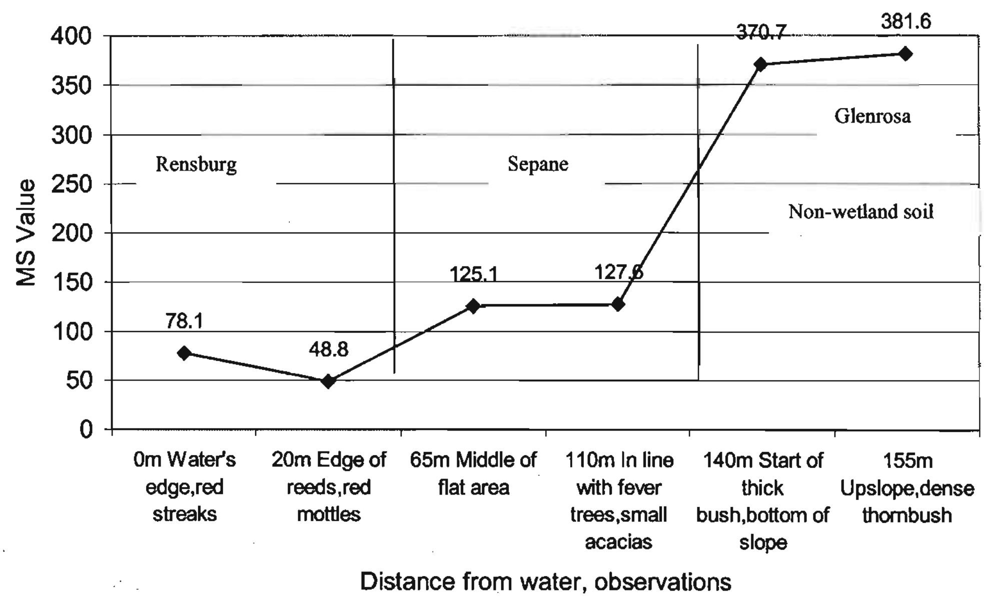


Figure 4.5 Nomaneni Pan detailed transect 1, soil samples were taken at each point.

4.1.2 KwaZulu-Natal North Coast

Site 4 : Mkuze Wetland

Mkuze is an example of a site where poor results were expected due to the nature of the regic sand parent material (Section 3.3.1). Figure 4.7 shows how the readings increased in the temporary zones. The MS readings did prove to be lower than those at Pongola but a trend could still be observed. The trough of low readings indicates the permanently wet zone. Readings then increase in the seasonal and temporary zones and drop again once outside the wetland.

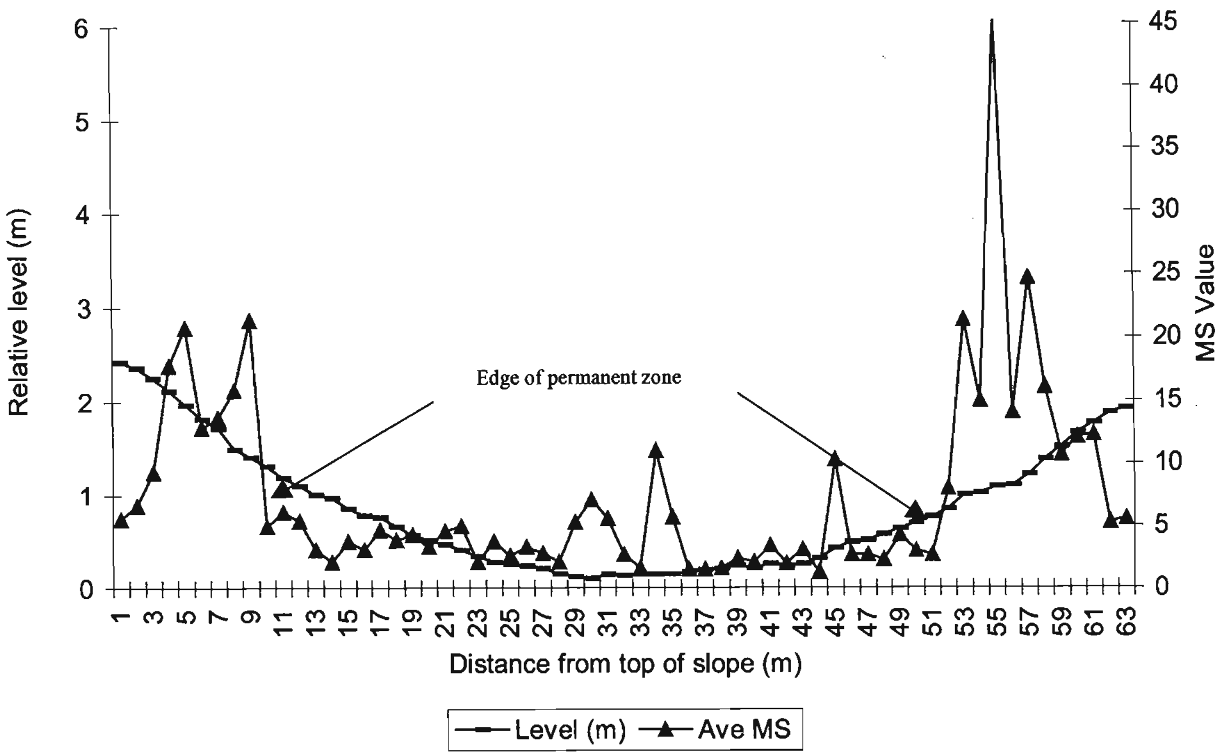


Figure 4.6 Mkuze wetland transect showing relative levels and their corresponding average MS reading. The edge of the wetland is visible at 1m and 63m where the MS values dropped to a minimum.

At Mkuze, the critical value was found to be approximately 25. The difference between this site, site 5 and the Pongola sites is that the MS values increase to a high point at the wetland boundary and then level off at the high point whereas in the sand parent material, the boundary is marked by a high point but then the values decrease in the non-wetland soil.

Site 5 : Yengweni Wetland

Two transects at different parts of the wetland and pan were studied. The first transect, depicted in Figure 4.7, was done through two tongues of wetland. The second transect (Figure 4.8) was from the edge of Yengweni Pan into the thick tree zone. This transect was very flat. As indicated in Figure 4.7 and Figure 4.8, a 'rule of ten' could be applied at this site. Readings above ten indicated the seasonal and temporary zones and readings below ten indicated the permanent and out of wetland zones.

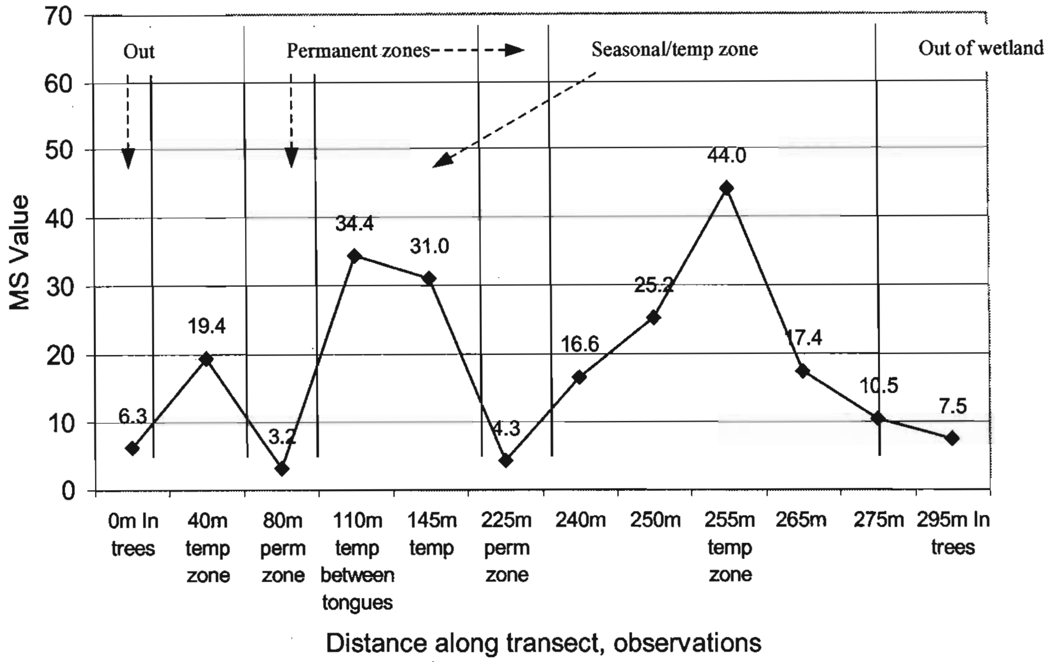


Figure 4.7 Yengweni transect across two tongues of wetland, joining at the pan.

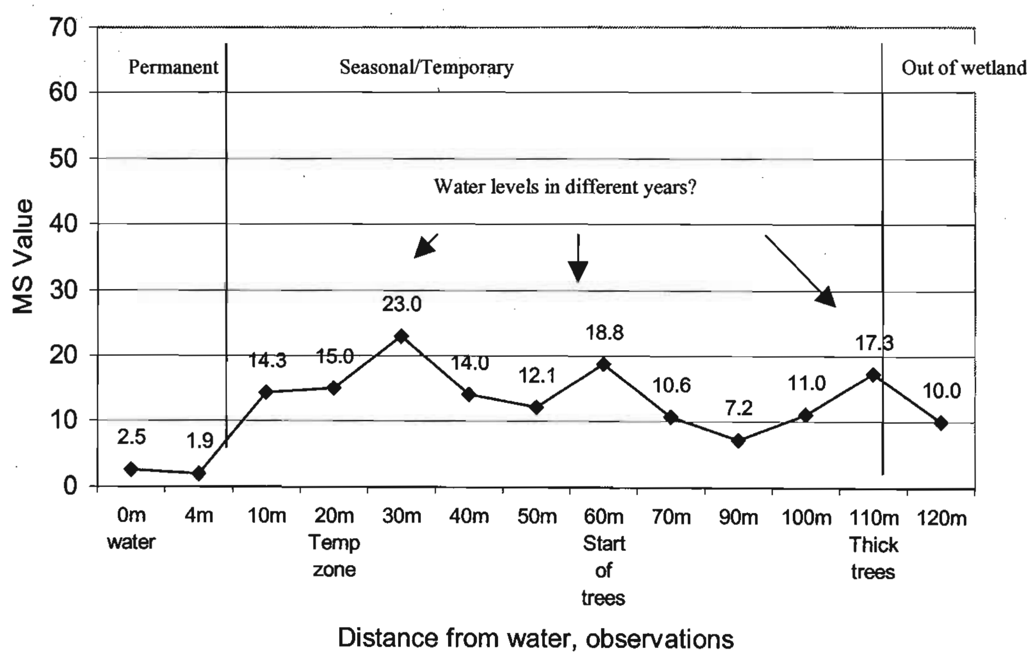


Figure 4.8 Yengweni pan transect from the water's edge into dense trees.

4.1.3 Drakensburg / Natal Midlands

Site 6 : Highmoor

Two different sites were studied at Highmoor, a seep (on a slope with no permanently wet basin) and a wetland. The results from the wetland transect can be seen in Figure 4.9. The results from the seep transect looked very similar, but without the trough representing the wetland. No trend could be identified in the seep transect. Figure 4.9 clearly indicates the edges of the permanent zone of the wetland but it is difficult to identify the edge of the temporary zone. The seep transect showed similar results where no MS boundary could be detected.

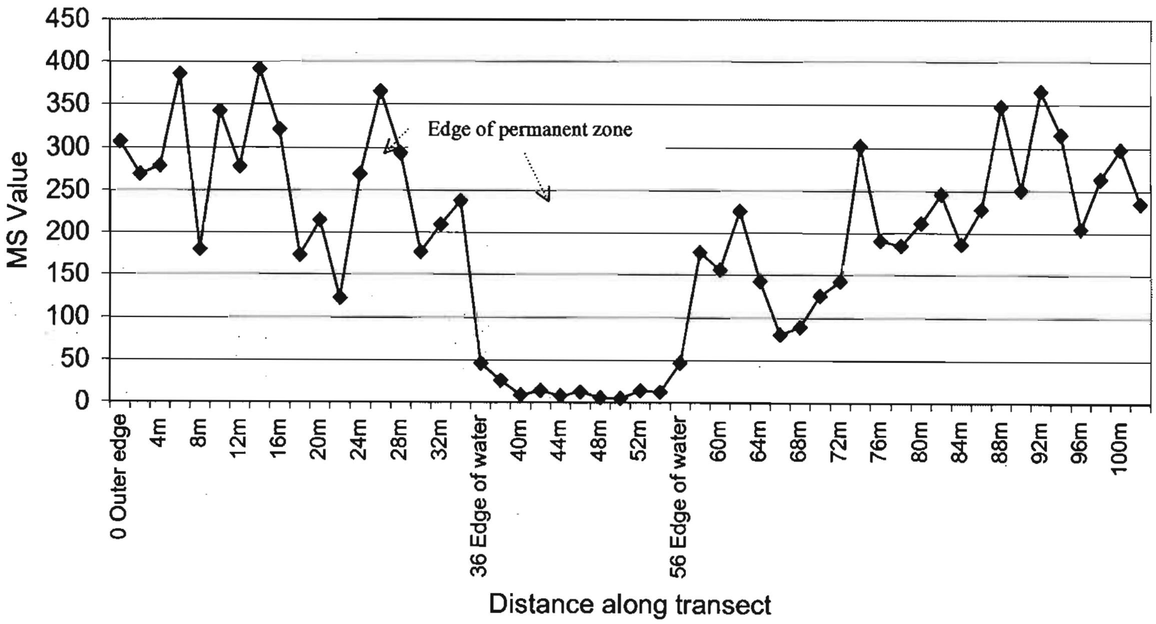


Figure 4.9 Highmoor wetland site.

Site 7 : Oribi

Two transects were studied at this site and Figure 4.10 shows the results from transect 1. The results were as expected with the lowest readings obtained in the wetland. The critical value was found to be approximately 200 at this site. The parent material was shale and no unusual conditions were observed at this site except that it had recently been burnt.

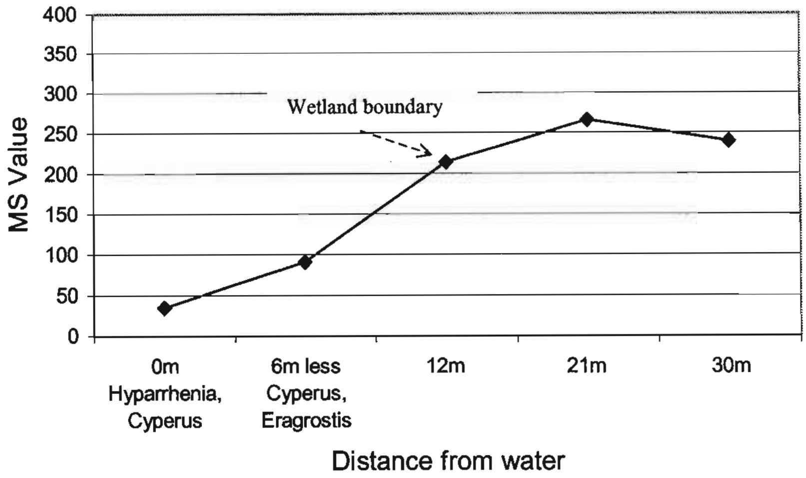


Figure 4.10 Oribi wetland showing transect 1

Site 8 : Hesketh Conservancy

Although the parent material was also shale at this site (like Oribi), readings did not reach 200 on the transect (Figure 4.11). This was probably due to the fact that a dirt road ran alongside the site and the transect extended into the road. It is suspected that the road fell within the temporary zone of the wetland.

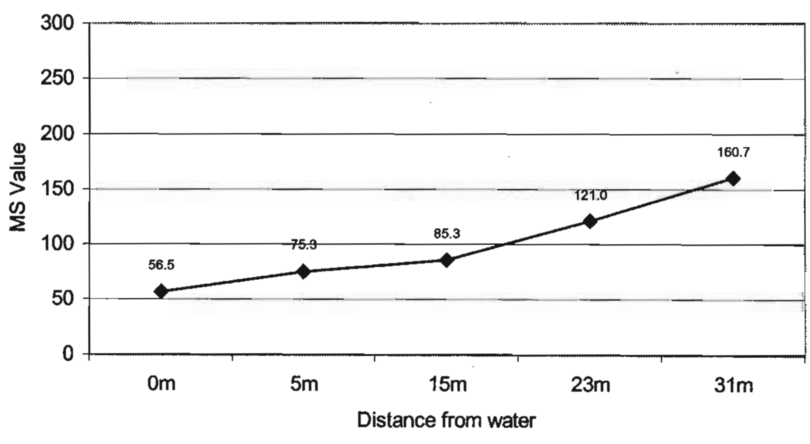


Figure 4.11 Hesketh conservancy wetland transect.

Site 9 : Shafton

Transect 2 is shown in Figure 4.12. Level readings were done at the same points as the MS readings. This transect showed an interesting decrease in MS readings in the last 8m of the transect.

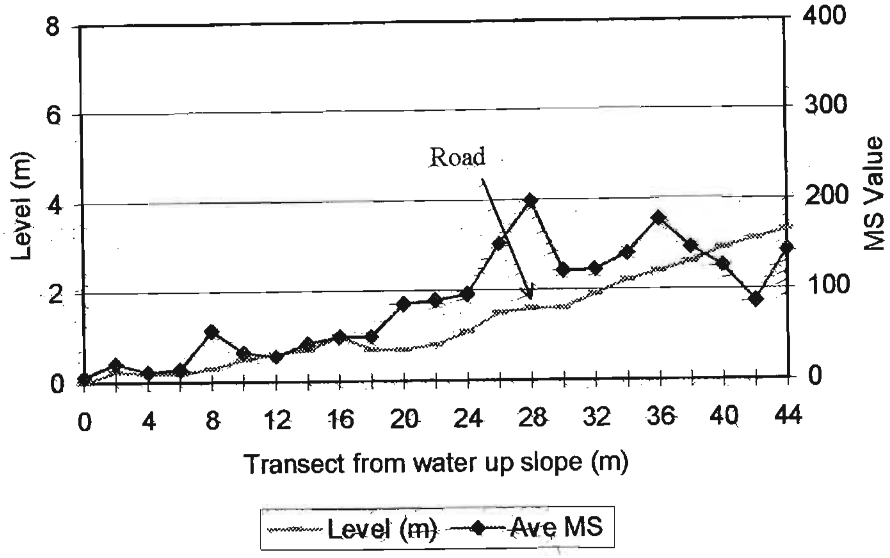


Figure 4.12 Shafton wetland transect 2.

4.2 Revised methodology : transect method

The MS readings on transects 1 to 4, used to identify the critical value, are represented in Figure 4.13 below. Transects 5 and 6, used to check the critical value are shown in Figure 4.14.

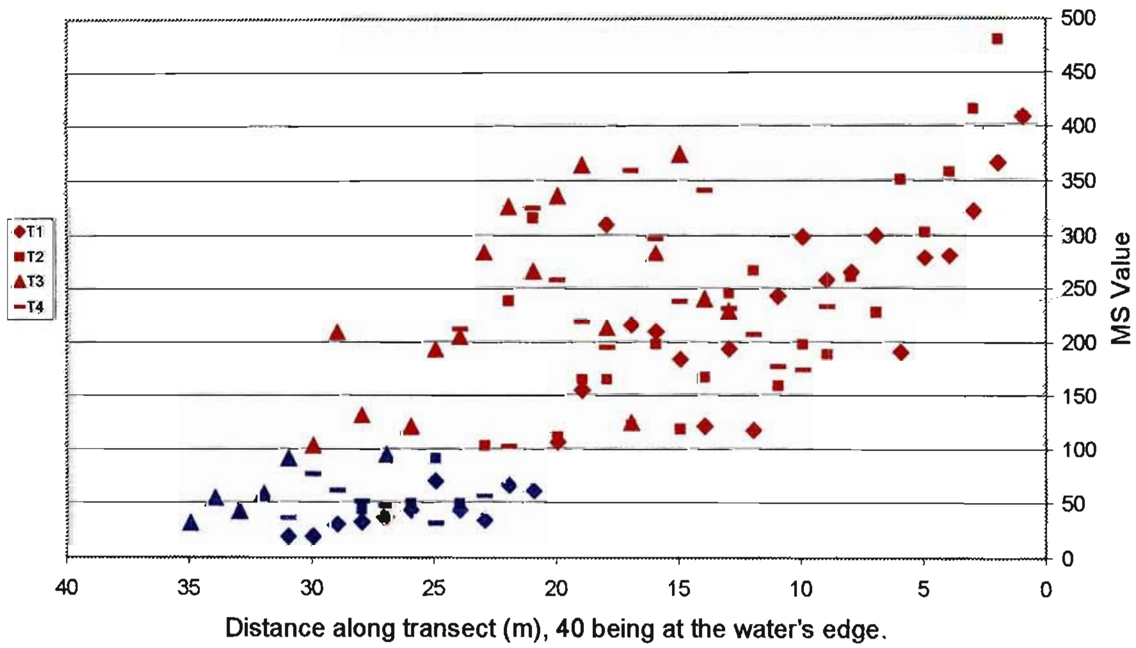


Figure 4.13 Transects 1 – 4 at the site near Mooi River (transect method) represented as a scatter diagram to detect the MS reading that separates the temporary zone from non-wetland soil (visible at MS 100 : blue points below 100 = wetland soil).

Correlations were done between the distances and MS readings for transects 1 to 4. The r-values for T1 to 4 were 0.90; 0.84; 0.79 and 0.68 respectively, showing that a positive correlation existed between distance from the permanent zone and MS value (the MS values increased with distance).

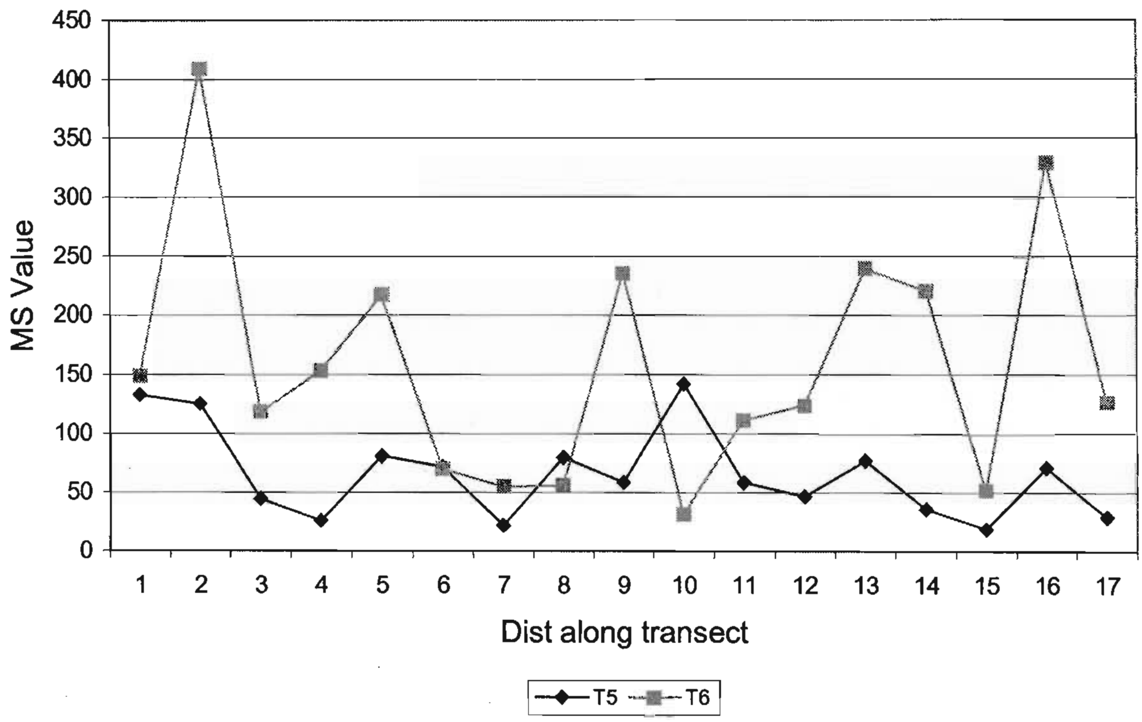


Figure 4.14 Transects 5 and 6 at Mooi River.

Transects 5 and 6 were used to verify the critical value by showing readings higher than 100 on the non-wetland side and lower than 100 on the wetland side but the readings showed large variations within a distance of 1m. Table 4.2 includes the soil data for each point. The location of the point numbers is visible in Figure 3.4.

Table 4.2 Soil data taken to verify the MS boundary identified at the Mooi River site.

Point number	Signs of wetness, chroma at 50cm depth	Soil form	MS reading	Wetland / non-wetland according to field procedure
1	None, chroma 4	Hutton	215	non-wetland
2	Few high chroma mottles, 3 (soil was wet)	Sepane	59	wetland, difficult decision though
3	None within 50cm, mottles at 1m, chroma 3	Sepane	283	non-wetland
4	Mottles, matrix chroma 2	Sepane	43	wetland
5	None within 50cm	Pinedene	277	non-wetland
6	Mottles, chroma 2 at 50cm	Sepane	47	wetland

4.3 Final methodology : grid method

4.3.1 Midmar

The first attempt at the final methodology was undertaken at a site at Midmar Dam in Howick. The MS readings showed no obvious trend and no boundary could be detected. After some investigation with the auger it was discovered that the soil form beneath the grid was a Westleigh consisting of a thin orthic A over soft plinthite. The soft plinthite is made up of nodules and concretions of iron and manganese within the top 20cm of the profile. Three transects were selected and are represented in Figure 4.15. The constant range of readings were due to the presence of the plinthite layer.

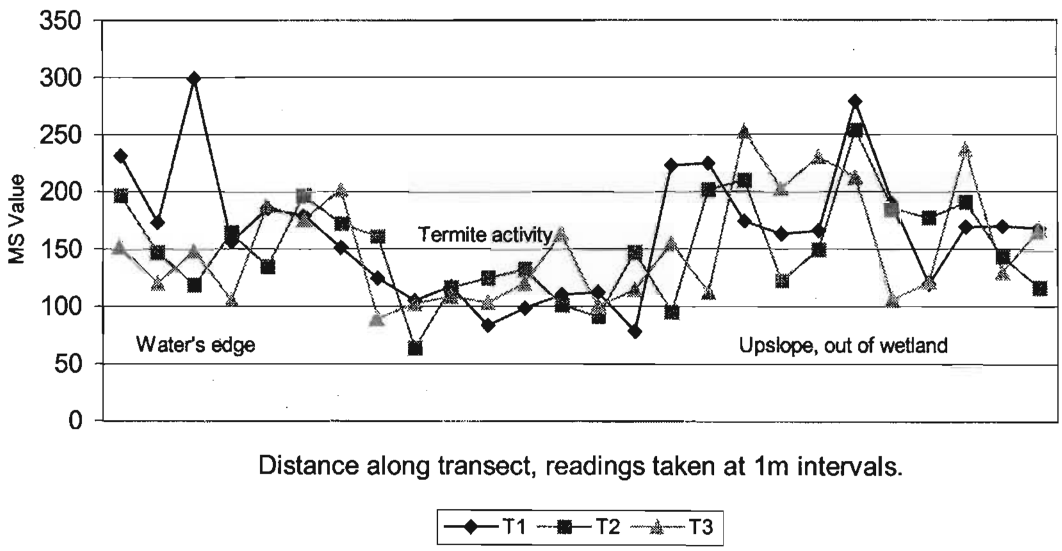


Figure 4.15 Transects at Midmar showing how the plinthite layer dominated the MS readings, preventing detection of a boundary.

4.3.2 Oribi

The final field site was at Oribi airfield in Pietermaritzburg. The area was surveyed prior to setting up the grid. The grid data is shown in Figures 4.16, 4.17, 4.18, 4.19 and 4.20. The grid was positioned right through the wetland, running in a strip from the upper side of the small basin up the opposite bank. Figure 4.18 is a scatter plot showing the relationship between elevation and MS, lower landscape positions, such as wetland sites, correspond with lower MS values.

The boundary at MS 250 was identified on the ground at the site by looking subjectively at the range of values and their distribution on the grid and was estimated at approximatel MS 250. The Wetland/Riparian Habitats : Practical Field Procedure for Identification and Delineation. Version 1.2. (Land -Use and Wetland/Riparian Habitat Working Group 1999) was used to verify it by taking auger points on either side and identifying the soil as being wetland or 'non-wetland' according to the criteria in the Field Procedure (Table 4.3). The position of the points is indicated in Figure 4.19.

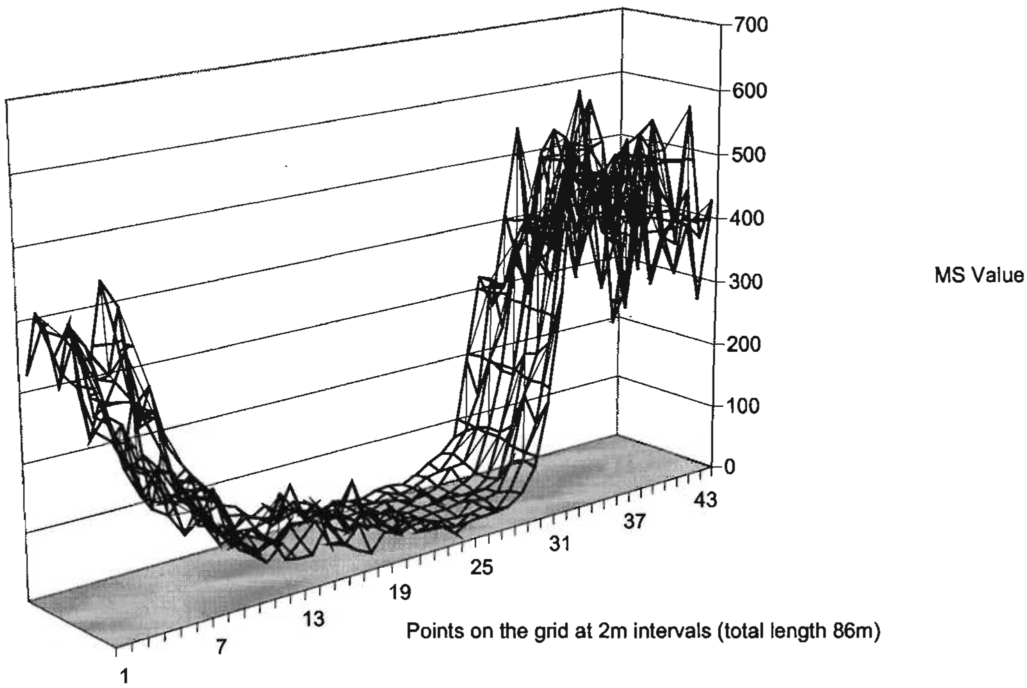


Figure 4.16 A graphical representation of the MS grid readings done through the centre of a wetland at Oribi airfield. The approximate MS boundary is visible at MS 250.

A histogram was constructed (Figure 4.17) from the grid MS values to calculate the critical value statistically in the same way as was done by Grimley and Verpraskas (2000) (Figure 2.4). As estimated in the field, the histogram shows the critical value can be taken at approximately MS 250. This value corresponds with the mean of the hydric soil MS values plus three standard deviations (a calculated value of 252).

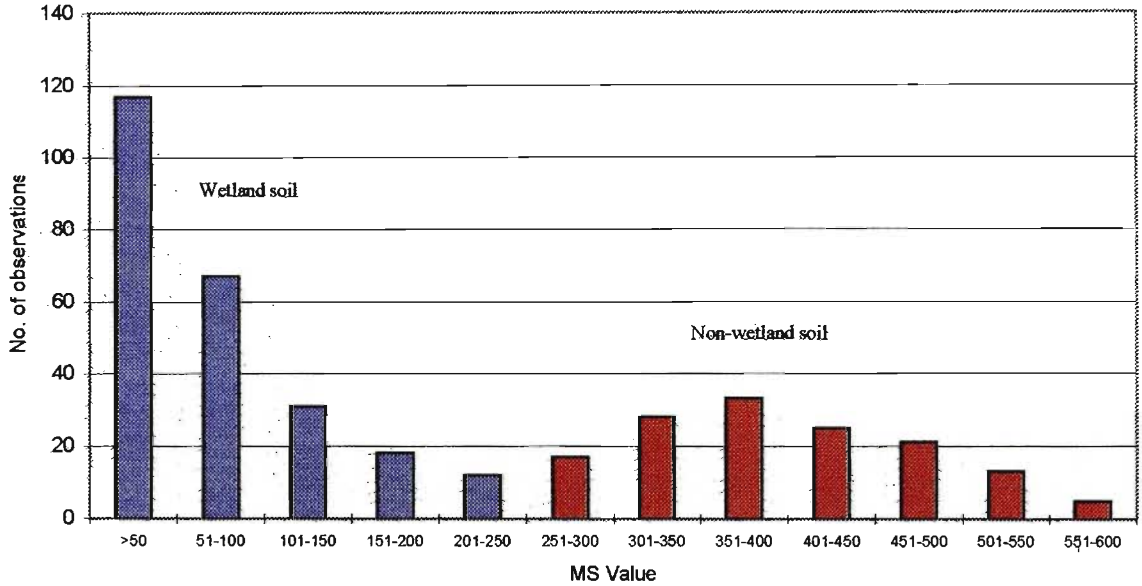


Figure 4.17 Distribution of magnetic susceptibility values collected for the grid method at Oribi. It can be seen that a magnetic susceptibility value of 250 could be used to separate wetland from non-wetland soil at this site.

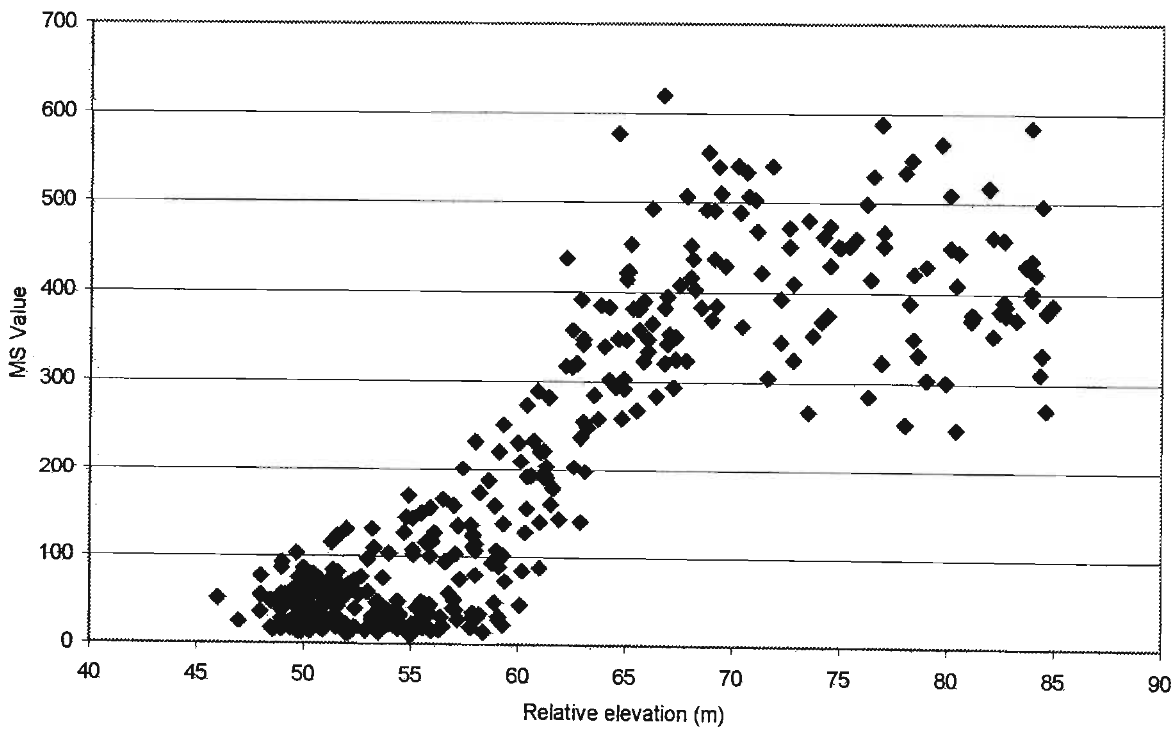


Figure 4.18 A scatterplot of the Oribi Grid MS Values against their relative elevation. This plot shows that low MS values correspond with low landscape positions, increasing as the elevation increases.

Table 4.3 Soil data taken to verify the MS boundary identified at the Oribi grid site.

Point number	Signs of wetness, chroma at 50cm depth	Soil form	Grasses	Wetland / non-wetland according to field procedure
1	None, chroma 4	Hutton	*Themeda triandra*	Non-wetland
2	Mottles, chroma 2	Sepane	*Setaria sphacelata*	Wetland
3	None, chroma 3	Hutton	*Themeda triandra*	Non-wetland
4	None, chroma 2	Deep Hutton	*Themeda/Setaria*	Non-wetland
5	Mottles, chroma 2	Sepane	*Setaria sphacelata*	Wetland
6	None, chroma 4	Hutton	*Themeda triandra*	Non-wetland
7	None, chroma 3	Mispah, 40cm deep	*Themeda triandra*	Non-wetland
8	Mottles?, chroma 2	Mispah	*Themeda/Setaria*	Wetland
9	None, chroma 3	Mispah, 40cm deep	*Themeda/Setaria*	Non-wetland
10	Mottles?, chroma 2	Mispah	*Themeda/Setaria*	Wetland
11	None, chroma 3	Mispah, 40cm deep	*Themeda/Setaria*	Non-wetland
12	Mottles?, chroma 2	Mispah	*Themeda/Setaria*	Wetland

REFERENCE	A	B	C	D	E	F	G	H	I
1	437	491	385	369	416	324	395	414	323
2	321	452	353	342	381	390	382	348	385
3	346	284	381	334	294	273	347	391	316
4	258	292	285	302	203	255	282	221	289
5	228	198	233	143	165	195	210	251	221
6	193	160	158	128	187	138	173	232	201
7	102	117	136	93	135	125	158	165	155
8	103	114	100	111	127	131	116	149	169
9	75	74	82	94	107	131	127	144	143
10	56	63	69	56	66	72	66	109	103
11	77	77	50	67	65	65	115	68	123
12	49	40	59	54	63	40	68	76	96
13	48	61	79	40	42	51	64	32	64
14	86	84	75	63	103	57	53	47	55
15	55	43	86	63	73	53	35	38	32
16	36	36	55	70	52	59	54	33	45
17	25	60	41	60	59	51	40	78	28
18	51	51	66	32	55	30	49	21	38
19	40	47	54	53	93	35	21	17	31
20	48	31	59	29	13	18	16	30	14
21	49	45	39	12	16	25	17	19	21
22	41	20	10	17	18	17	16	17	15
23	16	19	18	17	19	14	22	14	13
24	28	14	16	20	21	19	18	23	20
25	30	28	15	20	22	35	12	15	21
26	31	32	35	24	25	13	14	19	18
27	34	22	31	32	22	20	22	31	27
28	48	45	36	35	23	28	48	35	41
29	84	88	79	45	39	41	50	58	51
30	179	140	178	125	107	107	101	89	72
31	341	259	237	231	191	192	204	140	191
32	577	453	421	437	339	357	249	320	317
33	626	350	507	385	358	423	381	305	268
34	556	541	492	493	325	365	294	347	408
35	422	507	468	403	437	429	510	383	540
36	325	267	451	489	503	534	541	362	305
37	450	415	430	393	472	410	480	345	352
38	323	548	530	368	474	375	451	462	452
39	389	566	331	460	499	285	467	588	452
40	375	517	509	534	254	349	429	421	304
41	584	401	380	301	450	248	445	409	370
42	376	391	311	353	462	376	386	459	371
43	430	271	436	395	421	379	332	497	387

Suspected boundary

Auger point number

Suspected boundary

Auger point number

Figure 4.19 Points where field soil analysis were done to verify the MS boundary at Oribi. The data for the points appear in Table 4.3.

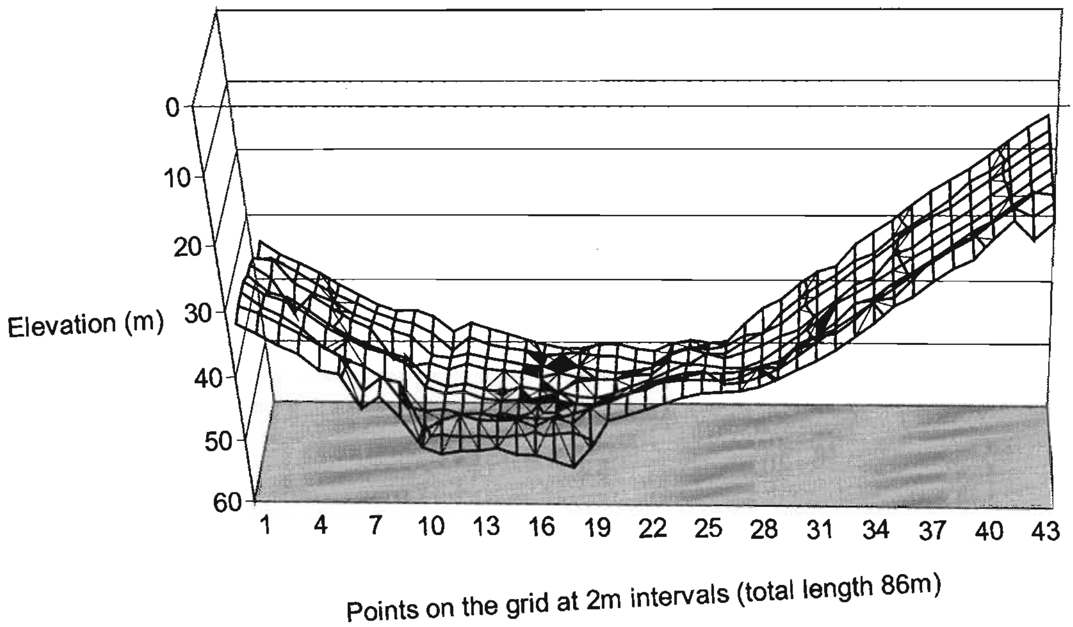


Figure 4.20 The levels taken on the same grid points as the MS readings at the Oribi site.

Chapter 5

Discussion

5.1 Initial fieldwork

This section discusses the first phase of the field work (Section 4.1). The initial fieldwork showed a variety of results. The work at Pongola, the Kwazulu-Natal North coast and the Midlands showed that, for the wetland sites studied, MS values were always lower at the water's edge than outside the temporary zone. It was determined that grass cover between the MS sensor and the soil decreases the sensitivity to the soil MS, a good contact between the sensor and the soil is required. The MS2D sensor gave quicker reading times than the MS2F sensor. It also detects a larger volume of soil and is therefore more representative of conditions at a transect point. The highest MS readings were obtained in the Midlands area and the lowest in the coastal wetlands. When related to the regional geology (section 3.3.1), these results are consistent with the concentrations of magnetic minerals and the distribution and abundance of maghaemite concentrations (Fitzpatrick 1978). It was not possible to determine a critical boundary value that could be used at all sites in an area since conditions at the sites varied causing MS values in different ranges for the same area. Soil verification of the MS wetland zone boundaries was always successful in that the MS range identified for a particular zone was always supported by soil indicators outlined in the field procedure but too much emphasis was placed on the zones within the wetlands, rather than the outermost wetland boundary.

The results obtained at Bubhe Pan (Pongola, site 1) indicated immediately that the MS delineation method had potential but very little was known about the MS meter, its operation and interpretation of the readings. Bubhe pan provided more of an opportunity to learn how to operate the MS meter than obtain useful results. The site at Nomaneni pan (site 2) on the Pongola floodplain presented an unusual set of conditions in that one side of the wetland was bounded by a rhyolite ridge. The boundary of the temporary zone was identified at MS 300 which is a much higher value than was obtained at the other sites in the same region. This is an example of how the MS method is site-specific and depends on the parent materials present at individual sites (rhyolite was not present at the other sites on the Pongola floodplain).

It is difficult to make general conclusions about the Pongola floodplain since the sites showed a variety of MS ranges and different trends. This was perhaps due to the fact that the floodplain consists of a mixture of parent materials, as well as much alluvium accumulated over years of deposit by the river of its various loads from upstream. However, the MS trends did coincide with the soil conditions at every site. When evidence of iron was present in the form of red streaks and mottles, the readings were higher than when the soil was sandier and obviously lower in iron, although this is a dangerous assumption to make since no soil testing was done to verify whether the mottles and streaks did indicate a higher iron content than that of the grey sands.

At Mkuze (site 4) wetland on the KwaZulu-Natal north coast region, the lowest values were obtained in the permanent zone due to the constant anaerobic conditions. These conditions cause much of the iron to become soluble and it is leached out of the profile (Section 2.6). MS values increase in the seasonal and temporary zones due to periodic wetting and drying. This in itself does not directly cause the increase but rather its effect on iron precipitation and accumulation. Low readings were once again found outside the wetland zone due to the low iron content of the sand. No extended periods of waterlogging are present to change the oxidation state of any iron present, keeping it relatively inert when compared with the seasonal and temporary zones. The in-zone variability is explained by the nature of the instrument used to take the readings. The sensitivity (of the detection of the soil MS) decreases when other substances are present. If there is more organic matter (for example a thick stem) in the topsoil at one point than the point next to it, the reading will be lower. If one patch of soil is better aerated than another, more iron will be oxidized and held in the profile for detection. These variations existed at Mkuze but usually remained within the zone critical values.

At this point, it is important to point out that although reasons can be given for the variations observed in the MS readings, it is perhaps not always necessary to try to describe every fluctuation. The variable nature of the soil surfaces studied, together with unknown and unstudied reasons for fluctuations in the instrument mean that the variations cannot always be explained. This study forms the very first research into the use of magnetic susceptibility for wetland delineation in South Africa and introduces many unknown factors that need to be investigated further before conclusions can be drawn. Much of this discussion, for example about the Mkuze site, is in the form of suggestions and ideas, rather than concrete reasons and conclusions.

The readings shown in Figure 4.8 (Yengweni wetland on the KwaZulu-Natal north coast, site 5) are particularly interesting. The terrain was flat and it was difficult to determine the zone boundaries by looking at the vegetation. Peaks and troughs were recorded, perhaps suggesting that the water level had risen to different points in previous years, influencing the iron content of the soil at these points. This idea was not tested further but could form an interesting study on it's own to investigate whether MS can be used to detect previous boundaries, especially in the case of disturbed, relict or altered wetlands.

The results obtained at Highmoor in the Drakensberg region (site 6) can possibly be explained by the fact that both the sites were situated in the Drakensberg mountain range where steep slopes and windy conditions result in thin soils and much exposed rock. The rock type was basalt, high in iron minerals, producing MS readings up to 400. The uneven surface resulted in some readings being of rock alone, while others represented a thin patch of soil, because the sensor only detects iron in the top 18cm of the soil. If the sensor was placed over a boulder buried 4cm beneath the surface, a much higher reading was obtained than if the profile consisted only of soil. These varying readings make it impossible to detect a boundary between the temporary and non-wetland soil, the permanent zone could be detected because of it's landscape position, being in a basin the soil was deeper and allowed for more consistent MS readings.

The site at Oribi (site 7) had been recently burnt. It was impossible to assess the effect of the burning since a similar, unburnt site was not available for study in the same area. Studying the same site over a number of years, when burnt and not burnt could perhaps provide useful guidelines as to how to interpret MS data collected at burnt wetland sites. The Hesketh conservancy wetland (site 8) was disturbed as there were compacted footpaths which have probably changed the way water flows through the system. A more detailed study would probably be able to identify the original flowpaths and wetland zones if previous boundaries can be identified like at site site 5 (Yengweni). This would be useful for rehabilitation and conservation of the site.

Shafton wetland (Site 9) showed a decrease in readings in the last 8m of the transect. This was not expected but can probably be explained by the fact that the upper part of the slope was under forestry and had recently been harvested. Buried stumps, branches and disturbed soil at the surface could all have accounted for lower readings. The road also influenced identification of a boundary and it was suspected that the road had been constructed just inside the wetland boundary. It was compacted and waterlogged giving variable MS readings. No conclusion could be drawn about the wetland boundary, it was difficult to interpret the MS readings in the disturbed conditions.

The results obtained in the Natal Midlands were of mixed success. Highmoor and Shafton were examples of sites where the MS method is unlikely to be useful while Oribi and Hesketh showed more promise. They all provided useful information about the MS meter and it's operation and about conditions where the method is more likely to be successful.

Northern Kwazulu-Natal showed readings that were in a similar range at all the sites in the area, even if the values were generally much lower than in the other areas. The results on the Pongola floodplain showed that the method was successful, but like the Midlands, the range of readings was site-specific. Critical values had to be determined for each site.

5.2 The transect method

The transect method carried out at Mooi River (Section 4.2) indicated that MS can be used to detect the outer boundary of the temporary zone, but not with great precision. An important point to note from Table 4.2 is the three different soil types within the limited study area. This probably also contributed to the variability in the MS readings. A variety of soil forming factors are acting at different rates, influencing the iron mineral content in localized patches. Difficulty was experienced when carrying out the Field Procedure (Land-Use and Wetland/Riparian Habitat Working Group 1999). It was found that a 'buffer' of about 6m was required on either side of the MS boundary in order to get successful soil verification, soil analysis at points closer to the MS boundary was not always consistent with the requirements for a wetland or non-wetland soil according to the field procedure thus points up to 6m away had to be studied in order to verify the wetland or non-wetland status of the soil. This meant that the MS method was only accurate to a resolution of about 12m. Previous experience with the instrument indicated that this was not the case, a resolution of 2-3 metres was suspected but not proven.

The variability of MS readings at the Mooi River site was problematic. Tree stumps, holes and animal activity (termites and duiker) all influenced the readings. An experienced user would be able to interpret the variation but a new user would probably not be able to detect the boundary. It was clear that the MS delineation did work at this site but the results were still not conclusive enough. The variation in MS readings needed to be represented more clearly and interpreted and the MS boundary needed to be determined more exactly, and proven. This led to the development of the grid method.

5.3 Grid method

As described in Section 4.3.1, the grid method at Midmar was not successful due to the presence of a plinthite (a concentration of iron and manganese nodules) layer near the surface. This explained why it did not work at all and served to improve the method, it should always be preceded by a reconnaissance soil survey and decision as to whether the nature of the surface soil is likely to allow the detection of an MS boundary.

The grid method undertaken at the final site near Oribi airfield in the KwaZulu-Natal Midlands gave an MS representation of a strip through a wetland, showing how the MS values vary over 2m intervals from the higher lying soil out of the wetland zones, through the wetland and up the opposite slope. It also described the relationship between MS values and landscape position noted in the initial work

(Figure 4.18). Using the field procedure to verify the MS boundary was successful but difficulties were experienced with it, at this site and at the others. Since the soil was wet, it was difficult to identify the chroma that, according to the field procedure, should be identified on dry soil. The horizon type also sometimes made it difficult to identify signs of wetness. In a shallow Mispah soil, as was found at Oribi, weathering rock fragments and the wet conditions made it difficult to identify mottling. It was noted that the field procedure took more than twice as long to carry out than the MS method, even though they both identified the same boundary line with a resolution of about 3m in width.

Although this method proved that soil MS can be used to detect wetland boundaries, it was only carried out at one site. Variation between all the sites studied showed that a large amount of field work needs to be conducted in order to devise a general method, and set of guidelines, that can be applied at any site in KwaZulu-Natal.

5.4 Problems and limitations

A number of problems were experienced when testing the method, the first being the fact that the MS2D sensor only detects magnetic minerals in the top 268.7cm^2, or to a depth of approximately 18cm (Table 3.1) of the soil. This is problematic since the field method for detecting wetland boundaries requires that signs of wetness be visible within 50cm for a wetland soil to be classified. Although the field soil analysis did verify the MS boundaries in most cases, it was not always verified and was often difficult to relate the soil wetland boundary to the MS boundary. In some cases they coincided almost exactly (grid method at Oribi) while in others they were positioned three or more metres apart (transect method at Mooi River). The reason for this is difficult to explain at this stage of the research. Perhaps it is due to the fact that the sensor does not detect iron below 18cm in the profile or perhaps the MS method is simply not a reliable way to delineate wetlands in KwaZulu-Natal, South Africa.

Evidence in this study shows that using MS to delineate wetlands was successful at some sites so the answer to getting more consistent and accurate results may lie in extensive study of the distribution of iron in soil profiles and how the iron content in top 18cm of a profile relates to the iron content at 50cm. This is especially important in soils such as the one experienced at the Midmar site with the plinthic layer. The relationship between these types of horizons, either at the surface or deeper in the profile, and the rest of the soil profile needs further investigation. Another solution could be the design of a different method to take measurements deeper in the profile or the design of a sensor that would enable quick measurements at 50cm depths. Grimley and Verpraskas (2000) took readings at two depths which is an obvious way of measuring the MS lower in the profile but this method was not used in this study since it defeats the object of developing a quick MS delineation method. Perhaps more research needs to be done in this fashion (taking readings at various depths) before a quick method can be developed. Sensing MS to a depth of 18cm only would not be useful when planning plantations since trees utilize water from below a depth of 50cm, a way of detecting MS to depth of 70 to 80cm would be needed to detect signs of wetness for this purpose.

The success of the method depends on the conditions at each individual site. The geology of the site and of the surrounding area is very important since even a narrow dolerite dyke can alter the range of readings experienced drastically, such as site 3 (Nomaneni). Material transported to the wetland from the surrounding catchment can also influence the MS readings. Even if a general critical value can be determined for a parent material, disturbed conditions such as at the Mooi River and Shafton sites, can make interpreting the readings difficult. Iron-rich rock or nodules and concretions, such as at Highmoor and Midmar, make the method completely unsuitable. It is therefore essential that a quick soil survey (three or four auger points along a transect across the suspected boundary) be done before the MS work is begun.

The MS meter itself is limited to about 2 hours of continuous reading time in the field before it needs to be charged (it has a car charger for field work), this is not a major limitation in most cases but the delineation of a large wetland might require a 30min break to charge the meter. This might cause difficulties if a site is inaccessible by vehicle and large distances have to be walked in order to charge the meter. At this stage in the research, only and experienced user would be able to carry out an MS delineation. Variations in MS readings can be difficult to interpret if the user does not have a full understanding of what the sensor is detecting. This limitation should be overcome with further research. The development of a specific protocol and MS guidelines for a range of sites would make the method accessible to users with a more limited background/knowledge in wetland delineation.

Problems were experienced with the field procedure for delineating wetlands (Land-Use and Wetland/Riparian Habitat Working Group 1999). Difficulty was experienced with identifying soil colours when the soil was wet and conditions were cloudy. Signs of wetness such as mottling were sometimes difficult to identify in horizons that contained rock fragments. Augering to a depth of 50cm at each point was time-consuming. The method is a subjective one, using a combination of this method and magnetic susceptibility readings definitely reduces the time taken to delineate a wetland and provides a more accurate boundary. At this stage in the research, this can be done by identifying a 'suspected boundary' using the MS meter along transects perpendicular to the outer edge of the wetland. Points inside and outside of this boundary can then be selected for soil analysis to identify whether the soil is wetland or non-wetland, and whether the MS boundary is accurate. It is important to emphasise that, at this stage, using MS cannot replace the soil survey technique but reduces the intensity of soil sampling, therefore the time taken to delineate a wetland.

A possible limitation to the study as a whole is the fact a large number of widely varying sites were studied. The initial intention was to provide different conditions under which to test the idea but getting such a varied range of results made it difficult to assess if the use of MS readings to delineate wetlands was generally successful or not. It was successful only at certain sites and it is difficult to know whether these results are repeatable without doing extensive fieldwork at a number of similar sites. The results from one site cannot be considered conclusive evidence as to whether the method was successful or not. Perhaps a more useful approach would have been to select one area only and study a number of similar sites in more detail. This would have given a better indication of the general potential of the method before it was tried under different conditions.

5.5 Guidelines for using MS to delineate wetlands

Much of the initial part of this study involved learning about the MS meter and sensors and how to operate them under the specific conditions experienced in KwaZulu-Natal, South Africa. The information in summary Tables 5.1 and 5.2 will be useful for future researches when carrying out similar studies.

Table 5.1 Guidelines for the operation of the MS meter and sensors for wetland delineation.

Operation of the MS meter
• Use the MS2D sensor for quick surface measurements
• Allow the meter to warm up for a few minutes before recording data. Check the consistency of the readings by doing triplicate readings at the same point. Drift sometimes occurs in the first 5min of use or if it is not fully charged.
• Clear all grass and debris from the soil surface, obtain good contact between the sensor and the soil surface
• Ensure that the meter is charged regularly (30mins for every 2hrs use) to avoid erratic, incorrect readings.
• Do a blank reading (hold the sensor at least 30cm away from any object) between every soil reading to obtain a zero reading.

Table 5.2 Guidelines for determining whether a site is suitable for the use of MS or not and the delineation procedure.

Site selection
• Find out what the parent material is by observing rocks at the surface or excavations, unusually high or low readings could be explained by the rock type.
• Investigate the soil depth using an auger, if the soil depth is less than 20cm the MS method is not likely to be successful
• Identify the soil form, if an iron-rich subsoil lies close to the surface, the method is not likely to work.
• Study the vegetation and identify the various wetland vegetation zones, the wetland boundary is most likely to be where the vegetation changes outside the temporary zone.
• Select at least two transects from the water's edge out of the wetland to identify the trend in values and a critical boundary value.
• Verify the critical value using soil analysis on at least one transect to rule out any MS abnormalities with the critical value (like buried boulders or rusted cans).

CHAPTER 6

Conclusions and Recommendations

6.1 Conclusions

Three objectives were outlined in Chapter 1 with the first being to test whether magnetic susceptibility (MS) is a viable option for delineating wetlands or not. Three different methodologies were developed to test this objective, the first being a reconnaissance phase after which it was decided that the MS readings did have potential for wetland delineation. A second methodology was designed to provide more conclusive evidence. The third grid methodology showed that the use of soil MS indicated the same boundary as that identified by the soil properties. This showed that using soil MS to delineate wetlands was a viable option that would warrant further investigation.

The second objective was to determine for which conditions the MS delineation procedure is likely to be successful. This objective was partially fulfilled in that twelve different sites were studied with mixed results. The method could be used in all three of the major areas studied (section 3.3.1) but was limited by specific site conditions. It is not suitable for use in areas where a plinthite layer is present in the upper 18cm of the profile since the sensor detects MS in the upper 18cm of the profile. It is also not suitable for use in areas where the soil is thin (less than 18cm depth) and the surface is dominated by exposed rocks. Time limits avoided a thorough study of all the possible conditions in KwaZulu-Natal, future projects should be able to eventually fulfill this objective.

Difficulty was experienced when using MS to delineate wetlands in disturbed areas. Most wetlands are situated in forests and farmlands are are often not in their natural state with trees or crops planted within their boundaries. Soil surfaces disturbed by vehicles, tree stumps, cattle and crop trash made interpreting the MS values difficult. This is a problem that needs further research since most wetlands that need to be delineated are disturbed. Undisturbed sites need to be selected for researching the method but consideration needs to be given to the effect of human and animal activity for a practical MS delineation procedure to be developed.

The third objective was to design a quick, user-friendly field method to delineate wetlands in KwaZulu-Natal using soil MS. This objective was not met due to the time limit of the project. The results were too variable between sites to draw general conclusions and too few sites were studied. A detailed study of different areas needs to be undertaken before specific MS guidelines can be drawn up. MS can be used as a supplement to the field procedure at this stage to reduce the intensity of sampling and therefore time taken to carry out the delineation. Problems with the method still need to be addressed and a method would need to be rigorously tested. Tables 5.1 and 5.2 outline the beginning of a field protocol and these guidelines can be taken further as more research is done.

The method was demonstrated to members of the forestry industry who expressed a keen interest. Further research, as outlined below, will be able to use the results of this project to test various other sites and hopefully, eventually, a quick MS field procedure will be able to be combined with a table of critical values for Kwazulu-Natal to delineate and contribute to the conservation of wetlands in the Province.

6.2 Recommendations for future research

Due to the lack of research into this particular topic, there are many recommendations for future studies. This project served to introduce the concept in South Africa and showed that it does have the potential to be useful in KwaZulu-Natal. The following list provides specific topics that need expansion.

I. A specific study of the top 50cm of soil profiles (including hydric soil), investigating how the iron content of the top 18cm relates to the iron content further down. This would provide some insight into how representative of the soil profile the MS2D sensor readings are. It could then be determined if using the sensor at the surface is the most accurate way of carrying out this method, perhaps a new sensor needs to be designed.

II. Another specific study would involve investigation of the chemical processes at the junction between the permanent zone and the seasonal zone. An MS peak at this point was observed at almost all the sites. Sometimes mottles and streaks of iron were observed in the surface soil, studying the iron reactions could explain in more detail how and why peaks such as this occur.

III. A quick, user friendly method needs to be developed and tested. Initially it would involve a combination of MS readings and soil verification techniques. This method can be updated and improved as more areas are studied.

IV. The results of this study need to be used to divide KwaZulu-Natal (and ultimately South Africa) into MS ranges to be expected in smaller, more uniform, land-type areas. This grouping has already been done by Camp (2000) in the form of Bioresource Units (BRU) and Bioresource Groups (BRG). These were not used in this study since it was not certain at the outset whether the MS readings would be useful for wetland delineation or not. Once the method has been proven conclusively work can been done in each BRG to determine critical values for particular sets of conditions in Kwa-Zulu-Natal.

V. Another possible application of the MS method is the detection of previous wetland boundaries. Yengweni wetland on the KwaZulu-Natal north coast showed possible previous years' floodlines. This type of study would potentially be able to identify the original boundaries of disturbed or drained wetlands. This could be a useful tool in wetland rehabilitation.

VI. The work in this project focused only on naturally occurring wetlands. It would be useful to conduct a similar study on man-made wetlands. Artificial wetlands are increasingly being used for water purification and flood attenuation and also need to be protected. Grimley and Verpraskas (2000) did not get successful results at an artificial wetland but since large variations are likely to exist between materials used, and the age of the wetlands will vary, certain sites might produce successful results.

VII. As was mentioned by Grimley and Verpraskas (2000), the MS delineation method has potential where visual signs of wetness may be difficult to identify. Some South African examples include humic, melanic or vertic soils. Further research conducted specifically on these types of conditions could make the MS method applicable to a wider range of conditions and enable more accurate wetland delineation in difficult cases.

References

Bartington Instruments. http://www.bartington.com accessed 05/06/2001.

Bartington Instruments LTD. 2001. Operation Manual for MS2 Magnetic Susceptibility System. Oxford.

Braak AM, Walters D and DC Kotze. 2000. *Practical Wetland Management*. Rennies Wetland Project -Booklets. http://www.wetland.org.za/ShareNet/Sharenet4/Share.htm, accessed 12/06/2001

Caitcheon GG. 1993. Sediment source tracing using environmental magnetism : A new approach with examples from Australia. *Hydrological Processes* 7: 349-358.

Caitcheon GG. 1998. The significance of various sediment magnetic mineral fractions for tracing sediment sources in Killimicat Creek. *Catena* 32 : 131-142.

Camp KG. 2000. The KwaZulu-Natal Department of Agriculture and Environmental Affairs. http://www.agriculture.kzntl.gov.za, accessed 10/01/2002.

Dearing JA. 1999a. Magnetic susceptibility. *In:* Walden J, Oldfield F and JP Smith (eds). 1999. *Environmental Magnetism : a practical guide*. Technical Guide No. 6. Quaternary Research Association, London.

Dearing JA. 1999b. *Environmental Magnetic Susceptibility : using the Bartington MS2 system*. Chi Publishing, Kenilworth.

Dearing JA. 2000. *Tracers in Geomorphology*. John Wiley & Sons Ltd.

de Jong E, Nestor PA and DJ Pennock. 1997. The use of magnetic susceptibility to measure long-term soil redistribution. *Catena* 32: 23-35.

Evangelou VP. 1998. *Environmental Soil and Water Chemistry*. John Wiley and Sons, New York.

Faulkner SP, Patrick WH, Sanders DR and BA Touchet. 1995. *Wetland Delineation Workshop Manual*. Wetland Biogeochemistry Institute, Louisiana State University, Baton Rouge.

Fitzpatrick RW. 1978. *Occurrence and properties of iron and titanium oxides in soils along the eastern seaboard of South Africa*. PhD thesis, University of Natal, South Africa.

Grimley DA and MJ Vepraskas. 2000. Magnetic Susceptibility for Use in Delineating Hydric Soils. *Soil Science Society of America Journal* 64: 2174-2180.

Hails S. 2000. *Background papers on Wetland Values and Functions*. The Ramsar Convention on Wetlands website : http://www.ramsar.org.htm, accessed 12/06/2001.

Holmes DL. 1978. *Principles of physical geology*. Thomas Nelson and Sons, Middlesex.

Hutchinson SM. 1993. Use of magnetic and radiometric measurements to investigate erosion and sedimentation in a British upland catchment. *Earth Surface Processes and Landforms* 20: 293-314.

King L. 1972. *The Natal Monocline : explaining the origin and Scenery of Natal, South Africa*. University of Natal, Durban.

Kotze DC, Hughes JC, Breen CM and JR Klug. 1996a. *The development of a wetland soils classification system for KwaZulu/Natal*. Report to the Water Research Commission by the Institute of Natural Resources and Department of Grassland Science University of Natal, WCR Report No 501/4/94

Kotze DC, Klug JR, Hughes JC and CM Breen. 1996b. Improved criteria for classifying hydric soils in South Africa. *South African Journal of Plant and Soil* 13(3): 67-73.

Land -Use and Wetland/Riparian Habitat Working Group.1999. *Wetland/Riparian Habitats : Practical Field Procedure for Identification and Delineation. Version 1.2*. Workshops convened by the Forest Owners Association Environmental Committee and for the Afforestation Permit Review Panel Sub-committee on Biodiversity and Wetland Delineation.

Lyon, J G. 1993. *Practical Handbook for Wetland Identification and Delineation.* Lewis Publishers, Boca Raton.

Marnewecke, G and D Kotze. 1999. Appendix W6 : *Guidelines for Delineation of Wetland Boundary and Wetland Zones. Version 1.0.* Department of Water Affairs and Forestry, South Africa.

Mitsch, W J and J G Gosselink. 1993. *Wetlands.* Van Nostrand Reinhold, New York.

McBride MB. 1994. *Environmental Chemistry of Soils.* Oxford University Press

Mullins CE. 1977. Magnetic susceptibility of the soil and its significance in Soil Science - A review. *Journal of Soil Science* 28: 223-246.

Oades JM and WN Townsend. 1963. The detection of ferromagnetic minerals in soils and clays. *Journal of Soil Science* 14(2):179-185.

Smith J. 1999. An introduction to the magnetic properties of natural minerals. *In:* Walden J, Oldfield F and JP Smith (eds). 1999. *Environmental Magnetism : a practical guide.* Technical Guide No. 6. Quaternary Research Association, London.

Soil Classification Working Group. 1991. *Soil Classification : a taxonomic system for South Africa.* Memoirs on the Agricultural Natural Resources of South Africa No 15, SIRI, D.A.T.S, Pretoria

Soil and Irrigation Research Institute and Department of Agriculture and Water Supply. 1998. Memoirs on the agricultural natural resources of South Africa No. 11 (Land types of the map 2830 Richard's Bay). Pretoria.

South African National Water Act 36 of 1998. Government Printers, Pretoria.

South African Wetlands Conservation Programme. www.ccwr.ac.za/wetlands/. Accessed 29 / 11/2001

Thompson R and F Oldfield. 1986. *Environmental Magnetism.* Allen & Unwin, London.

Thompson R, Bloemdal J, Dearing JA, Oldfield F, Rummery TA, Stober JC and GM Turner. 1980. Environmental Applications of Magnetic Measurements. *Science* 207: 481-486.

Tite & Linington. 1975. Effect of climate on the magnetic susceptibility of soils. *Nature* 256: 565-566.

United States Department of Agriculture Natural Resources Conservation Service Wetland Science Institute and Soil Survey Division. http://www.statlab.iastate.edu/soils/hydric/overview.html. Accessed 16/11/2001.

Williams RD and JR Cooper. 1990. Locating Soil Boundaries Using Magnetic Susceptibility. *Soil Science* 150: 889-895.

Williams M (ed) 1990. *Wetlands : A threatened landscape*. Basil Blackwell Ltd, Oxford.

APPENDIX 1

Bartington Magnetic Susceptibility System

MS2

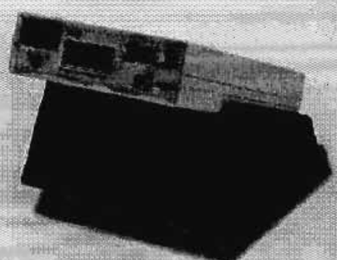
Magnetic Susceptibility System

This system comprises a meter with a wide range of sensors for measuring the magnetic susceptibility of soils and rocks, in both the field and laboratory, with a resolution to 2 x 10^{-6} SI units. Equipment is available for the measurement of susceptibility over the temperature range -200°C to +900°C.

Applications include geological and soil surveys, palaeomagnetics, archaeological prospecting, palaeoclimatic studies, hydrology, sedimentology, core logging and magnetic fabric analysis.

The measurements are non-destructive and the low frequency used ensures that the results are unaffected by sample conductivity. The sensors are temperature compensated to minimise drift during measurements.

With a unique range of sensors the Bartington *MS2* system is well established as the world standard for field and laboratory use.



• *MS2*

MS2

Magnetic Susceptibility Meter

The *MS2* meter can be connected to a wide range of individually calibrated sensors. When sample material is placed within the influence of the low frequency, 100μT alternating magnetic field produced by the sensor, a change in frequency results. This is converted to a value of magnetic susceptibility, which is displayed digitally in SI or CGS units, as selected. Diamagnetic (negative) values can be measured.

The instrument is powered from internal batteries, rechargeable from the mains or a vehicle dashboard, with indicators for battery status and charging.

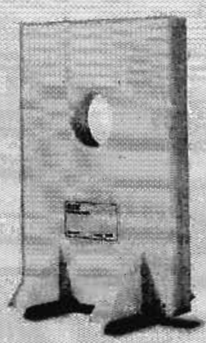
Push buttons or a toggle switch are used for zeroing or taking measurements. A range switch adds one place of decimal to the resolution with an increase in measurement time.

A serial interface provides computer control and data tansfer. A switch, situated on the back panel of the instrument, enables selection of the appropriate communications protocol. All switches and sockets are environmentally sealed.

The *MS2* meter is portable and is supplied with a carrying bag for field use.

Specification

Display - x1 range x0.1 range	 1-9999 0.1-999.9
Display exponent - volume specific mass specific	 10^{-6} CGS or 10^{-5} SI 10^{-6} CGS or 10^{-8} SI
Internal battery	0.6 Ah sealed Ni-Cad gives 8 hours continuous use before recharge is required
Enclosure	high impact ABS
Operating temperature	-10°C to 40°C
Weight	1.3kg
Dimensions (mm)	255 x 158 x 50
Sensor cable	50 ohm TNC to TNC, 1m length (alternative lengths to 100m available on request)
Battery charger inlet	2.1mm socket, 6-18V d.c., 100mA maximum, polarity protected
RS232 interface	standard 1200 baud rate, 9600 baud rate selectable
Interface connector	4-way rear panel Fischer socket



• *MS2C*

MS2C

Core Logging Sensor

This series of sensors, ranging from 36 to 162mm in diameter, is available for high resolution volume susceptibility measurements on whole cores. They are suitable for measuring any type of peat, lake, or marine sediment core, provided it is not metal clad.

These rugged sensors, with a low temperature induced drift, are designed for laboratory, field or shipboard use. They can be used with automated core analysis systems - details of these are available on request.

The *MS2C* sensors are used in prospection, core correlation and the identification of palaeoclimatic sequences. Optimum measurement accuracy is achieved with 5-10mm core clearance. Calibration graphs are provided for varying core to sensor diameters.

Specification

Loop internal diameter	**36, 40, 45, 60, 72, 80, 90, 100, 125, 130, 135, 140, 145, 150, 160 or 162mm standard**
Calibration accuracy	**5%**
Measurement period - **on x1 range** **on x0.1 range**	 **0.9 seconds** **9 seconds**
Operating frequency	**0.565kHz**
Drift - at room temperature	**<2 x 10^{-6} CGS in 10 minutes after 5 minutes operation**
Enclosure	**white polyacetal**
Weight	**2-2.65kg depending on diameter**
Dimensions (mm)	**290 x 200 x 162**

• *MS2D*

MS2D

Probe

This is designed for rapid assessment of the concentration of ferrimagnetic materials in the top 60mm of the land surface. It is used in studies of slope processes and in archaeological prospecting. The probe can only be operated in conjunction with the *MS2* probe handle.

Specification

Depth of response	**50% at 15mm, 10% at 60mm**
Measurement period - **on x1 range** **on x0.1 range**	 **0.5 seconds** **5 seconds**
Operating frequency	**0.958kHz**
Drift - at room temperature	**<20 x 10^{-6} CGS in 20 minutes after 20 minutes operation**
Enclosure	**reinforced epoxy**
Weight	**0.5kg**
Dimensions	**mean diameter 185mm, overall height 87mm**

• *MS2*EI

*MS2*EI

Surface Scanning Sensor

This sensor is designed to perform high resolution measurements on the surface of split drill or soft sediment cores. The sensitive area of the probe, as defined by 50% maximum response, is in the form of a rectangle of 3.8mm x 10.5mm allowing very fine resolution surface measurements. The position of the long axis is identified by marks on the circumference of the ceramic cylinder. The sensor is supplied in a protective case.

Specification

Area of response	**3.8mm x 10.5mm at the end of the ceramic cylinder**
Depth of response	**50% at 1mm, 10% at 3.5mm**
Measurement period - **on x1 range** **on x0.1 range**	 **1.2 seconds** **12 seconds**
Operating frequency	**2kHz**
Drift - at room temperature	**<2 x 10^{6} CGS in 10 minutes after 5 minutes operation**
Enclosure	**Aluminium and ceramic**
Weight	**0.22kg**
Dimensions (mm)	**64 x 25 x 140**

• *MS2*F

*MS2*F

Probe

This miniature probe is ideal for the stratigraphic study of exposed geological and archaeological sections. It is also used where difficult surface conditions prevent good contact with the *MS2*D loop. The probe can only be operated in conjunction with the *MS2* probe handle.

Specification

Area of response	**end face and cylinder wall up to the shoulder**
Depth of response	**10% at 6mm from end face and 4.5mm from outer diameter of cylinder**
Measurement period - **on x1 range** **on x0.1 range**	 **0.9 seconds** **9 seconds**
Operating frequency	**0.58kHz**
Drift - at room temperature	**<20 x 10^{6} CGS in 20 minutes after 20 minutes operation**
Enclosure	**Nylon 6.6**
Weight	**0.075kg**
Overall dimensions	**35mm diameter x 85mm length**

APPENDIX 2

Magnetic susceptibility data for the initial reconnaissance work

PONGOLA

Site 1 : Bubhe Pan

Table A Transect 1 using the MS2D (loop) sensor.

Location	Plot no.	Dist from water (m)	Sample numbers	MS readings			Average MS reading	Notes
S26°59.777'	1	1	1 & 2	22.4	28.5	28.4	26.4	Water's edge
E32°18.023'	2	2		45.5	44.5	45.8	45.3	
	3	3		65.2	62.0	65.7	64.3	
	4	4		62.9	59.9	62.7	61.8	Edge of Cyperus
	5	5	7 & 8	64.6	67.3	67.0	66.3	
	6	6		36.3	32.4	34.6	34.4	
	7	7		47.6	50.2	47.1	48.3	
	8	8		47.0	48.7	49.6	48.4	
	9	9		57.7	56.5	58.5	57.6	
	10	10		36.1	33.3	30.9	33.4	
	11	11		36.1	39.3	42.8	39.4	
	12	12		45.8	48.9	49.6	48.1	
	13	13		38.9	35.1	34.4	36.1	
	14	14		43.3	41.5	40.1	41.6	
	15	15	17 & 18	50.6	54.4	50.9	52.0	
	16	16		51.1	54.3	49.6	51.7	
	17	17	19 & 20	37.3	46.8	38.0	40.7	
	18	18		52.0	52.1	48.0	50.7	
	19	19		50.4	49.4	49.7	49.8	
	20	20		53.6	49.8	49.6	51.0	
	21	21		50.8	48.1	49.9	49.6	
	22	22		61.1	54.3	60.4	58.6	Fever tree canopy
	23	23		70.0	71.9	71.3	71.1	
	24	24		73.2	73.9	73.9	73.7	
	25	25		66.7	68.0	67.6	67.4	
	26	26	25 & 26	90.4	81.2	85.3	85.6	Between two fever trees
	32	32		110.8	113.9	109.5	111.4	Above fever trees
	40	40		130.2	120.8	130.7	127.2	

Table B **Transect 1 (the same transect as Table B) using the MS2F sensor for comparison**

Location	Plot number	MS readings			Average MS reading
S26°59.777'	1	7.5	7.1	9.2	7.9
E32°18.023'	2	57.4	58.3	53.1	56.3
	3	44.5	43.6	42.2	43.4
	4	30.1	30.4	31.4	30.6
	5	45.9	41.9	37.0	41.6
	6	28.4	28.4	29.1	28.6
	7	23.6	24.4	26.0	24.7
	8	23.7	28.2	24.5	25.5
	9	43.7	36.2	35.4	38.4
	10	27.8	26.4	28.1	27.4
	11	40.6	41.4	47.5	43.2
	12	29.8	27.8	22.8	26.8
	13	25.4	24.5	26.8	25.6
	14	33.6	33.1	25.9	30.9
	15	23.3	27.6	31.9	27.6
	16	29.0	45.0	39.0	37.7
	17	31.6	28.2	34.2	31.3
	18	33.1	34.5	33.8	33.8
	19	41.6	35.5	37.4	38.2
	20	43.5	37.7	36.6	39.3
	21	30.5	33.3	29.6	31.1
	22	39.1	35.2	37.5	37.3
	23	40.0	48.7	46.7	45.1
	24	48.9	51.9	54.8	51.9
	25	44.1	44.9	40.1	43.0
	26	45.0	54.1	67.6	55.6
	32	59.2	58.3	60.0	59.2
	40	61.3	61.2	61.2	61.2

Table C Test by observation in each visual zone

Zone / description	MS values										Average MS value
Zone 1 along water's edge	22.5	17.5	31.2	22.8	34.2	26.1	13.9	14.8	10.7	29.5	22.3
Upper zone 1 in reeds	35.7	21.1	15.4	11.8	17.7	18.6	11.2	28	16.4	17.1	19.3
Zone 2 above reeds	49.8	48.5	50.7	70.3	55.7	42.8	53.8	39.4	46.2	30.5	48.8
Upper zone 2	38.3	35.6	42.8	63.3	28.7	57.8	47	54.7	36.2	73.3	47.8
Start of zone 3 in Fever trees	59.2	46.2	70.4	39	65.2						56.0
Above Fever trees	61.3	61.2	56.6	61.2	50.4						58.1

Site 2 : Sokhunti Pan

Table D Reconnaissance Transects – visual zones

Transect	Description	Co-ordinates	Zone/site	MS readings										Ave MS reading
1	From water to beyond tree line, flat	S27^{o01}.359' E32°17.837'	Zone 1, mud next to water	20.2	27.9	22.7	26.5	35.6	14.4	28	29.8	22.9	23.4	25.14
			Zone 1, drier mud	26.5	24.9	30	21	23.6	27	22.3	22.7	18.3	34.3	25.06
			Zone 1, drier mud with grass	36	35.7	30.5	37.2	37.2	36.9	39.3	32.6	32.4	31.9	34.97
			Zone 2,drier, taller vegetation	26.8	24.1	42.3	42	40.3	47.4	39.2	37.2	37.3	29	36.56
			Zone 2, small trees, large surface cracks.	41	38.9	61.5	57.9	77.2	58.8	81	75.2	69.8	83.1	64.44
			Zone 2, small trees and thick grass	65.5	77.6	80.5	77.8	88.8	87.4	74.7	84.5	77.4	63.5	77.77
			Zone 3, edge of fig and acacia thicket	85.4	86	76.1	98.7	88.6	96	117.2	100.5	104.4	108.9	96.18
			Zone 3, I in tree thicket, adjacent to river.	101.5	100.8	128.3	117	100.5	115.7	98.5	112.1	113.5	105.5	109.34
2	Opposite side of pan, up a slope.	S26°59.777' E32°18.023'	Zone 1, water's edge	4.1	6.8	5.7	5	8.3	7	9.3	10.6	6.9	6.8	7.05
			Between grass and mud, Cyperus reeds	11.6	20.4	26.7	18.8	23.5	25.5	19.6	24.2	22.3	20.5	21.31
			Zone 2, upslope, before tree line	51	75	64.3	52	44.8	37.7	54.1	43.6	75.2	56.2	55.39
			Zone 3, further upslope, start of trees	70.8	86.1	53.1	65.3	77.2	64.4	73.4	68.9	68.3	57.9	68.54
			Zone 3, under big trees, sandy soil	56.9	49.5	40.7	68.1	54.2	41.7	60	47	52.7	49.3	52.01

Table E Detailed Transects

Transect 1

MS sensor	Co-ords	Plot no.	Dist from water (m)	Sample numbers	MS readings			Average MS reading	Notes
MS2D (loop)	S27°01.447' E32°17.845'	1	0	27, 28	12.8	14.5	11.7	13.0	Water's edge
		2	4	29, 30	13.1	16.6	18.4	16.0	Between reeds and water
		3	8	31, 32	17.7	19.6	18.8	18.7	In Cyperus reeds
		4	12	33, 34	42.0	41.0	40.1	41.0	Between reeds and trees
		5	32	35, 36	58.4	58.9	60.1	59.1	In line with acacias
		6	52	37, 38	54.9	51.9	54.7	53.8	In big trees

Transect 2

MS sensor	Co-ords	Plot no.	Dist from water (m)	Sample numbers	MS readings			Average MS reading	Notes
MS2D (loop)	S27°01.359' E32°17.837'	1	0	39, 40	30.3	30.7	31.4	30.8	Water's edge
		2	20	41, 42	27.7	32.7	33.8	31.4	Slightly drier, large surface cracks
		3	50	43, 44	27.6	29.6	29.6	28.9	Just before small acacias and long grass
		4	85	45, 46	62.3	62.9	61.5	62.2	In acacias and long grass, before big trees
		5	125	47, 48	90.1	92.8	87.0	90.0	In line with big trees
		6	175	49, 50	104.1	103.6	104.8	104.2	Behind big trees, adjacent to river.

Site 3 : Nomaneni Pan

Table F Detailed transects

Detailed transect 1

MS sensor	Co-ords	Plot no.	Dist from water (m)	Sample numbers	MS readings			Average MS reading	Notes
MS2D (loop)	S26°59.218' E32°16.662'	1	0	51, 52	79.1	75.4	79.7	78.1	Water's edge, red streaks visible
		2	20	53, 54	48.8	48.9	48.8	48.8	Edge of reeds, red mottles
		3	65	55, 56	131.6	119.8	124.0	125.1	Middle of flat area
		4	110	57, 58	127.2	128.8	126.9	127.6	In line with fever trees, small acacias
		5	140	59, 60	373.6	365.4	373.2	370.7	Start of thick bush, bottom of slope
		6	155	61	400.0	354.3	390.5	381.6	Slightly upslope, dense thornbush, too rocky to sample subsoil

Transect 2

MS sensor	Co-ords	Plot no.	Dist from water (m)	Sample numbers	MS readings			Average MS reading	Notes
MS2D (loop)	S27°01.359' E32°17.837'	1	0	62, 63	33.3	35.1	36.3	34.9	Water's edge
		2	24	64, 65	39.3	44.0	42.4	43.1	In line with reeds, lots of red streaks
		3	59	66, 67	35.4	37.3	38.1	38.3	Outer edge of reeds, soil reddish
		4	109	68, 69	79.8	75.9	76.5	74.4	Start of small trees
		5	139	70, 71	59.7	63.0	62.8	62.0	In line with big trees
		6	189	72, 73	143.1	137.5	142.2	140.9	Beyond big trees

KWAZULU-NATAL NORTH COAST

Site 4 : Mkuze Wetland

Table G Detailed MS transect with levels

Dist from slope top (m)	MS readings			Ave MS	Level (m)
0	6.4	6.6	3.9	5.6	2.43
1	6.2	6.8	7.1	6.7	2.37
2	9.4	10.4	8.4	9.4	2.26
3	17.7	17.6	18.5	17.9	2.12
4	23.8	20.7	18.1	20.9	1.97
5	13.5	12.2	13.0	12.9	1.82
6	14.8	12.8	13.4	13.7	1.72
7	12.6	16.2	18.9	15.9	1.50
8	22.5	21.8	20.2	21.5	1.41
9	4.0	4.9	6.1	5.0	1.31
10	6.0	6.1	6.1	6.1	1.19
11	3.6	6.3	6.3	5.4	1.10
12	2.2	2.8	4.2	3.1	1.01
13	2.7	1.7	1.9	2.1	0.97
14	4.9	2.9	3.6	3.8	0.86
15	4.2	1.7	3.3	3.1	0.78
16	2.8	6.2	5.0	4.7	0.76
17	3.8	5.2	2.7	3.9	0.67
18	5.5	5.1	2.4	4.3	0.57
19	3.9	3.6	2.5	3.3	0.52
20	5.9	4.6	3.4	4.6	0.47
21	4.8	5.2	4.9	5.0	0.41
22	3.0	2.0	1.2	2.1	0.34
23	3.1	3.7	4.6	3.8	0.28
24	2.5	4.0	1.4	2.6	0.26
25	3.3	4.2	2.3	3.3	0.24
26	2.6	2.4	3.3	2.8	0.21
27	3.0	1.2	2.2	2.1	0.15
28	4.3	5.7	5.8	5.3	0.12
29	6.5	6.6	8.1	7.1	0.10
30	6.5	4.7	5.6	5.6	0.14
31	3.3	2.2	2.5	2.7	0.13
32	3.5	0.3	1.1	1.6	0.14
33	10.1	11.2	11.7	11.0	0.14
34	4.4	5.8	6.8	5.7	0.15
35	1.6	2.2	0.8	1.5	0.18
36	2.1	0.9	1.5	1.5	0.20
37	0.5	2.0	2.2	1.6	0.21
38	2.6	2.2	2.5	2.4	0.24
39	2.6	2.8	1.0	2.1	0.21
40	3.2	4.1	2.8	3.4	0.26
41	2.1	1.7	2.2	2.0	0.24
42	2.9	2.8	3.5	3.1	0.26
43	1.0	2.0	1.0	1.3	0.32
44	10.0	11.0	10.0	10.3	0.43

45	1.0	4.0	3.0	2.7	0.50
46	2.0	4.0	2.0	2.7	0.52
47	2.0	3.0	2.0	2.3	0.58
48	6.0	4.0	3.0	4.3	0.64
49	3.0	4.0	2.0	3.0	0.70
50	5.0	2.0	1.0	2.7	0.76
51	10.0	6.0	8.0	8.0	0.85
52	19.7	21.9	22.7	21.4	1.00
53	17.0	13.2	14.7	15.0	1.02
54	48.3	40.7	46.7	45.2	1.09
55	15.8	13.8	12.6	14.1	1.10
56	21.4	25.1	27.6	24.7	1.22
57	17.4	15.6	15.4	16.1	1.38
58	11.4	9.6	11.1	10.7	1.51
59	13.5	10.5	12.3	12.1	1.66
60	10.7	12.3	13.9	12.3	1.76
61	3.2	5.3	7.4	5.3	1.87
62	3.2	6.8	6.9	5.6	1.92

Table H Reconnaissance transect

Dist along transect, notes	MS readings				Ave MS reading
0m top of ridge	6.9	4.9	5.6	5.6	5.8
10m	2.2	4.9	6.4	5.0	4.6
20m top side of road	5.8	9.4	8.3	8.6	8.0
25m	3.9	4.2	3.9	4.1	4.0
30m ncema zone	1.3	2.8	3.7	2.1	2.5
35m	3.1	2.9	2.6	2.8	2.9
45m	2.3	2.1	2.0	1.1	1.9
55m	2.8	3.5	2.4	3.0	2.9
65m	3.2	1.4	2.8	3.4	2.7
75m	3.6	4.2	4.6	4.5	4.2
85m	3.3	3.6	5.0	3.5	3.9
95m	9.3	7.5	10.1	10.2	9.3
105m	26.3	28.1	25.4	25.6	26.4
115m ncema zone	11.2	9.5	10.3	8.8	9.9
125m	30.2	34.4	34.4	32.0	32.8
126m	60.3	66.4	65.9	62.9	63.9

Table I Detailed transects

MS sensor	Co-ords	Plot no.	Dist along transect (m)	Sample numbers	MS readings			Average MS reading	Notes
MS2D (loop)	S27°35.061' E32°28.512'	1	0	74, 75	3.3	3.6	2.9	3.3	Grey sand, recently burnt, sparse vegetation
		2	10	76, 77	3.7	3.4	3.2	3.4	Grey sand, burnt, under tree
		3	20	78, 79	2.8	2.9	2.9	2.9	Grey sand, burnt, edge of wet zone
		4	35	80, 81	1.2	1.4	1.5	1.4	In middle of wetland, black organic soil
		5	55	82, 83	15.4	19.1	19.7	18.1	Burnt, edge of permanent zone / reeds
		6	65	84, 85	41.7	40.9	40.9	41.2	In temp zone, mottles and streaks in subsoil
		7	75	none	62.3	63.2	62.6	62.7	
		8	80	none	20.2	24.3	23.9	22.8	
		9	83	none	8.1	8.0	7.9	8.0	
		10	85	86, 87	6.3	6.2	6.6	6.4	Just beyond tree line

Transect 2

MS sensor	Co-ords	Plot no.	Dist along transect (m)	Sample numbers	MS readings			Average MS reading	Notes
MS2D (loop)	S27°35.340' E32°28.470'	1	0	88, 89	4.5	4.3	4.5	4.4	Grey sand, in trees, top of slope
		2	30	90, 91	16.0	15.3	13.8	15.0	Temp zone
		3	60	92, 93	3.0	2.8	2.4	2.7	In water
		4	100	94, 95	18.2	18.3	19.5	18.7	Temp zone
		5	120	96, 97	4.5	5.0	5.5	5.0	In trees, top of slope

Site 5 Yengweni Wetland

Table J Detailed transect

MS sensor	Co-ords	Plot no.	Dist along transect (m)	Sample numbers	MS readings			Average MS reading	Notes
MS2D (loop)	S27°37.913' E32°25.924'	1	0	98, 99	6.3	6.7	6.0	6.3	In trees
		2	40	100, 101	20.5	17.5	20.2	19.4	In temp zone
		3	80	102, 103	3.3	3.4	2.9	3.2	In perm zone
		4	110	104, 105	30.5	35.7	37.0	34.4	In temp zone between tongues
		5	145	106, 107	29.9	32.2	30.8	31.0	Temp zone
		6	225	108, 109	3.9	4.6	4.5	4.3	Perm zone
		7	240	none	16	16.8	17	16.6	
		8	250	none	27.5	25.3	22.9	25.2	
		9	255	110, 111	44.2	42.9	44.8	44.0	Temp zone
		10	265	112, 113	18.4	17.1	16.8	17.4	Temp zone
		11	275	none	10.4	10.8	10.2	10.5	
		12	295	114, 115	7.8	7.6	7.1	7.5	In trees

Table K MS only transect

Dist from water, notes	MS Values			Ave MS Value
0m water	1.6	2.9	3.1	2.5
4m	2.5	1.2	2.0	1.9
10m	13.4	14.7	14.9	14.3
20m Temp zone	14.5	14.1	16.3	15.0
30m	22.3	23.1	23.6	23.0
40m	14.4	13.1	14.7	14.0
50m	11.9	11.7	12.7	12.1
60m Start of trees	20.4	15.6	20.5	18.8
70m	10.3	9.9	11.7	10.6
90m	6.7	7.0	7.9	7.2
100m	10.9	11.2	11.0	11.0
110m Thick trees	17.1	18.2	16.6	17.3
120m	10.2	9.9	9.9	10.0

NATAL MIDLANDS

Site 6 : Highmoor

Table L Seep transect

Co-ordinates	Dist along transect (m), notes	MS readings			Ave MS
S29°19.352'	0	170	158	152	160
E29°36.904'	2	127	124	112	121
	4	178	168	180	175
	6	161	150	159	157
	8 Edge of ridge	174	158	152	161
	10	316	353	354	341
	12	130	142	136	136
	14 In wetland	199	196	207	201
	16	350	355	323	343
	18	417	394	398	403
	20	312	325	303	313
	22	369	367	379	372
	24	233	284	235	251
	26	305	280	241	275
	28	270	276	243	263
	30	330	321	324	325
	32	393	389	322	368
	34	272	296	285	284
	36	253	273	273	266
	38	258	251	254	254
	40 Lowest flow path	246	244	249	246
	42	376	352	311	346
	44	424	367	398	396
	46	364	368	359	364
	48	410	364	380	385

50	318	290	301	303
52 Edge of wetland	199	208	259	222
54 Up ridge	258	237	225	240
56	284	244	265	264
58	170	169	149	163
60	391	373	395	386
62	472	468	456	465
64	450	450	450	450

Table M Wetland transect

Co-ordinates	Dist along transect (m), notes	MS readings			Ave MS
S 29°19.214'	0 Outer edge	317	314	289	307
E 29°36.724'	2m	263	280	264	269
	4m	285	275	277	279
	6m	396	380	381	386
	8m	171	178	192	180
	10m	352	344	334	343
	12m	284	279	271	278
	14m	404	407	365	392
	16m	321	334	309	321
	18m	156	182	181	173
	20m	216	210	218	215
	22m Spiky grass	128	122	120	123
	24m	309	277	221	269
	26m	343	399	356	366
	28m	319	273	290	294
	30m	191	172	167	177
	32m	189	213	228	210
	34m	239	240	234	238
	36 Edge of water	46	45	47	46
	38m	26	26	25	26
	40m	5	11	11	9
	42m	14	14	13	14
	44m	10	8	5	8
	46m	14	14	12	13
	48m	8	6	5	6
	50m	6	5	4	5
	52m	16	13	14	14
	54m	12	14	14	13
	56 Edge of wet	55	41	44	47
	58m	187	171	172	177
	60m	158	158	151	156
	62m	233	228	216	226
	64m	145	141	143	143
	66m	86	80	73	80
	68m	95	88	84	89
	70m	134	119	126	126
	72m	156	132	140	143
	74m	291	317	298	302
	76m	198	178	196	191

78m	185	165	206	185
80m	222	210	204	212
82m	246	245	248	246
84m	191	185	184	187
86m	229	235	220	228
88m	352	339	352	348
90m	249	246	257	251
92m	333	395	369	366
94m	327	355	262	315
96m	197	206	212	205
98m	252	266	273	264
100m	304	333	256	298
104m	247	238	220	235

Site 7 : Oribi

Table N Detailed transect 1

Co-ordinates	Dist along transect (m), notes	MS readings			Ave MS
S 29°39.122	0m Hyparrhenia, Cyperus	34.6	35.2	35.1	35.0
E 30°24.340'	6m less Cyperus, Eragrostis	96.7	88.2	86.6	90.5
	12m	228.5	222.2	191.5	214.1
	21m	274.8	283.6	238.0	265.5
	30m	240.6	242.0	237.5	240.0

Table O Detailed transect 2

Co-ordinates	Dist along transect (m), notes	MS readings			Ave MS
S 29 39.151	0m Cyperus	44.2	44.0	45.7	44.6
E 30 24.337'	10m Edge of long grass	45.1	48.5	49.2	47.6
	20m	159.0	126.7	131.1	138.9
	28m	248.2	260.3	269.3	259.3

Site 8 : Hesketh

Table P Detailed transect

Co-ordinates	Dist along transect (m), notes	MS readings			Ave MS
S 29°39.166	0m In wetland	57.5	54.2	57.9	56.5
E 30°24.323'	5m Edge of wetland	72.1	77.4	76.5	75.3
	15m	86.8	81.4	87.8	85.3
	23m	119.5	123.1	120.3	121.0
	31m	166.0	162.2	153.8	160.7

Site 9 : Shafton

Table Q Transect 1

Dist from water	Co-ordinates	Sample numbers	MS readings			Ave MS	Notes
0	S29 27.129'	145, 146	0	0.6	0.8	0.5	In water
2	E30 14.768'		13.2	13.2	12.8	13.1	Edge of reeds
3			10.5	11	10.1	10.5	
4			23.5	18	21.1	20.9	
5			10.1	9.2	9.2	9.5	
6			17.3	16.6	17.1	17.0	
7			12.8	14.2	14.1	13.7	
8			21.7	18	18.4	19.4	
9			35.5	35.7	30.5	33.9	
10			25.3	21.5	22.7	23.2	
11		147, 148	44.6	33	33.6	37.1	
12			63	63.1	57.1	61.1	
13			37.3	36.9	37.6	37.3	
14			18.1	17.3	17.9	17.8	
15			58.3	53.5	49.9	53.9	
16			55.7	64	58	59.2	
17			19.8	18.1	16.8	18.2	
18			31.2	22.9	20.6	24.9	
19			50.7	51.4	46.8	49.6	
21			76.1	76.9	78.1	77.0	
23			84.6	85	84.6	84.7	
25			68.3	67.3	54.2	63.3	
27			31.4	34.9	34.7	33.7	Edge of road, disturbed
29			130.6	141.3	133.6	135.2	On road
31			55.6	57.9	56.2	56.6	
33			51.7	57.2	53.3	54.1	Recently harvested trees
37		151, 152	114.5	111.5	114	113.3	
40			129.1	123.7	131.2	128.0	
46		153, 154	160.9	162.1	159	160.7	
54			159.6	168.1	175.2	167.6	
66			315.7	321.8	315.4	317.6	Top of hill

Table R Transect 2

Dist from water (m)	Co-ordinates	Sample numbers	MS readings			Ave MS	Level (m)
0	S29 27.111'	155, 156	5	8	7	6.7	0.0
2	E30 14.761'		22	23	19	21.3	0.2
4			10	12	11	11.0	0.2
6			16	14	13	14.3	0.2
8			54	61	56	57.0	0.3
10			34	33	30	32.3	0.5
12			30	27	27	28.0	0.6
14		157, 158	42	43	41	42.0	0.7
16			49	50	50	49.7	1.0
18			48	51	49	49.3	0.7
20			84	92	81	85.7	0.7
22			87	84	95	88.7	0.8
24			95	100	91	95.3	1.1
26			150	154	149	151.0	1.5
28		159, 160	200	193	201	198.0	1.6
30			115	127	120	120.7	1.6
32			127	116	122	121.7	1.9
34			133	148	138	139.7	2.2
36			181	170	183	178.0	2.4
38		161, 162	146	152	140	146.0	2.6
40			132	121	124	125.7	2.9
42		163, 164	85	90	83	86.0	3.1
44			143	140	145	142.7	3.3

APPENDIX 3

Field soil analysis data for the initial reconnaissance work.

PONGOLA

Site 1 : Bubhe Pan

Table A1 Soil data for transect 1

Sample no.	Depth (cm)	Colour field	wet	Mottles abundance	chroma	Soil form
1	0-20	7.5YR 3/1	7.5YR 3/1	few	low	
2	20-40	10YR 3/1	10YR 3/1	few	very low	Rensburg
7	0-20	7.5YR 3/1	7.5YR 3/1	few	low	
8	20-40	7.5YR 3/1	7.5YR 3/1	few	low	Rensburg
17	0-20	7.5YR 3/2	7.5YR 3/1	few	low	
18	20-40	7.5YR 3/2	7.5YR 3/2	few	low	Rensburg
19	0-20	7.5YR 3/2	7.5YR 3/2	few	high	
20	20-40	7.5YR 3/1	7.5YR 3/1	common	high	Sepane
25	0-20	5YR 3/2	5YR 3/2	few	high	
26	20-40	5YR 3/2	5YR 3/2	common	high	Sepane

Site 2 : Sokhunti Pan

Table B1 Soil data for transects 1 and 2

Sample no.	Depth (cm)	Colour field	wet	Mottles abundance	chroma	Soil form
Transect 1						
27	0-20	N3/	N3/	nil		
28	20-40	N3/	N3/	nil		Rensburg
29	0-20	N3/	N3/	nil		
30	20-40	N3/	N3/	nil		Rensburg
31	0-20	N3/	N3/	few	low	
32	20-40	N3/	N3/	few	low	Willowbrook
33	0-20	5YR3/1	5YR3/1	many	high	
34	20-40	5YR2.5/1	5YR2.5/1	many	high	Willowbrook
35	0-20	7.5YR3/2	7.5YR3/2	few	low	
36	20-40	7.5YR3/2	7.5YR3/2	few	low	Sepane
37	0-20	7.5YR3/2	7.5YR3/2	nil		
38	20-40	7.5YR3/2	7.5YR3/2	nil		Valsrivier
Transect 2						
39	0-20	N3/	N3/	few	low	
40	20-40	N3/	N3/	few	low	Rensburg
41	0-20	7.5YR2.5/1	7.5YR2.5/1	many	low	
42	20-40	7.5YR2.5/1	7.5YR2.5/1	many	low	Rensburg
43	0-20	7.5YR2.5/1	7.5YR2.5/1	many	low	
44	20-40	7.5YR2.5/1	7.5YR2.5/1	many	low	Rensburg
45	0-20	7.5YR3/2	7.5YR3/2	many	high	

46	20-40	7.5YR4/4	7.5YR4/4	many	high	Pinedene
47	0-20	7.5YR3/2	7.5YR3/2	few	high	
48	20-40	7.5YR4/4	7.5YR4/4	nil		Pinedene
49	0-20	7.5YR3/3	7.5YR3/3	nil		
50	20-40	7.5YR3/3	7.5YR3/3	few	high	Pinedene

Site 3 : Nomaneni Pan

Table C1 Soil data for transects 1 and 2

		Colour			Mottles		
Sample no.	**Depth (cm)**	**field**	**wet**	**dry**	**abundance**	**chroma**	**Soil form**
Transect 1							
51	0-20	7.5YR3/1	7.5YR3/1	10YR 3/2	few	low	
52	20-40	N2.5/	N2.5/	10YR 3/2	many	low	Rensburg
53	0-20	7.5YR3/2	7.5YR3/2	7.5YR 4/3	many	high	
54	20-40	7.5YR3/1	7.5YR3/1	7.5YR 3/2	many	low	Sepane
55	0-20	7.5YR3/2	7.5YR3/2	7.5YR 4/3	few	low	
56	20-40	7.5YR3/2	7.5YR3/2	7.5YR 3/2	few	low	Sepane
57	0-20	7.5YR3/2	7.5YR3/2	7.5YR 3/2	nil		
58	20-40	7.5YR3/2	7.5YR3/2	7.5YR 3/2	nil		Sepane
59	0-20	7.5YR3/2	7.5YR3/2	7.5YR 3/2	nil		
60	20-40	7.5YR3/2	7.5YR3/2	7.5YR 3/2	few	high	Sepane
61	0-20	7.5YR3/2	7.5YR3/2	7.5YR 3/2	nil		Glenrosa
Transect 2							
62	0-20	N3/	N3/	10YR 4/2	nil		
63	20-40	N3/	N3/	10YR 4/2	nil		Rensburg
64	0-20	7.5YR3/1	7.5YR3/1	7.5YR 3/1	many	low	
65	20-40	7.5YR3/1	7.5YR3/1	7.5YR 3/1	few	low	Rensburg
66	0-20	7.5YR3/2	7.5YR3/1	7.5YR 4/3	many	high	
67	20-40	7.5YR3/2	7.5YR3/1	7.5YR 4/3	many	high	Sepane
68	0-20	7.5YR3/1	7.5YR3/1	7.5YR 4/3	few	low	
69	20-40	7.5YR3/1	7.5YR3/1	7.5R 4/2	many	low	Sepane
70	0-20	7.5YR3/2	7.5YR3/2	7.5YR 3/2	many	low	
71	20-40	7.5YR3/2	7.5YR3/2	7.5YR 4/2	few	low	Sepane
72	0-20	7.5YR3/3	7.5YR3/3	7.5YR 3/3	nil		
73	20-40	7.5YR3/3	7.5YR3/3	7.5YR 3/3	nil		Valsrivier

SODWANA

Site 4 : Mkuze

Table D1 Soil data for transects 1 and 2

Sample no.	Depth (cm)	Colour field	wet	dry	Mottles abundance	Soil form
Transect 1						
74	0-20	10YR 5/1	10YR 3/1	10YR 5/1	nil	
75	20-40	10YR 4/2	10YR 3/2	10YR 5/2	nil	Namib
76	0-20	10YR 3/2	10YR 2/1	10YR 3/2	nil	
77	20-40	10YR 3/2	10YR 2/1	10YR 3/2	nil	Namib
78	0-20	10YR 2/1	10YR 2/1	10YR 2/1	nil	
79	20-40	10YR 2/1	10YR 2/1	10YR 2/1	nil	Sweetwater
80	0-20	N2.5/	N2.5/	N2.5/	nil	
81	20-40	N2.5/	N2.5/	N2.5/	nil	Champagne
82	0-20	10YR 2/1	10YR 2/1	10YR 2/1	nil	
83	20-40	10YR 2/1	10YR 2/1	10YR 2/1	nil	Sweetwater
84	0-20	10YR 3/2	10YR 2/1	10YR 3/2	nil	
85	20-40	10YR 3/2	10YR 2/1	10YR 3/2	nil	Namib
86	0-20	10YR 3/2	10YR 2/1	10YR 3/2	nil	
87	20-40	10YR 3/2	10YR 2/1	10YR 3/2	nil	Namib
Transect 2						
88	0-20	10YR 5/1	10YR 3/1	10YR 5/2	nil	
89	20-40	10YR 5/2	10YR 3/2	10YR 5/2	nil	Namib
90	0-20	10YR 2/1	10YR 2/1	10YR 2/1	nil	
91	20-40	10YR 2/1	10YR 2/1	10YR 2/1	nil	Sweetwater
92	0-20	N 2.5/	N2.5/	N2.5/	nil	
93	20-40	N2.5/	N2.5/	N2.5/	nil	Champagne
94	0-20	N2.5/	N2.5/	N2.5/	nil	
95	20-40	N2.5/	N2.5/	N2.5/	nil	Sweetwater
96	0-20	10YR 5/1	10YR 3/1	10YR 5/2	nil	
97	20-40	10YR 5/2	10YR 3/2	10YR 5/2	nil	Namib

Site 5 : Yengweni

Table E1 Soil data for transect 1

Sample no.	Depth (cm)	Colour field	wet	dry	Mottles abundance	Soil form
Transect 1						
98	0-20	10YR 4/2	10YR 3/2	10YR 4/2	nil	
99	20-40	10YR 4/3	10YR 4/2	10YR 4/2	nil	Namib
100	0-20	10YR 3/1	10YR 3/2	10YR 3/2	nil	
101	20-40	10YR 4/1	10YR 3/1	10YR 4/1	nil	Sweetwater
102	0-20	N2.5/	N2.5/	10YR 2/1	nil	
103	20-40	N2.5/	N2.5/	10YR 3/1	nil	Champagne
104	0-20	10YR 2/1	10YR 2/1	10YR 3/1	nil	
105	20-40	10YR 3/2	10YR 3/2	10YR 4/1	nil	Sweetwater
106	0-20	10YR 2/1	10YR 2/1	10YR 3/1	nil	
107	20-40	10YR 4/1	10YR 4/1	10YR 5/2	nil	Sweetwater
108	0-20	N2.5/	N2.5/	10YR 2/1	nil	
109	20-40	N2.5/	N2.5/	10YR 2/1	nil	Champ
110	0-20	10YR 2/2	10YR 2/2	10YR 2/2	nil	
111	20-40	10YR 3/2	10YR 3/2	10YR 4/1	nil	Sweetwater
112	0-20	10YR 4/2	10YR 4/2	10YR 4/1		
113	20-40	10YR 2/2	10YR 2/2	10YR 3/1	nil	Namib
114	0-20	10YR 3/2	10YR 3/1	10YR 3/2	nil	
115	20-40	10YR 4/2	10YR 3/2	10YR 3/2	nil	Namib

NATAL MIDLANDS

Site 6 : Highmoor

No soil samples were taken at this site.

Site 7 : Oribi

Table F1 Soil data for transects 1 and 2

Sample no.	Depth (cm)	Colour field	wet	dry	Mottles abundance	chroma	Soil form
Transect 1							
116	0-20	7.5YR 3/1	7.5YR 2.5/1	7.5YR 3/2	few	low	
117	20-40	7.5YR 2.5/1	7.5YR 2.5/1	7.5YR 2/2	nil		Sepane
118	0-20	7.5YR 3/2	7.5YR 3/1	7.5YR 3/2	nil		
119	20-40	7.5YR 3/2	7.5YR 3/1	7.5YR 3/2	nil		Sepane
120	0-20	7.5YR 3/2	7.5YR 3/1	7.5YR 3/2	nil		
121	20-40	7.5YR 3/3	7.5YR 3/2	7.5YR 3/2	nil		Sepane
122	0-20	7.5YR 4/3	7.5YR 3/2	7.5YR 4/3	nil		
123	20-40	7.5YR 3/3	7.5YR 2.5/3	7.5YR 4/3	nil		Mispah
124	0-20	7.5YR 4/3	7.5YR 3/2	7.5YR 4/3	nil		
125	20-40	7.5YR 4/4	7.5YR 3/2	7.5YR 4/4	nil		Mispah
Transect 2							
127	0-20	7.5YR 2.5/1	7.5YR 2.5/1	7.5YR 3/1	nil		
128	20-40	7.5YR 2.5/1	7.5YR 2.5/1	7.5YR 3/1	few	low	Sepane
129	0-20	7.5YR 3/1	7.5YR 2.5/1	7.5YR 3/2	nil		
130	20-40	7.5YR 2.5/1	7.5YR 2.5/1	7.5YR 3/2	few	low	Sepane
131	0-20	7.5YR 4/2	7.5YR 3/2	7.5YR 4/2	nil		
132	20-40	7.5YR 3/3	7.5YR 2.5/3	7.5YR 3/3	nil		Mispah
133	0-20	7.5YR 4/3	7.5YR 3/2	7.5YR 4/3	nil		
134	20-40	7.5YR 4/3	7.5YR 2.5/2	7.5YR 4/2	nil		Mispah

Site 8 : Hesketh

The soil samples for this site were not analysed since a new methodology had been developed. Time constraints prevented their analysis for comparative purposes.

Site 9 : Shafton

The soil samples for this site were not analysed since a new methodology had been developed. Time constraints prevented their analysis for comparative purposes.