SOIL HYDROLOGY AND HYDRIC SOIL INDICATORS OF THE BOKONG WETLANDS IN LESOTHO

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DECLARATION

I declare that the dissertation hereby submitted by me for the Doctor of Philosophy in Soil Science degree at the University of Free State is my own independent work and has not previously been submitted by me at another university / faculty. I furthermore cede copyright of the dissertation in favour of the University of the Free State.

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ABSTRACT

Wetland hydrology controls the function of the wetland ecosystem and hence it is the principal parameter for delineation and management of wetlands. It is defined as the water table depth, duration, and frequency required for an area to develop anaerobic conditions in the upper part of the soil profile leading to the formation of iron and manganese based soil features called redoximorphic features. The redoximorphic features must occur at specific depths in the soil profile with specific thickness and abundance to qualify for a hydric soil indicators. Therefore, hydric soil indicators are used to evaluate the wetland hydrology if such a relationship has been verified. The aims of the study were i) to determine soil variation and hydric soils indicators along a toposequence, ii) to determine the relationships between soil water saturation, redox potential and hydric soil morphological properties and iii) to determine the distribution of soil properties and accumulation of soil organic carbon in hydric and non-hydric soils.

The study was conducted at the upper head-water catchment of the Bokong wetlands in the Maloti/Drakensberg Mountains, Lesotho. The soil temperature ranged between -10 and 23°C. The soils had a melanic A overlying an unspecified material with or without signs of wetness, or a G horizon. The organic O occurred in small area. Soil profiles were dug along a toposequence and described to the depth of 1000 mm or shallower if bedrock was encountered. Redoximorphic features were described using standard soil survey abundance categories. Soil samples were collected from each horizon and analysed for selected physical and chemical soil properties.

The soils had low bulk density ranging from 0.26 in the topsoil to 1.1 Mg m^{-3} in the subsoil. Significantly low bulk density was observed in the valleys and highest bulk densities were observed on the summits. The soil organic carbon content ranged between 0.18% in the subsoil and 14.9% in the topsoil. The soil also had a high dithionite extractable Fe (mean 93±53 g kg^{-1}) and low CEC (mean 26±9 $cmol_c$ kg^{-1}). Soil pH and CEC were relatively lower in the valleys and higher on the summits. Principal component analysis indicated four principal components accounted for 60% of the total variance. The first principal component that contributed 23% of the variation showed high coefficients for soil properties related to organic matter turnover, the second components were related to inherent fertility, the third and fourth were related to acidity and textural variation.

Hydric indicators identified in Bokong were histisols (A1), histic epipedon (A2), thick dark surfaces (A12), redox dark surfaces (F6), depleted dark surfaces (F7), redox depressions

(F8), loamy gleyed matrix (F2) and umbric surfaces (F13). The thick dark surfaces with many prominent depletions and gley matrix (A12 and F7) occurred in the valleys, while the midslopes and footslopes were dominated by umbric surfaces (A13). The indicators F6, F7 and F8 were not common. Indicators that were related to the peat formation (A1, A2 and F13) were frequently observed.

The relationship between soil water saturation and redoximorphic features was verified by monitoring the groundwater table with piezometers, installed in ten representative wetlands at depths of 50, 250, 500, 750, and 1000 mm for two years from September 2009 to August 2011. Redoximorphic feature abundance categories were converted into indices. Strong correlations were observed between redoximorphic indices and cumulative saturation percentage. The depth to chroma 3 and 4 (*d_34*) and depth to the gley matrix (*d_gley*) correlations were $R^2 = 0.77$ and $R^2 = 74$ respectively. All redoximorphic indices were poorly correlated with average seasonal high water table. Strong correlation were also observed between profile darkening index (PDI) and cumulative saturation ($R^2 = 0.88$) and weak correlations were observed between PDI and average seasonal high water table ($R^2 = 0.63$).

A paired t test indicated that soil pH, exchangeable Mg and Na, dithionite extractable Fe and Al were significantly different between hydric and non-hydric soils. Hydric soils had significantly higher Mg, Na and Fe content, and significantly low soil pH and Al content. Generally it appeared that soluble phosphorus, Fe and exchangeable bases accumulated in hydric soils, while the soil pH and Al content decreased. The mean soil organic carbon contents were 3.61% in hydric soils and 3.38% in non-hydric soils. However, non-hydric soil relatively stored more organic carbon (174.4 Mg C ha^{-1}) than hydric soils (155.1 Mg C ha^{-1}). The mean soil organic carbon density of the study area was 166±78.3 Mg C ha^{-1}) and the estimated carbon stored was 21619 Mg C (0.022 Tg C; 1Tg = 10^{12}g) within the 1000 mm soil depth. About 384.9 Mg C was stored in the hydric soils within the study area, which was about 1.9% of the total carbon stored in the area to the bedrok or depth of 1000 mm. Among the wetland types, bogs had significantly higher organic carbon levels (6.17%) and stored significantly higher carbon (179 Mg C ha^{-1}) with at least 44% was store in the A1 horizon.

It was concluded that the strong correlation observed between PDI, *d_34*, *d_gley* and cumulative saturation representing hydric indicators such as histisols (A1), histic epipedon (A2), umbric surfaces (F13), loamy gleyed matrix (F2) can be used to determine the duration and frequency of the water table in the landscape studied. These hydric indicators can be used to delineate wetlands, however, more indicators can be developed.

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C/N	Carbon Nitrogen ratio
CEC	Cation Exchange Capacity
DWAF	Department of Water Affairs and Forestry
FAO	Food and Agricultural Organisation
GWT	Groundwater table
LHWP	Lesotho Highlands Water Project
NRCS	Natural Resource Conservation services
NTCHS	National technical committee for hydric soils
PCA	Principal Component Analysis
PDI	Profile Darkening Index
SA	South Africa
SANBI	South African National Biodiversity Institute
SOC	Soil Organic Carbon
SSSA	Soil Science Society of America
USDA	United States Department of Agriculture
WRB	World Reference Base for soil resources

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Wetlands have free water near the soil surface during most part of the year (Spray & McGlothlin, 2004). The Ramsar Convention (1971) regards wetlands as "*areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters*". The Ramsar wetlands definition was adopted by all signatory countries including Lesotho (Mokuku *et al*., 2002) and South Africa with minor modifications (SANBI, 2009).

Inventories on the wetlands of Lesotho, classifies these as Palustrine, sub-class alpine-mires best referred to as peatlands (Schwabe & Whyte, 1993; Schwabe, 1995; Marneweck & Grundling, 1999). The classification was adapted from the "Cowardin" wetland classification developed in the USA (Cowardin *et al.,* 1979), which uses vegetation types to classify wetlands. Extensive work has been done to draw-up the wetland vegetation species lists for different wetlands types of Lesotho (Schwabe & Nthabane, 1989; Schwabe, 1993; Schwabe & Whyte, 1993; Schwabe, 1995; Marneweck & Grundling, 1999; Mokuku *et al*., 2002; Kobisi, 2005; Mucina & Rutherford, 2006). The distribution of different vegetation species in different wetlands of Lesotho is more affected by altitude, terrain, soil moisture, and soil type (Schwabe & Nthabane, 1989; Schwabe, 1993; Schwabe & Whyte, 1993). Schwabe (1995) observed that the decomposition of the dominant vegetation types of these wetlands encourages the development of peat. However, the peat charecteristics have been used by few studies to further characterise the wetlands.

Peatlands are wetlands that have a peat substrate and have vegetation that encourages peat formation (Ramsar, 1997). According to SSSA (1997) peat is the "*unconsolidated soil material consisting largely of undecomposed, or slightly decomposed, organic matter accumulated under conditions of excessive moisture*". However, most soil classification systems describe peat as an organic material that contain organic carbon content greater than 12 to 18% depending on clay content of the mineral fraction (FAO, 2006; Soil survey staff, 2010). Few studies have quantified the soil organic carbon content of Palustrine wetlands of Lesotho (Walter *et al*., 2006; Nkheloane *et al*., 2012). Marneweck and Grundling (1999) characterised the peat profile of these wetlands by peat colour, colour of expressed water, Von Post humification scale and description of fibre content. This was the only study found that has tried to characterise wetland soils of Lesotho and relates peat characteristics to their hydrology. However, water is the key parameter defining a wetland, therefore, wise use of wetlands requires knowledge about the hydrology of the wetland.

The concept of hydric soils has been coined to describe soils formed under prolonged water saturation to develop anaerobic conditions within the root zone and have unique soil morphology (Mausbach & Parker, 2001). Hence, soil morphology such as soil colour and diagnostic horizons are used to interpret soil genetic processes and relate them to soil water regimes (Lin *et al.*, 2008; Lindbo *et al.*, 2010). The wetland ecosystems are dominantly anaerobic but also have aerobic-anaerobic interfaces characterised by large gradients in redox potential created by a fluctuating water table. Redox reactions under saturated anaerobic conditions use secondary electron acceptors such as iron and manganese. These elements are reduced and become mobile. The redistribution of Fe^{2+} and Mn^{2+} in the soil leaves colour imprints that represent different redox states in the profile. The soil colour imprints are called redoximorphic features (Faulkener, 2004) and are used reliably to estimate the water table dynamics (O'Donnell *et al.*, 2010; Calzolari & Ungaro, 2012). Efforts to quantify and interpret redoximorphic features can successfully be used as pedo-transfer functions in wetland hydrology (Lin, 2003; Lin *et al.*, 2004).

Even though the relationship between redoximorphic features and soil water saturation are expected, literature has indicated explicitly that such relationships should be verified locally because several interactions in the soil may affect their development (Lindbo *et al.*, 2010). Vepraskas and Caldwell (2008) observed that redoximorphic features did not develop because of low organic carbon or low Fe reserves in the subsoil. In some cases, features might be relict (which does not represent the current hydrology). Hence it is important to verify whether or not such existing features are related to the present hydrology.

The initial work of Kotze *et al.* (1994) in South Africa developed soil indicators of wetland hydrology for KwaZulu-Natal. They realised that most studies relating the soil redoximorphic features and water regime are localized to sets of environmental conditions, hence are therefore unsuitable for universal application. However, such studies can be extended to larger areas if verifications are carried out (Kotze *et al.*, 1996). This has encouraged further work to define soil pedogenegic processes from relationships studied between soil profile morphology and water regime relationships for different soils of agricultural importance in South Africa (Van Huyssteen *et al.*, 2005; Jennings *et al.*, 2008; Van Tol *et al.*, 2010a; 2010b; Smith & Van Huyssteen, 2011; Van Huyssteen, 2012). Redox indicators such as Fe^{3+} and Mn^{4+} concentrations and depletions confirm the relationship between soil water regime and redoximorphic features. Thus the linkages between soil morphology and hydrology in the wetlands of South Africa and Lesotho can provide further insight on identifying hydric soils, and defining the wetland hydrology.

1.2 MOTIVATION

The high altitude catchments of Lesotho form part of the largest watershed in Southern Africa, renowned for its large water storage from their wetlands, vast rich rangelands and unique biological diversity (Strategic Environmental Focus (Pty) Ltd, 2007). The wetlands cover approximately 1.36% of the total land area of Lesotho (Mokuku *et al*., 2002), which play a major role in sustaining the perennial water flow and regulating the water quality of the major Senqu-Orange river system. These wetlands serve as an economic trade in quality water between South Africa (SA) and Lesotho, through Lesotho Highlands Water Project (LHWP). Scovronick and Turpie (2007) estimated grazing value of the three representative degraded alpine wetlands namely; Khalong-la-Lithunya, Kotisephola (LHWP) and Letšeng-la-Letsie (the only Ramsar site in Lesotho; Turpie & Malan, 2010) at 111 000 Maloti/year (1 US dollar = 8 Maloti). The projected value 10 years after rehabilitation is 450 000 Maloti/year.

The wetlands that were identified to represent various wetland types in the mountains of Lesotho by Marneweck and Grundling (1999) include the wetlands of Bokong, Maliba-Mats'o, Motete, and Matsoku rivers. They are major catchments of the Katse reservoir. It was noted that the Bokong wetlands are facing a serious problem of land degradation owing to soil erosion due to the high altitude system, steep topography, and increased anthropogenic influence on land resources (Lesotho Highlands Development Authority, 1998). Gully erosion accelerated by grazing pressure has been a historic record. Schwabe (1995) articulated the causes of the damage of these wetlands to overgrazing and trampling by livestock. According to Mokuku *et al.* (2002), the degradation was exacerbated by the construction of the road to Katse dam that traverses through these wetlands. Marneweck and Grundling (1999) observed the impact of the road causing gully erosion to the extent of draining the wetlands.

The Bokong catchment was designated as a reserve as part of the strategy to conserve the environment around the Malibamats'o river at the Katse LHWP. It was renamed the Bokong Nature Reserve (BNR) within the biosphere nature reserves. Under this BNR, grazing has been discontinued since 2005. Communal grazing was the major land use prior to the designation of the BNR, therefore, there was no pristine condition in the BNR. Even though the degraded wetlands of the Bokong have been recommended for restoration, the success of such restoration activities should be informed by hydrologic information. The purpose of the restoration activities is to recreate the former or new hydrology which is a primary factor influencing plant community and ecosystem functioning.

Restoration success depends on properly restoring the former hydrology. Wetland restoration projects frequently fail or fall short of expectations because the hydrology of the proposed site was not properly assessed (Mitsch & Gosselink, 2007). It is important that long term monitoring of the hydrologic variables, including groundwater flow, surface water recharge, water level fluctuation, precipitation input, and others, are evaluated to enable restoring wetland hydrology to become "easier" and a more attainable goal (Zedler, 2000).

1.3 PROBLEM STATEMENT

Lack of continuous long-term data on hydrology in many countries has restricted the use of hydrologic data for assessment of wetland hydrologic functions (Kotze, 1994; Clausnitzer *et al.*, 2003; Karathanasis *et al.*, 2003; Vepraskas, 2008). While direct evidence of saturation may be used as an indicator, the seasonality of wetland hydrology also makes it difficult to use hydrologic data for wetland delineation which is a prerequisite in the restoration of wetlands. There is generally little information from which to define minimum hydrological thresholds for any wetlands in Lesotho. Thus the hydrology can only be assessed by the biotic and soils criterion. It is expected that a sufficient period of water saturation must be present to create anaerobic conditions to develop wetland indicator soils and support wetland indicator plants. Therefore, indicators of wetland hydrology such as vegetation and soil are used to identify and delineate wetlands, as well as assess wetland performance (Hurt, 2005; Vepraskas, 2008).

The problem of using vegetation indicator is that it tends to change when hydrology changes, but soil indicator remains for a longer time in the soil. There are no soil indicators that have been developed or adopted for the Lesotho wetlands. The high organic matter content associated with natural fertility, high Fe content in the parent material, and mixing of soil materials due to cattle grazing and rodent’s disturbance can also mask redoximorphic features in the surface soil horizons. The aim of this study was therefore to determine spatial variability of soils of Bokong and the key hydric soil indicators for the evaluation of wetland hydrology. This should provide a list of minimum soil data sets to evaluate wetland hydrology for proper wetland delineation and management.

1.4 HYPOTHESES

The study was based on the hypotheses that:

- The relationships between water regimes and redoximorphic features will not hold if microbial activity is limited by soil pH, soil temperature, low organic matter, or low Fe content in the soil.
- Wetland hydrology determines the redox potential gradients which will influence redistribution and accumulation of soil elements and soil organic carbon in the profile.

1.5 RESEARCH OBJECTIVES

The aims of this study were:

- To determine the soil properties and hydric soil indicators in selected toposequences.
- To determine the relationship between soil redoximorphic features, redox potential, and hydrology.
- To determine the distribution of Fe and Mn oxides between hydric and non-hydric soils.
- To determine the distribution and stock of soil organic carbon between hydric and non-hydric soils.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Wetlands have gained global interest since the Ramsar Convention of 1971 that aimed at protecting the remaining wetlands and the wise use thereof. This initiated many national regulatory instruments or enforcement of previous existing laws to protect wetlands. Nevertheless, the existing legislations in most countries are not specific on wetlands but are aimed at restricting utilization of wetlands for the purposes of conserving other natural resources. The policies and Acts that deal with wetlands protection in Lesotho include the Government of the Kingdom of Lesotho (1969; 1999; 2007; 2008a; 2008b; 2008c). These are the Land Husbandry Act 1969, which restricts cultivation and grazing of wetlands for soil conservation purposes, while the Livestock and Range Management Policy of 1999 regulate the grazing pressure on the wetlands. The Lesotho Environmental Bill of 2000 was followed by the development of environmental impact assessment (EIA) tools and guidelines for the conservation of natural resources. The Bill led to the enactment of the National Environmental Act 2008 which encompasses protection of all natural resources and prevails over all laws where inconsistencies exist. The Bill also initiated the development of Water and Sanitation Policy 2007, which shifted focus to ecological protection and integrated management of water resource including wetlands. The Water Act of 2008 also restricts the use of wetlands for purposes of conserving water resources. However, there is still no specific National Wetland Policy in Lesotho.

Similarly in South Africa, laws protecting wetlands are presented in various acts such as the Conservation of Agricultural Resources Act of 1983, the Integrated Environmental Management and Environmental Conservation Act of 1989, the National Environmental Management Act of 1998, and the National Water Act of 1998 (Republic of South Africa, 1998). National Wetland Policy is embedded in the Policy on the Conservation and Sustainable Use of South Africa’s Biological Diversity of 1997 (Department of Environmental Affairs and Tourism, 2006). Guidelines for delineating wetlands used the definition given in the National Water Act 36 of 1998 (DWAF, 2005). The Act defines a wetland 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 under normal circumstances supports or would support vegetation typically adapted to life in saturated soil”* (Republic of South Africa, 1998). The Lesotho Water Act No.15 of 2008 also adopted the South African definition of wetlands. The Act identifies lands between terrestrial and aquatic systems as wetlands, and the aquatic ecosystems are not part of the delineable wetlands since they are easy to identify. It also implies that any saturated land without anaerobic conditions is not a wetland because vegetation would be different.

In the United States of America, a wetland is synonymous to a hydric soil, defined as "*a soil that formed under conditions of water saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part*" (Hurt *et al*., 2002). The definition was used to serve the Food security Act 1989 (USDA-NRCS, 2010) and Clean Waters Act 1972 (U.S. Army CoE, 1987). The Intergovernmental Panel on Climate Change (IPCC) defines wetlands as: "*lands that are inundated with water for at least part of the year leading to physio-chemical and biological conditions characteristic of shallowly flooded systems*" (Watson *et al*., 2000). The accord in wetland definition is that they have wetland hydrology, soils are hydric, and they support hydrophytic plant communities (Skaggs *et al*., 1994; Hurt & Carlisle, 2001; Karathanasis *et al*., 2003). The concept of hydric soil has been adopted by many countries to represent wetland hydrology.

This literature review focused on the measurements of soil water saturation and anaerobic conditions required to satisfy wetland hydrology and the development of a hydric soil. The review tried to establish consensus and gaps among wetland studies on the relationship between wetland hydrology and hydric soils and the use of pedo-transfer functions to describe the wetland hydrology. Lastly, the redistribution and accumulation of soil properties as influenced by water saturation is reviewed.

2.2 HYDRIC SOILS

Hydric soils experience repeated prolonged saturation or inundation to develop anaerobic conditions in the upper part of the soil profile. The United States of America through the National Technical Committee for Hydric Soils (NTCHS) has developed specific tools for determining and delineating hydric soils in the field (USDA-NRCS, 2010). This was to complement the insufficiency of the USDA soil taxonomy system (Soil Survey Staff, 2010) to delineate wetlands. The USDA soil taxonomy aquic moisture regime is a saturated anaerobic condition (Soil Survey Staff, 2010); however, the moisture control section is too deep to include many soils which are not hydric. The newly developed NTCHS tools included the criteria on the water table levels as additional data to the soil survey data. The NTCHS hydric soil criteria provide soil information such as natural drainage classes, water table depth, flooding, and aquic moisture regime (Hurt & Carlisle, 2001; Mausbach & Parker, 2001; USDA-NRCS, 2010). The USDA soil taxonomy system was then used to develop a hydric soil list using the criteria. The list includes all Histisols except Folists, and other soils in the aquic suborders, great groups, or subgroups that have a high water table (Federal Register, 1995).

The soil classification of South Africa does not specify or determine soil moisture classes or soil drainage classes (Soil Classification Working Group, 1991), yet they are very important in differentiating different soil morphology. Soil moisture regime is not required to classify soils even at family level. A family can contain a wide range of water regimes hence have different morphological features. Kotze *et al.* (1996) developed a similar criterion to NTCHS for the hydric soils of South Africa. Their three-class soil water regime (permanent, seasonal and temporary) system is used as a hydric soil indicator to delineate wetlands in South Africa (DWAF, 2005).

The wetland delineation manual of South Africa (DWAF, 2005) considers four wetlands indicators, including terrain unit, soil form, soil wetness and vegetation indicators. While a combination of the four indicators may be used in delineation, the existence of the soil wetness indicator is primary and vegetation indicator is confirmatory (DWAF, 2005). This criterion uses the soil forms in the Soil Classification of South Africa to delineate wetlands. The soil forms indicators in the permanent zone include the Champagne, Katspruit, Willowbrook and Rensburg forms. The existence of any of the four soil forms represents a wetland (DWAF, 2005). The temporary and seasonal zones appear in many forms and families in the SA Soil Classification system.

Wetland soils in Australia belong to five soil orders in the Australian Soil classification (Dear & Svensson, 2007). They are soils which are seasonal and permanently wet for two to three months in a year (Hydrosols), soils of aquic suborders (Podosols, and Vertosols), soils with high organic carbon content (Organosols), and soils with high water table because of human interference (Anthroposols). The Australian Soil classification has similar problems to the USDA soil taxonomy in defining the moisture control section and most soils listed as hydric may not support hydrophytic plants because saturation occurs too deep in the profile.

Bryant *et al*. (2008) prepared a comprehensive report on the wetland soil indicators and methodologies to support wetland definition with respect to hydric soils in Australia. A field guide to soil indicators is a user friendly system which separates indicators into more and less conclusive indicators. The hydric soil indicators were included in the wetland delineation manual of Department of Environment and Resource Management (2010). The manual recommends the independent use of the more conclusive soil indicators to identify wetlands, while indicators such as mottles require consideration of the current hydrology.

The World Reference Base (WRB) for Soil Resources (FAO, 2006) classifies hydric soils as Gleysols and uses diagnostic properties such as gleyic properties, gleyic colour and stagnic colour patterns. Also all organic soils (Histisols) are hydric except those developing on bedrocks with shallow depth and high drainage. Stagnosols are also other major soil groups introduced in WRB in 2006 that are hydric. Van Ranst *et al*. (2011) observed the possibility of a serious overlap between Stagnosols and other major soil groups with stagnic properties such as Planosols especially in Ethiopian highlands.

The hydric soil lists developed by all of the above mentioned wetland delineation tools still require on-site field verification. However, there are other soils that do not require field confirmation such as Histisols and the four SA soil forms in the permanent zones. This has made it possible to use soil surveys to preliminarily map wetlands and use site investigations to identify and delineate wetlands (McBratney *et al*., 2003; Thompson *et al*., 2012). Spatial information on soils allows the use of geographic information systems to update conventional maps and to predict the distribution of hydric soils (Tiner, 1999; Galbraith *et al*., 2003). The digital elevation models, satellite imageries, and soil survey data are used prior the soil survey to reduce the time and labor required for detailed field survey (Galbraith *et al*., 2003). This can be followed by detailed large scale soil surveys (scales of 1:400 to 1:10 000) and onsite investigations to effectively identify hydric soils.

2.3 WETLAND HYDROLOGY MEASUREMENTS

Wetland hydrology is the key variable in wetland ecosystem functioning (Tiner, 1999). The area that is wet, but has not developed anaerobic conditions does not have a wetland hydrology. Therefore, the necessary wetland hydrology parameter measurements include both the measuring of the soil water saturation and the determination of reducing conditions. The common methods used to measure these parameters are reviewed and employed in this study.

2.3.1 Determination of soil water saturation

Soil water saturation in wetlands is determined by monitoring the water table using monitoring wells such as piezometers. The purpose of recording the water level is to determine the depth, frequency, duration, depth, and the change in the water storage budget. A piezometer is a water well that measures the hydraulic head and the vertical direction of groundwater. It is constructed by a small diameter unslotted stand pipe or tube open at both ends (Richardson *et al.,* 2001).

Timing and frequency of the water table measurements is an important factor in establishing relationships between redoximorphic features and water table. Measurements taken at weekly and bi-weekly intervals are recommended (Morgan & Stolt, 2006). Water table response reaches the maximum height immediately after precipitation, therefore, the maximum water level can occur between site visits. Morgan and Stolt (2004) used the maximum water level recording device (MWTRD), to record highest water table level reached between site visits. The device was made up of a metal rod inserted in a water table well fitted with a float and a magnet. In this study the adjusted hydrographs using MWTRD accounted for >80% of the underestimation of the height of the water table compared with the weekly measurements. However, the two weeks interval has accounted for the saturation duration at which anaerobic conditions may develop (Morgan & Stolt, 2006).

Soil water saturation depends on hydrodynamics and the hydroperiod of the system. The hydrodynamics refers to the movement of ground and surface water to and from a given wetland, while hydroperiod is defined as temporal fluctuations in water table (Richardson *et al*., 2001). Hydrodynamics affect the hydroperiod through controls on the water balance where the losses balance the gains plus or minus storage. The losses include evapotranspiration and the gains include precipitation. The components of the water budget include precipitation (P), surface water inflow (SWI), groundwater inflow (GWI), evapotranspiration (ET), surface water outflow (SWO), groundwater outflow (GWO) and change in storage (ΔS) and they are related as follows:

$$\mathrm{P} + SWI + \mathrm{GWI} = \mathrm{ET} + SWO + GWO + \Delta S \qquad (2\text{-}1)$$

There are three soil water interaction zones in the profile. These are the saturation, vadose, and capillary fringe zones (Silliman & Dunn, 2004). The saturated zone is the free water and the water flow responds to local water table recharge. This can be measured with a piezometer. The vadose zone is characterized by a mean vertical flow and the water is held under tension. The capillary fringe is between these two extremes. The soil water moves vertically up through capillary rise (Richardson *et al*., 2001). The depth occupied by this upward flow is called the capillary fringe (Silliman & Dunn, 2004). The thickness of the capillary fringe (Richardson *et al.*, 2001) depends upon the size of soil pores (r), resistance of gravity (g) and the density of water (ρ):

$$Hc = 2\sigma(cos\gamma)/\mathrm{r\rho g} \tag{2-2}$$

Where: Hc is the capillary rise, σ is the surface tension and γ is the contact angle. In a wetland the capillary rise of medium sand with an effective diameter of 0.1 mm, is 150 mm above the water table (Richardson *et al.*, 2001). This means that the capillary fringe keeps the soil wet to the surface as long as the water table is within the rooting zone of 300 mm. Daka (1993) found that the availability of water during the dry season is an important factor in classification of wetlands in semi-arid regions. He observed that Dambos of Zambia become completely dry and without groundwater within several metres depth in dry seasons and a fall of 1 to 2 m of the water table from the soil surface induces capillary rise (Daka, 1993).

The capillary fringe presents zones of accumulations, and is important in interpreting the depth of the water table. Fiedler *et al.* (2004) postulated that mobilised elements in the reducing zones are transported upward along redox gradients through capillary rise and accumulate in the capillary fringe above the depth of the fluctuating water table. It can therefore be deduced that, since mobile Fe^{2+} and Mn^{2+} ions diffuse upward and precipitate in the capillary fringe, the measurement from the soil surface to the upper area of Fe and Mn accumulations can be an interpretative tool in the determination of a seasonal water table (Dear & Svensson, 2007).

2.3.2 Determination of reducing conditions

The determination of reduced soil conditions is required to document hydrological performance standards linked to wetland function. Measurement of redox potential has been a challenge for a long time (Rabenhorst & Castenson, 2005). The common approach to determine reducing conditions in soils is either to measure the redox potential using platinum electrodes or to use the, *α, α* dipyridyl colour indicator dye (Bohn *et al*., 2001).

Redox potential is a voltage that is measured to predict the types of reduced species that would be expected in the soil solution (Vorenhout *et al*., 2004). Free electron concentration has specific activity expressed as potential electron (pe). Potential electron is the negative logarithm of the electron concentration in a solution. However, potential electron cannot be measured but Eh can be measured to represent the reducing intensity. Potential electron is related to redox potential (Eh):

$$\mathrm{pe} = -\log(\mathrm{e}^-) = \frac{\mathrm{Eh(mV)}}{59} \qquad (2\text{-}3)$$

A solution with a high electron activity (low pe) and a low Eh value has a high concentration of free electrons and will be reducing (Vepraskas & Faulkner, 2001; Fiedler *et al.*, 2007). The one with a low electron activity (high pe) and a high Eh will have no free electrons and will maintain reducible elements in their oxidized forms. Therefore, Eh measurements are used to quantify the tendency of the soils to oxidize or reduce elements (Fiedler & Sommer, 2004).

One of the more useful calculations in redox reactions is the Nernst Equation. This equation allows for the calculation of the electric potential of a redox reaction in "non-standard" situations:

$$\mathrm{Eh(mV)} = \mathrm{E} - \frac{59}{\mathrm{n}}\log\frac{\mathrm{(Red)}}{\mathrm{(Ox)}} - \frac{59\mathrm{mV}}{\mathrm{n}}\mathrm{pH} \qquad (2\text{-}4)$$

The Nernst equation describes that the Eh value at equilibrium will vary according to the soil pH and the concentration or activity of the oxidised and reduced species in the soil (Vepraskas & Faulkner, 2001). The equation is used to construct Eh/pH diagrams used to monitor reducing species in the field under different conditions. Eh measurements obtained in the field are evaluated along with pH data and Eh/pH phase diagram to determine the type of species reduced at certain Eh and pH levels. For example Severson *et al*. (2008) determined the threshold Eh value for the beginning of iron reduction from a Eh/pH phase diagram developed for the mineral FeOOH.

$$\mathrm{Eh(Fe^{2+})} = 1409 - 177\mathrm{pH}(\mathrm{pH} < 7.5) \qquad (2\text{-}5)$$

A correction for pH is given as:

$$\mathrm{Eh} - \mathrm{corrected} = \mathrm{Eh} - 59 * (\mathrm{pH}\ 7) \qquad (2.6)$$

Platinum electrodes used in the laboratory are easily available but only very few probes are commercially available for *in situ* measurements such as the platinum tip or copper electricity wire (Wafer *et al.*, 2004), the plastic/epoxy based combination electrode (Vorenhout *et al.*, 2004), and glass fiber based (Wafer *et al*., 2004). Most researchers construct their own electrodes. Instrumentation problems pose challenges for permanently installed Eh electrodes because of leakage at the platinum wire/copper wire junction of the Pt electrodes. Furthermore, lack of a stable, long-term salt bridge connection result in longer stabilization times especially in low moisture content soils (Dowley *et al*., 1997).

Continuous redox potential measurements in the field are important, however, thermodynamic equilibrium is never reached in natural soil systems and as a result redox measurements tend to be less stable and less reproducible (Dowley *et al*., 1997; Siggs, 2000; Vepraskas & Faulkner, 2001; He *et al*., 2003; Veronhout *et al*., 2004; Fiedler *et al*, 2007; Vepraskas, 2008; Rabenhorst *et al*., 2009). Redox potential can fluctuate within short distances of 1 mm (Fischer, 2000). Vepraskas & Faulkner (2001) associated this with oxidation of organic tissues and reducing reactions in microsites. Hence, several measurements taken from a horizon should not be averaged but rather ranked to show ranges of Eh within a horizon (Fischer, 2000). To overcome temporal and spatial variability in redox measurements data should be collected through both saturating and draining cycles and by replicating the measurement. At least five Pt electrodes are recommended per depth (Vepraskas & Faulkner, 2001).

The most recent approach for assessing reduction in soils known as IRIS tubes (“Indicator of Reduction in Soil”) was introduced by Jenkinson (2002). The method uses PVC pipes (approximately 21 mm in diameter) painted with synthetic ferrihydrite, which are then inserted into the soil. The basic concept of this approach is that synthetic ferrihydrite will be reduced under anaerobic conditions and removed from the PVC tubes leaving white portions of uncoated tube (Castenson, 2004; Castenson & Rabenhorst, 2006; Rabenhorst, 2007; Berkowitz, 2009; Rabenhorst, 2009). The white portion of the tube then represents the degree of reduction. A more quantitative analysis of the depleted area on the tube using digital images softwares still poses some challenges (Jenkinson & Franzmeieir, 2006).

The, α dipyridyl method is a colour indicator that reflects either the presence or absence of Fe^{2+} in the soil (Bohn *et al*., 2001). The qualitative nature of the method makes it ineffective to determine the concentration of Fe^{2+} that can lead to the development of redoximorphic features.

2.4 DEVELOPMENT OF REDOXIMORPHIC FEATURES

2.4.1 Redox reactions and redoximorphic features

Redox reactions are microbial processes driven by soil microorganisms that use organic compounds for photosynthetic energy (Bohn *et al*., 2001). The decomposition of organic compounds under aerobic conditions uses O_2 as the electron acceptors. Under anaerobic conditions, secondary electron acceptors are used in the order: Nitrate, MnO_2, $Fe(OH)_3$, SO_4^{2-} , CO_2, and finally H^+ (Vepraskas & Faulkner, 2001). Molecular O_2 yields higher energy for oxidation (-686 kcal mol^{-1}) than secondary electron acceptors hence more electron acceptors are required to meet microbial energy demands. Constant reducing conditions therefore result in decreasing electrode potential. Decreasing electrode potential is followed by reduction and redistribution of different species of secondary electron acceptors and development of redoximorphic features (Table 2-1; Bohn *et al.,* 2001). Redoximorphic features are colours and odour that develop due to redistribution and accumulation of reducible elements under alternating unsaturated and saturated and anaerobic conditions (SSSA, 1997; Hurt *et al*., 2002; USDA-NRCS, 2010).

The unsaturated aerobic soil has relatively high Eh (>500 mV at soil pH 7). In water saturated soil, there is a rapid exhaustion of O_2 and NO_3^- accompanied by a falling Eh to 400 mV at pH 7 where MnO_2 is reduced (Fiedler *et al*., 2007). The mobile reduced Mn^{2+} may accumulate as black coloured bodies (Mn^{4+}) if the electrode potential increases again after drainage. The Eh continues to fall as long as water saturation and reduction continues (Vepraskas, 2001). At Eh values below 200 mV at pH 7 Fe^{3+} is reduced to a mobile Fe^{2+} which will be oxidised again and accumulate when the Eh rises. Iron accumulations change the matrix colour to yellow, orange and red. If the soil is frequently reducing, Fe^{2+} is lost through leaching from the horizon (Fiedler & Sommer, 2004). The leaching of Fe^{2+} from a soil horizon leaves low chroma grey soil colours (Bohn *et al*., 2001). The accumulation or loss of Fe is accompanied by accumulation or loss of Mn too, and the redoximorphic features that are formed represent either accumulation or loss of both elements. When the Eh reaches values below -150 mV, SO_4^{2-} may be reduced to H_2S gas. This usually requires a relatively long period of water saturation and anaerobic respiration (Vepraskas, 2001). This feature is identified by the odour similar to that of rotten egg. All the mentioned redoximorphic features can be identified in the field and used to identify and define the wetland hydrology.

Table 2-1 Half reaction Redox potential measured in soil (Bohn *et al.*, 2001).

Reducing reactions	Eh value (pH7) mV	Redoximorphic features formed	Examples of features
$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$	600 to 400	Organic C features	Organic and some black A horizons
$MnO_2 + 2e^- 4H^+ \leftrightarrow Mn^{2+} + 2H_2O$	400 to 200	Manganese-based features	Manganese masses, black and grey mottles
$2FeOOH + 4e^- + 6H^+ \leftrightarrow 2Fe_{2+} + 4H_2O$	300 to 100	Iron-based features	Iron masses, red, yellow and grey mottles
${SO_4}^{2-} 8e^- 10H^+ \rightarrow H_2S + 4H_2O$	-150 to 0	Sulfur-based features	Odour of rotten egg gas
$H^+ + e^- \rightarrow 1/2\,H_2$	-220 to -150		

2.4.2 Types of redoximorphic features

Redoximorphic features are described by their type, abundance, size, contrast, colour, and distinctness of boundaries. Hurt *et al*. (2002) divided redoximorphic features into redox concentrations, redox depletions, depleted matrix, and reduced matrix.

2.4.2.1 Redox concentrations

Reduced forms of Fe or Mn accumulate under aerobic environments where they oxidise to form concentrations of soft masses on the matrix, pore linings on ped surfaces and along the root channels or cracks (Vepraskas, 1995; Vepraskas, 2001). These features are often called high chroma mottles. A high chroma of greater than 4 represent colour ranges from yellow, orange and red. Soft masses are patches of high chroma within the matrix formed as a result of Fe and Mn accumulation under oxidised environments on the soil particles. The pore linings are accumulations on pore surfaces or occur as high chroma bodies on matrix surfaces next to the pores. Pore linings are similar to an oxidised rhizosphere, which develop along root channels of growing hydrophytic plants at the root soil interface. However, the pore linings can also develop at the capillary fringe. Jacobs *et al*. (2002) cautioned the use of redox concentrations in identifying hydric soils because these features may reflect either capillary action up from the zone of saturation, or high water table levels that occur during extreme rainfall events.

The soft masses may harden to form nodules or concretions. Nodules and concretions are hard spherical bodies of cemented Fe^{3+} differentiated by concentric layers in their internal structure of the latter indicating repeated processes. Nodules and concretions are never used to define hydrology because they may be deposited material and not formed in place (Vepraskas, 2001).

2.4.2.2 Redox depletions

The loss of Fe-Mn and clay under anaerobic conditions is observed by low chroma bodies of grey colours called redox depletions (Fiedler & Sommer, 2004). They are also called grey mottles. Fe depletions and clay depletions are two kinds of redox depletions differentiated by their texture in relation to the matrix. Clay depletions will result in coarser texture than the matrix due to loss of both Fe and clay while Fe depletions have the same texture as the matrix. Clay depletions are not important in hydric soils since they occur lower than the rhizosphere (Vepraskas, 2001). A chroma of 2 or less is expected from the depletions according to the USDA soil taxonomy, while the South Africa soil classification system describes low chroma as 2 or less if the value is less than 6 and chroma 4 if the value is above 6 except for 5Y colours (Soil Classification Working Group, 1991).

2.4.2.3 Depleted matrix

If the redox depletions have occupied the whole matrix, it is considered a depleted matrix. According to USDA-NRCS (2010) a depleted matrix is a low chroma matrix of less than 2 and value of 4 or more. It develops as a result of loss of Fe-Mn under longer saturated and reduced periods than the duration required to form grey mottles.

2.4.2.4 Reduced matrix

Reduction of iron and subsequent gleying develop the reduced matrix. It has a low chroma *in-situ* because of the presence of Fe^{2+} but the colour changes immediately when exposed to air. It is also called gleyed matrix identified by bluish-grey or grey colour from the gleyed pages of the Munsell colour book (Hurt *et al.,* 2002). Time required to observe colour changes is uncertain and if it is used as an indicator of wetland hydrology. A colour test is also used to show the presence of Fe^{2+}.

The reduced and depleted matrixes are also termed gley soil colours (Vepraskas, 2001). The two have similar colours but are differentiated by change of colour when exposed to air. If Fe^{2+} is present the matrix chroma increases in the case of the reduced matrix. The G horizon in the SA soil classification is a reduced matrix with blue or green tints with or without mottles. The E horizon also has grey matrix colours similar to the G horizon (Soil Classification Working Group, 1991). The E horizon is the result of weathering and eluviation of colloidal material including iron oxides from the lower part of the A horizon to form the Bt or Bs horizons (Soil Survey Staff, 2010). The elluviated layer has a low chroma because most colouring agents have been leached out. The genesis of the E horizon depends on the climatic conditions and the drainage of the underlying horizon. It may have high chroma mottles if periodic saturation occurs due to impermeable underlying horizon.

Ferrolysis which is the acid decomposition of clay minerals and may influence the formation of E horizon under periodic saturation due to alternating oxidation and reducing conditions (Brinkman, 1970; Van Ranst & De Conink, 2002; Lindbo *et al.*, 2010). However, the E horizon is excluded from a depleted matrix unless it has 2% or more of high chroma mottles (USDA-NRCS, 2010).

2.4.3 Soil organic carbon features

Anaerobic decomposition rates of organic matter are slower by 10-30% compared to aerobic decomposition rates (Hurt, 2005). Reduced mineralisation of organic matter result in the accumulation of organic matter and the development of an O horizon with black to dark grey colours differentiated from the A horizon by a higher chroma of 3 or more of the latter (Bridgham *et al.*, 2001). The South Africa soil classification has the O horizon as a diagnostic horizon formed under prolonged saturation. The Organic O horizon is a surface horizon with organic carbon content >10% throughout the depth of 200 mm (Soil Classification Working Group, 1991). USDA soil taxonomy and WRB has the Histic epipedon as a layer with organic soil material and is characterised by saturated reduced conditions for 30 or more consecutive days (Soil Survey Staff, 2010; FAO, 2006). According to the FAO (2006) and Soil Survey Staff (2010) the organic soil material must have 12% or more organic carbon content when added to clay content multiplied by 0.1 or must have 18 percent organic carbon of the fine earth. The Organic O horizon and Histic epipedon are therefore organic carbon features of reduction.

Another indicator to quantify the thickening and darkening of surface horizons as a result of water saturation is called Profile Darkness Index (PDI) (Bell *et al.*, 1995; Thompson & Bell, 1996; Thompson & Bell, 1998; Thompson & Bell, 2001). It is calculated for each horizon with Munsell value of 3 or less and chroma of 3 or less. It is expressed as the total sum of each horizon thickness with Munsell colour value of 3 or less and chroma of 3 or less (equation 2-7). The thickness is divided by Munsell colour value and chroma.

$$\mathrm{PDI} = \sum_{i=1}^{n} \frac{\text{A horizon thickness}}{(V_i C_i) + 1} \tag{2-7}$$

Where:

The A horizon thickness is measured in centimetres, V_i is the Munsell value and C_i is the Munsell chroma. However, a threshold value that separates hydric and non-hydric soils should be set which depends on local climate and parent material, hence it requires local calibration.

2.4.4 Problems in using redoximorphic features

Four soil conditions are needed to form redoximorphic features in soils: i) Saturation with stagnant water inorder to exclude oxygen (Franzmeier *et al*. 1983; Vepraskas & Wilding, 1983; Dear & Svensson, 2007). (ii) Suitable pH for microorganism to survive. Thompson and Bell (1998) observed that iron does not reduce in high pH soils even under anaerobic conditions. (iii) A supply of organic C, which serves as the energy source for microorganisms (Vepraskas & Faulkner, 2001), and (iv) suitable soil temperature (Vepraskas, 2001). There is a lag period between onset of saturation and the onset of Fe^{3+} reduction, which depends on both soil temperature and organic matter percentage which directly influence the microbial activity (Vepraskas, 2001). It takes longer for soil to be reduced in low soil organic carbon content and temperatures below 5°C (biological zero; Burdt *et al.*, 2005).

Relict redoximorphic features are footprints left by previous soil water fluctuations, but are not active due to geologic changes (Hurt, 2005). They are useful in identifying soils whose hydrology has changed. However, Vepraskas (2001) indicated that morphology alone cannot identify relict features with certainty but hydrological data are necessary to confirm if they are relict. The morphological characteristics that can distinguish between contemporary and relict redoximorphic features are described below (Vepraskas, 1995; Greenberg & Wilding, 1998; Hurt, 2005). Contemporary features have diffuse boundaries, indicating that they are continuing developing, while relict features have abrupt boundaries. Contemporary Fe depletions are not overlain by redox concentrations which are overlain by oxidized stable macropes in relict features. Relict redox concentrations are redder than 5YR and value and chroma less than 4. Contemporary pore linings may be continuous while relict pore linings may be broken.

2.5 INTERPRETING SOIL WATER SATURATION FROM REDOXIMORPHIC FEATURES

The depth of the water table fluctuates greatly throughout the year with the highest levels closest to the surface occurring during the high precipitation or low evapotranspiration seasons of the year. This variation in water table depth is called seasonal saturation (Severson *et al.* 2008). Seasonal saturation can be represented by Seasonal High

Saturation (SHS) or Seasonal High Water Table. This is the highest expected annual elevation of soil water saturation or water table (Hurt, 2005; Morgan & Stolt, 2006).

The seasonal high water table is widely applied as a hydrological criterion for many land uses. The few include delineation, restoration, and protection of wetlands criteria (He *et al.,* 2002; Hurt, 2005; Severson *et al.* 2008), onsite wastewater design and construction criteria (Galusky *et al*. 1997; He *et al.,* 2003; Morgan & Stolt, 2006; Humphrey & O'Driscoll, 2011a; 2011b), and land suitability for agricultural use criteria (Soil Survey Division Staff, 1993). The determination of seasonal high water table requires the presence of a wet season or long term hydrological data. The long term hydrologic data is not easily obtained, hence redoximorphic features are used. However, most hydropedological correlation studies are only based on one to three years of weekly or bi-weekly water table measurements (Morgan & Scolt, 2004; 2006; Vepraskas, 2001; Lindbo *et al*., 2010). Few studies have 10 years data (Zobeck & Ritchie, 1984; Khan & Fenton, 1994). Zobeck and Ritchie (1984) compared the length of water table monitoring study periods from 1 year to 10 years and recommended a minimum of three years water table monitoring period which does not give large deviations like one to two years studies.

Furthermore, the determination of seasonal high water table using redoximorphic features makes the definition of seasonal high water table ambiguous. Redoximorphic features are indicative of the depth at which the water table rises and remain at the depth for a certain period. The period differs with soil texture, soil organic matter content, soil pH, soil temperature, and iron content (He *et al*., 2002). The foregoing factors lead to confusion in the interpretation of seasonal high water table from redoximorphic features.

2.5.1 Applications of redoximorphic features and soil water table studies

Studies that have interpreted soil water table in relation to redoximorphic features are numerous considering the importance of the determinations. Soil drainage classes from soil taxonomy (Soil Survey Division Staff, 1993; Schoeneberger *et al.,* 2002) can also be interpreted from redoximorphic features. Somewhat poorly drained, poorly drained, and very poorly drained soils are associated with a water table at or close to the surface (Soil Survey Division Staff, 1993; Tiner, 1999). Fletcher and Veneman (2008) described redoximorphic features associated with soil drainage classes in New England as follows: Excessively, somewhat excessively, well drained and moderately well drained soils do not have mottles within the upper 2 meters of soil profile and the water table is below 2 meters. However, moderately well drained soils can have Seasonal high saturation at 300 to 600 mm which last for a very short duration. Somewhat poorly drained soils have chroma 3 or 4 within 600 mm and cumulative saturation is higher than moderately drained. Poorly and very poorly drained soils have grey subsoil with or without mottles and a water table at or near the surface for a significant portion of the year. In poorly drained soils Fe depletions occur higher in the profile and in well drained and moderately drained soils Fe depletions and reduced matrix occur in deeper horizons (Jacobs *et al*., 2002).

The soil drainage classes and water regime describe the movement of water and moisture condition of the profile but do not indicate the degree of water saturation (*s-value*). Degree of water saturation is the fraction of pores filled with water, calculated as a ratio of volumetric water content with respect to the soil pore volume (Hillel, 1980). Van Huyssteen (2004) hypothesised that there is a level of water saturation at which a sufficient fraction of soil pores are filled with water to interfere with normal oxidative respiration. The ratio is lower than 1 as it would be expected in water saturated soils because of the effect of hysteresis and the ratio of micropore to macropore porosity. Therefore, a soil with lower micropores (compact soil) will hold less water to obtain the same degree of water saturation than a soil with a high porosity. Hence, the degree of water saturation at which the soil becomes anaerobic differs with soil types. The concept of degree of soil wetness takes into account the capillary fringe concept.

Van Huyssteen *et al*. (2005) approximated that the onset of reduction in the soils in the Weatherly catchment in South Africa will occur at a degree of soil water saturation of 0.7 ($S_{0.7}$). Jennings (2007) found the onset of reduction of a yellow brown B horizon to correspond to $S_{0.78}$ under laboratory conditions. Follow-up studies to this findings included calculating the number of days in the year the *s*-value was 0.78 of porosity in a horizon expressed as $AD_{s>0.78}$ (Kuenene, 2008; Van Huyssteen *et al*., 2010; Van Huyssteen, 2012). The number of days the water table remained at a particular depth could be fewer than the $AD_{s>0.78}$. The cumulative saturation calculated from $AD_{s>0.7}$ or $AD_{s>0.78}$ can also be used to develop a wetland hydrologic criteria.

There are few studies on wetlands soils in South Africa but a lot of hydropedology work has been developed on non-wetland soils which also included soils with wetness in the surface and subsoil horizons (Van Huyssteen *et al*., 2005; Jennings *et al*., 2008; Kuenene, 2008; Van Tol *et al*., 2010a; Van Tol *et al*., 2010b; Le Roux *et al*., 2010; Le Roux *et al*., 2011; Smith & Van Huyssteen, 2011; Van Tol *et al*., 2012). Van Huyssteen (1995) realised that soil colour is largely used in South Africa soil classification system to identify diagnostic horizons and colour is a reflection of the soil water regime. Van Huyssteen (1995) determined the mean duration of free water saturation for some diagnostic subsoil horizons. The duration of saturation increased in the order of red apedal B horizons (1.3%), yellow-brown apedal B horizons (18.8%), yellow E (42.4%), and for grey E horizons (54.2%).

Van Tol *et al*. (2012) described the hydrological behaviour of the diagnostic horizons in a profile to interpret spatial variability of hydrologic processes. The orthic A overlying a neocutanic B was saturated only once in 6 months of the study period, while orthic A overlying a G horizon at Weatherly catchment indicated saturated conditions throughout the study period of 6 months. The neocutanic B horizon is free draining with no evidence of saturation while a G horizon has a longer duration of saturation. The neocutanic B will result in deep drainage while the G horizon will produce more overland flow. The presence of impermeable layers such as a lithocutanic B will cause periodic saturation above it and it is identified by a bleached overlying A horizon or E horizon. Van Huyssteen (2012) also observed similar results on the same soils that the degree and duration of wetness of the surface horizon depends on the underlying horizon. His study indicated that the duration of water saturation in the orthic A horizons generally increased with order of occurrence of the following subsoil horizons: neocutanic B < yellow-brown apedal B < yellow E < grey E < soft plinthic B < G horizon. Lilly *et al*. (2012) supported studies that classify soils into functional hydrologic units as a way to make soil information user friendly to the hydrologist.

The use of redoximorphic features for siting and construction of on-site wastewater systems (OSWWS) throughout the United States by some regulatory agencies has been found misleading (He *et al*., 2003; Morgan & Stolt, 2006). This is because the criteria either consider only the abundance and not the type of redoximorphic features or consider the depth of high water table and not the duration of saturation. Morgan and Stolt (2006) observed that 13 out of 17 moderately well drained soils of New England had seasonal high water table above the horizon with common redoximorphic features with a mean cumulative saturation of 6% and 21% in loamy and sandy soils respectively. This also shows that soil texture should also be considered when making interpretations for redoximorphic features. The improvement from this criterion considers the kind of redoximorphic features that develop due to longer water saturation to compromise wastewater treatment.

The shallowest depth to 2 chroma redox depletions sometimes referred to as the chroma 2 index is used to determine the depth of the seasonal high water table and has been used as a crude index to regulate permits for on-site wastewater systems throughout the United States (Franzmeier & Jenkinson, 2004; Humphrey & O'Driscoll, 2011a; 2011b). The 2 chroma redox depletions that occupy 2% of the soil volume are expected to indicate depth at which the water table is likely to rise and remain for 14 consecutive days seasonal high water table. The seasonal high water table is used to set the maximum depth of the dispersal trench bottom for effective treatment which will occur only when the separation distance between the water table and the bottom dispersal trench is adequate.

The 14 days cumulative saturation has been found not suitable for development of 2 chroma redox depletions in some soils (He *et al*., 2003; Vepraskas, 2008; Vepraskas & Caldwell, 2008). He *et al*. (2003) observed a mean of 21 days to develop 2 chroma colours for soils of North Carolina. Humphrey and O'Driscoll (2011a) observed that seasonal high water table occur above the low chroma depletions. This means that low chroma colours require saturation longer than 14 days to develop. Therefore, if occurrence of a seasonal high water table for 14 consecutive days compromises the treatment plant, the separation distance from low chroma colours to the bottom of the dispersal trench must be increased to accommodate the higher seasonal high water table above 2 chroma colours (Humphrey & O'Driscoll, 2011b).

Franzmeier and Jenkinson (2004) suggested the use of Dsat8, defined as "the depth below which the soil is saturated more than 8% of the time". This is equal to 29 cumulative days for saturation to develop reduction depletions, which is equivalent to "20 or more consecutive days or 30 or more cumulative days in a normal year" as used to describe acquic conditions in USDA soil taxonomy.

2.5.2 Indices used to evaluate seasonal high water table

Indices are always suggested based on the scientific background underlying the relationships. Galusky *et al*. (1998) derived the following redoximorphic indices for correlation with estimated water table regimes:

- Depth to gleyed horizon with chroma of 2 or less and value of 4 (*d_gley* horizon).
- Depth to matrix chroma of 3 or 4 (*d_34* horizon)
- Depth to first incidence of redox concentrations (*d_conc* horizon)
- Depth to first incidence of redox depletions (*d_depl* horizon)

The gleyed horizon is identified by matrix chroma of 2 or less indicating the depth of wet season water table Galusky *et al*. (1998) or seasonal high water table (Veneman *et al*., 1998). The G horizon in the South Africa Soil Classification (Soil Classification Working Group, 1991) is a gleyed horizon with matrix chroma of 2 or 4. USDA-NRCS (2010) separates gleyed matrix from depleted matrix. A depleted matrix meets one of the following colours: If the value is 4, the chroma should be 1 or 2 with common redox concentrations, if the value is 5, the chroma must be 2 with redox concentrations or value of 5 or 6, the chroma must be 1 or less with or without redox concentrations. The horizon becomes a gleyed matrix if the matrix has a gley colour (USDA-NRCS, 2010).

Galusky *et al*. (1998) included the *d_34* index as the horizon that has experienced longer saturation. South Africa soil classification has a depleted (E) horizon with chroma of 4. This indicates prolonged saturation with a partial removal of sesquioxides (Soil Classification Working Group, 1991). Amongst the indices, the *d_34* index is mostly highly correlated with average monthly water table levels derived from a first order auto-regressive model (Galusky *et al*., 1998). The correlation was highest in March when seasonal water tables are highest. The gleyed matrix also has higher correlations during the same rainy season. Galusky *et al*. (1998) observed low to poor correlations or no correlations with the *d_depl* and *d_conc* respectively. The *d_conc* and *d_depl* indices indicate a fluctuating water table (Franzmeier *et al*., 1983; Zobeck & Ritchie, 1984; Evans & Franzmeier, 1986; Vepraskas & Caldwell, 2008).

Two other indices established from the studies were used: C1 representing only chroma and C2 represents both chroma and hue (Evans & Franzmeier, 1988). The C1 and C2 indices have been tested in different locations but have given irregular results. The inconsistency of these indices made them not to be further developed for use as indicators of seasonal high water table. Other soil colour indices are associated with levels of dithionite extractable Fe (Gobin *et al*., 2000; Minasny & Hartemink, 2011). Gobin *et al*. (2000) observed positive correlation of colour index and redness index with dithionite extractable Fe.

Hydrologic models are being adopted as an alternative approach to estimate water table data over long periods to determine frequency and duration for individual horizons at a few benchmark sites (Skaggs, 1978; Skaggs *et al*., 1994; Galusky *et al*., 1997; Galusky *et al*., 1998; Vepraskas & Lindbo, 2000; He *et al*., 2002; He *et al*., 2003; Vepraskas *et al*., 2004; Vepraskas, 2008; Vepraskas & Caldwell, 2008; Le Roux *et al*., 2011). Short-term water table data sets are extended into the past through modelling to develop indices of hydrology. DRAINMOD is one hydrological model that has been extensively used in the USA to calculate how often the soil is saturated within a given depth for a specific duration in a year (Vepraskas & Lindbo, 2000; He *et al*., 2002; He *et al*., 2003; Lindbo *et al*., 2006; Vepraskas, 2008).

Skaggs *et al*. (1994) evaluated seven hydrologic criteria sufficient to determine the presence or absence of wetland hydrology using DRAINMOD. Each criterion includes the critical water table depth, duration of high water table and the minimum growing season. Morgan and Scolt (2006) used a simple model to calculate average monthly water table hydrograph using daily temperature and rainfall as well as soil properties. The hydrographs were used successfully to establish the relationship between cumulative frequencies of water table versus depth of redoximorphic features.

Photography using digital cameras coupled with image analysis software has been used to quantify soil colour in hydropedological studies (Van Huyssteen, 2004; O'Donnell *et al*., 2010) O'Donnell *et al*. (2010) developed a new method of identifying and quantifying redoximorphic features from soil cores using a digital camera and image classification software which enable determination of uncertainty in visual estimates. It gave an accuracy of 99.6% based on Munsell soil colour groupings used for redoximorphic features identification. Rewetting of samples with deionized water demonstrated mean change in identified low chroma and high chroma of 2% (SD ± 4) and 0.03% (SD ± 0.3), respectively.

Advances to this study were to determine the minimum measurement scale which is independent of sample size and accounted for spatial heterogeneity. O'Donnell *et al*. (2011) called this representative elementary area (REA). The REAs for low chroma and high chroma of clay-pan in Missouri, USA, are 1770 mm^2 ± 0.40 and 2540 mm^2 ± 0.70 for low chroma and high chroma respectively. However, large sampling diameters of 80 mm for simultaneous capture of low and high chroma and a ≥50 mm diameter core is recommended to capture low chroma separately.

2.5.3 Indicators of seasonal high water table

Indicators of hydric soils for wetland delineation must be present within 500 mm of the soil surface according to DWAF (2005) and within 300 mm for both USDA-NRCS (2010) and Australia Bryant *et al*., 2008 respectively. These depths were chosen because they comprise the rhizosphere of the most hydrophytic vegetation in the respective areas. The hydric soil field indicators in the US are identified as “soil layers with precisely defined colours, thickness and depth that contain morphological features of reduction in specific amounts” (Vepraskas, 2001). Hydric soil field indicators developed by the NTCHS differ between soil textures. There are indicators of organic layers for “all soils” regardless of the soil texture, and indicators for “sandy soil materials” and “loamy soil materials” (Hurt *et al*., 2002; USDA-NRCS, 2010). Dear and Svensson (2007) argued that USDA-NRCS (2010) hydric soils determination tools are subjective. However, they acknowledge that the tools still remain the most comprehensive and commonly used methods for delineating wetland in many countries.

Megonigal *et al*. (1993) observed the most useful field indicators in flooded forest soils of South Carolina are a low-chroma matrix or a surface horizon high in organic matter with the matrix chroma of a mineral horizon in the top 30 cm less than 1 when mottles are absent or less than 2 when mottles are present. Hurt (2005) developed linkages between soil morphological features and wetland hydrology for the entire coastal zone of the United States, which indicates depths where soil saturation reliably occurs, or did occur on a regular basis before site modifications. There is a strong correlation between the depth of seasonal high saturation and the depth to approved NTCHS field indicators in hydric soils and the depth to other organic and contemporary redox features in non-hydric soils which increase the probability of success for the restoration and creation of wetlands.

A similar tool was developed for soils of Australia (Bryant *et al*., 2008). Some soil indicators are conclusively used to identify wetlands in Australia. The soil indicators include organic materials, acid sulphate soil material, and gleyed soil matrix colours. Redox concentrations such as root channel and pore linings masses and decreasing matrix chroma are just used as indicative of a wetland soil and require verification of the hydrology (Bryant *et al.* 2008).

Kotze *et al*. (1996) modified soil water regime classes which relate the soil morphology in a wetland. This was because the soil moisture regime classes used by Cowardin *et al.* (1979) to classify wetlands and Begg (1990) to differentiate between wetland types are too narrow to identify in the field hence insufficient to apply for management purposes. The eight Cowardin *et al.* (1979) saturation classes were narrowed to three soil water regimes which are permanent, seasonal and temporary flooded or saturated regimes (Table 2.2). The three soil water regimes are determined by the depth, duration and frequency of the water table.

Three types of morphological indicators including the matrix chroma, degree of mottling and presence of sulphur based characteristics at different depths differ under each soil water zone. Kotze *et al*. (1996) indicated that mottles are better developed in temporary and seasonal zones than in permanently wet soils. The temporary soil water regime represents the outer boundary of the wetland. This is the zone that was used by the USDA-NRCS (2010) to develop the hydric soil indicators. If the indicators exist in the temporary zones, it is assumed that soils in the interior of the wetland also are hydric. Delineators using these tools are therefore expected to sample only the edge of the wetland.

Table 2.2. A provisional three class system for determining the degree of wetness of wetland soils based on soil morphology (Kotze *et al*, 1996).

Soil depth (mm)	Temporary	Seasonal	Permanent
0 – 100	Chroma 1-3 Few or no mottles Low/intermediate OM Nonsulphudic	Low Chroma 0-2 Many mottles Intermediate OM Seldom sulphudic	Chroma 0-1 Few or no mottles High OM Often sulphudic
100 – 400	Chroma 0-2 Few/many mottles	Chroma 0-2 Many mottles	Chroma 0-1 No/few mottles

2.5.4 Common generalisations and gaps in the relationship of redoximorphic features and seasonal high water table

Broad generalisations that can be drawn from the studies that relate redoximorphic features to soil saturation are as follows:

- Mottle abundance initially increases then steadily decreases as the soil becomes increasingly wet (Dear & Svensson, 2007). Abundance categories were evaluated by Morgan and Stolt (2006).
- The depletions with chroma 2 or less or Fe concentrations with chroma 6 or more are related to water table fluctuations and saturation for a shorter time (Severson *et al.,* 2008). Galusky *et al*. (1998) derived the *d_conc* and *d_depl* indices.
- Soils that are predominantly grey with brown or red mottles are often waterlogged for a longer period than those that are yellow or brown with grey mottles (Dear & Svensson, 2007). Galusky *et al*. (1998) derived the *d_34* index.
- The presence of depleted or reduced matrices indicates a longer duration of saturation (He *et al*., 2002; Jacobs *et al*., 2002; Dear & Svensson, 2007). Galusky *et al*. (1998) associated this with the water table of a wet season. Galusky *et al*. (1998) derived the *d_gley* index.

Deficiencies in the studies that relate redoximorphic features to soil saturation are as follows:

- Steeper redox gradients in wetlands result in more expressive redoximorphic features than in drier soils with a lower water table. However, interpretations from redoximorphic features in wetlands are less developed with little quantitative data than those made from drier areas. For example, redoximorphic features are used solely to regulate permits for waste disposal in the United States of America. Criteria for seasonal high water table for a given period or $AD_{s>0.7}$ have not been developed for wetlands soils of South Africa and Lesotho. McKenzie and MacLeod (1989) indicated that the establishment of a relationship between morphology and other soil properties is hindered by the nature of soil morphological data which lack ratio or interval scales.

- Redoximorphic features associated with that seasonal high water table have not been tested in enough areas to generalisation on their use. Kotze *et al*. (1996)'s literature review and generalised three soil water regime class model in SA soils have not been tested elsewhere in South Africa other than in Kwazulu-Natal.
- Criteria may not necessarily be the same for all wetland types with different climatic conditions but technically sound criteria is important to allow regulation and protection of wetlands functions.

2.6 SOIL PROPERTIES AND SOIL WATER SATURATION

The redox processes together with the soil water saturation redistribute elements in the soil. The redistribution occurs through several processes such as element fixation, solubility, diffusion, immobilization, and accumulations. Soil water saturation and anaerobic environments change soil pH towards pH 7. This is due to the fact that H^+ ions are used in reducing reactions (Vepraskas & Faulkner, 2001; Dear & Svensson, 2007). Ferrolysis also produces acidity that decomposes clay minerals during alternating reducing and oxidizing conditions in the soil (Brinkman, 1970; Schaetzl & Anderson, 2005). During reduction, organic matter is oxidized into H_2CO_3, organic acids, and strong mineral acids (Van Ranst & De Conink, 2002). Reducing conditions result in Fe^{3+} oxides being reduced to Fe^{2+} and under oxidising environments it will be re-oxidised and hydrolysed to produce H^+ (Schaetzl & Anderson, 2005). The accompanying acidity releases interlayer cations from silicate clay minerals which result in the destruction of clay minerals (Brinkman, 1970; Van Ranst & De Conink, 2002; Schaetzl & Anderson, 2005).

Le Roux *et al*. (2005) indicated that ferrolysis is the underlying processes for the formation of duplex and plinthic soils in the eastern Free State in South Africa characterised by acidity, matrix colour, Fe-Mn mottles and abrupt textural change. On the other hand Van Ranst *et al*. (2011) observed that ferrolysis cannot explain the genesis of duplex soils of Ethiopian highlands since they have high pH and high reserves of weatherable minerals at the point of the abrupt textural change.

The low soil pH mainly influences the solubility of various elements in the soil such as Mn^{2+}, Fe^{2+}, Ca^{2+}, Mg^{2+}, K^+, and Na^+. At low pH values (<5.8), Ca^{2+}, Mg^{2+}, and P solubility are limited while Al^{3+} and Mn^{2+} availability is increased and may reach levels toxic to some plants (Kolka & Thompson, 2006). Craft (2001) indicated that in wetlands, plant growth is always limited by the availability of nutrients, with nitrogen and phosphorus being the most limiting. Phosphorus is cycled through sediments as recalcitrant organic compounds or bound with iron and aluminum at low pH and calcium at high pH. Ewing *et al.* (2012) observed increased solubility of excess P in a drained wetland as compared to natural wetland soils not used for agriculture, including significantly greater amounts of extractable P, Ca, Mg, Mn, Zn and Cu. Increased solubility of residual P when wetland hydrology and anaerobic soil conditions are restored may degrade water quality.

The distribution of Mn^{2+} and Fe^{2+} are also affected by redox potential and degree of saturation (McDaniel & Buol, 1991). The distribution of these elements follows the thermodynamic model since they become soluble and precipitate at different redox potentials (McDaniel & Buol, 1991). Manganese is a more mobile component of soil systems than Fe and is therefore subject to more extensive redistribution (McDaniel *et al.*, 1992). Iron precipitates at lower redox potentials than Mn. Mn^{2+} does not precipitate until draining has caused more oxidised conditions. Therefore Mn^{4+} is found in lower depths than Fe^{3+} because Mn^{2+} remains in a reduced, soluble form longer than Fe^{2+} (Bartlett, 1986).

Moore (2006) determined the effect of hydromorphism on the Fe and Mn fractions. The ratio of the oxalate to dithionite-extractable Fe fractions (Fe_o/Fe_d) was higher in gleyed horizons suggesting higher amounts of poorly crystalline extractable Fe. Jennings (2007) observed an exponential ($R^2 = 0.92$) increase in Fe^{2+} concentration as degree and duration of water saturation increases. Jokova and Filcheva (2003) observed high contents of dithionite and oxalate forms in meadow bogs Gleysols indicating an intensive modern weathering process due to the greater water influence. Olaleye *et al.* (2000) observed increasing dithionite extractable Fe (Fe_d) with depth from 0.70 to 2.95% and from 0.50% to 2.70% in two pedons in wetland soils of humid climates. Fiedler *et al.* (2004) indicated that elemental distribution along redox gradients is a phenomenon linked to topography, upward and lateral diffusion from the reduced areas along a concentration gradient. However, Fiedler *et al.* (2004) recommended future research to validate the upward transport of elements using radioactive labeled elements.

2.7 CONCLUSIONS

Wetlands are areas characterised by the presence of hydric soils and wetland hydrology that supports wetland vegetation. The difficulties in acquiring data on wetland hydrology have resulted in the sole use of hydric soil indicators to delineate wetlands for planning and restoration. Hydric soils are formed as a result of redox reactions under different water regimes in wetlands. It is evident that redox processes involve the redistribution of reducible elements in the soil and the accumulation of organic matter.

The relationship between soil water saturation and the development of redoximorphic features requires additional data on the redox potential, contents of organic carbon and Fe reserves in the soils, soil pH, and soil temperature. The differences in these soil properties in different landscapes affect the direct use of redoximorphic features to interprete soil water regime as applied in soil surveys. A system of soil water regime classification is therefore vital if soil survey interpretations are to be used in hydric soil determinations. Kotze *et al*. (1996) summarised hydric soil indicators observed in the three soil water regime classes for soils of South Africa Soil. USDA-NRCS (2010) has developed more site specific hydric soil indicators for United States. The two systems can be used as reference to develop relevant indicators for the wetlands of Lesotho. The relationship between hydric soil indicators and soil water regime is useful to establish the wetland hydrologic criteria for different wetland types. Proper criterion applied will ensure success of restoration efforts.

CHAPTER 3

MATERIAL AND METHODS

3.1. DESCRIPTION OF THE STUDY SITE

3.1.1 Geography and climate

Lesotho is situated approximately between 28°30’ - 30°52’ South and 26°58’ - 29°32’ East. It is land locked and surrounded by the Republic of South Africa. The total land area of Lesotho is about 30 355 km^2. Lesotho held a central position in the former Gondwana which resulted in high altitude prior to the breakup event (Partridge, 1997). A large part of Lesotho is made up of basalt flows of the Drakensberg Group (Figure 3.1). This study was conducted at the upper head-water catchment of the Bokong wetlands in the Maloti/Drakensberg Mountains. Figure 3-2 delineated the study area from Satellite imagery showing the Bokong catchment and the part of Maliba-Mats’o River harnessed to create the Katse dam (Pour L’Observation de la Terre – SPOT- 30 m resolution).

Mean annual precipitation in the Bokong catchment is 1510 mm according to the only available 20 year (1991 to 2010) precipitation record from the rainfall station in the Bokong Nature reserve (BNR). The records from 1991 to 1997 gave a range from 932 to 2018 mm total annual rainfall (Lesotho Highlands Development Authority, 1998). Snowfall occurs between May and November. Snow falls contribute a significant amount of precipitation for maintenance of stream flow relative to high intensity rainfalls of which a larger part evaporates or runs off. The closest temperature records are those of the nearby alpine areas in Maliba-Mats’o with a mean minimum and maximum of 2 and 22°C in summer and -3 and 13°C in winter (Mokuku, 1991). The mean annual temperature is 10°C. The mean soil temperature is 9°C giving a *Mesic* soil temperature regime (Soil Survey Staff, 2010).

According to the Lesotho Meteorological Services, the monthly mean totals of evaporation in Lesotho range from 60 to 70 mm during June and July, and 175 to 225 mm in December and January (Lesotho Meteorological Services, 2008). In general, evaporation is greater than rainfall over most of the year, with the deficit at its greatest in summer.

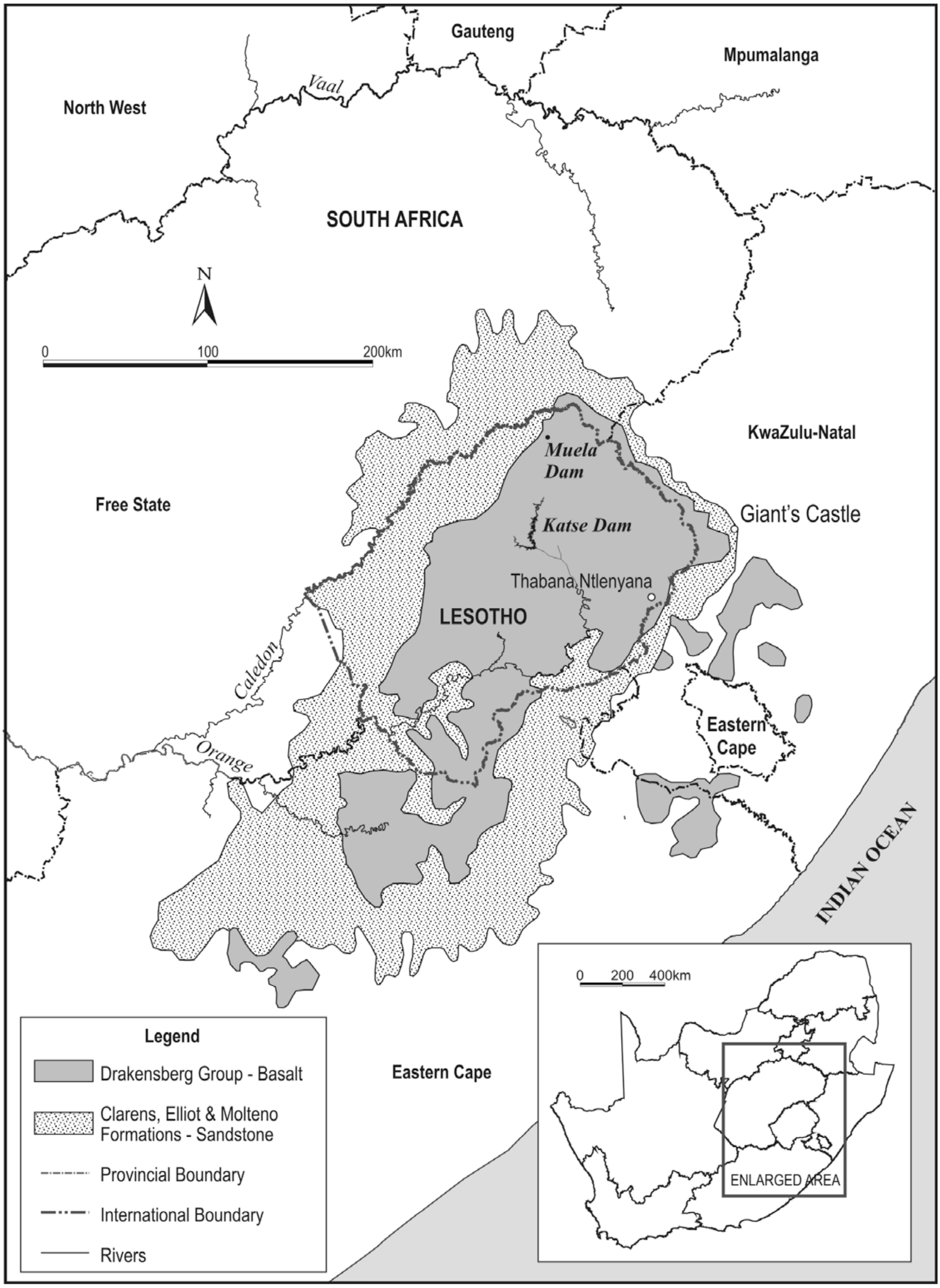

Figure 3-1 Geography of Lesotho showing the Katse Dam (Sumner *et al.*, 2009)

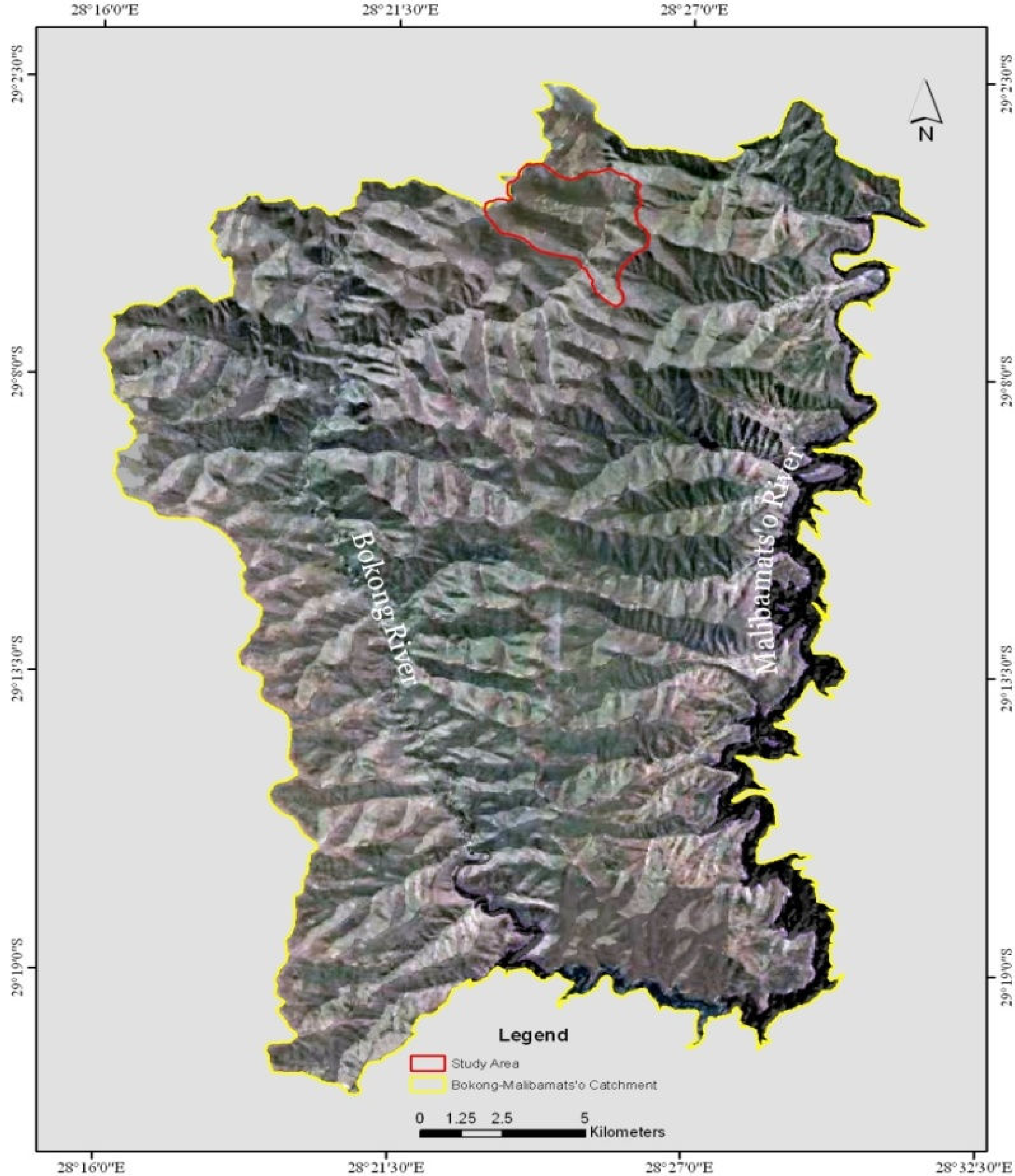

Figure 3-2 Katse Dam and the Bokong catchment delineated on SPOT imagery.

Monthly mean wind speed range from 1.4 m s^{-1} in October to 8 m s^{-1} in August and are generally westerly varying between 200° and 300°. High winds of up to 20 m s^{-1} can sometimes be reached during summer thunderstorms. Sunshine records indicate that the country receives between 60% and 80% of the maximum possible sunshine throughout the year. The annual total solar radiation over the country for the past 20 years is estimated to be between 5700 MJ m^{-2} and 7700 MJ m^{-2} and therefore does not constrain plant growth. The north facing slopes are generally warmer than south facing due to the differences in radiation. Steep south facing slopes are also shaded by other mountains and therefore very cold, especially in winter.

3.1.2 Geomorphology.

The geomorphology of Lesotho has been created by the start of Cainozoic era but the subsequent uplift resulted in renewed incision of river systems to new base levels (Lesotho Highlands Development Authority, 1998). Drainage systems have developed from preferentially weathered zones along fractures and dolerite dykes. The succession of lava flows forming the Lesotho Formation (Drakensberg Group) comprise basalt flows of similar chemistry which vary texturally as a function of cooling rate (Duncan *et al*., 1997). This resulted in basalt flows with varying weathering resistance and it has the dominant influence on micro-relief. The Bokong catchment has three land systems including the high plateau, high mountain flats and higher slopes ranging from 3200 m to 2600 m asl (Lesotho Highlands Development Authority, 1998). Slopes facing south are dominated by slow mass movement processes whereas the opposite north facing valley flanks have lower gradients with sheet erosion dominant. There was also renewed slope erosion and gravel deposition on lower slopes and subsequent organic matter accumulation in the valleys (Lesotho Highlands Development Authority, 1998; Marneweck & Grundling, 1999).

The variations in geomorphology and topography including the micro-climatological influences have a significant impact on the ecology. The Bokong wetlands are found in the Maloti Mountains ecological zone, which cover an area of 18 047 km^2 (about 65% of the total Lesotho land area) and forms part of the Drakensberg range.

3.1.3 Soils

The earliest classification of Lesotho soils are the ones presented by Carroll and Bascomb (1967) and Binnie and Partners (1972) which grouped Lesotho soils into associations. These two systems and USDA soil taxonomy were embraced in the current system presented by the Office of Soil Survey (1979) on the Soils of Lesotho, which mapped Lesotho soils into soil associations on a scale of 1:250 000 (Figure 3-3). Table 3-1 gives the classification of the soil series that form the soil associations shown in Figure 3-3.

Soil associations are soil series occurring together. The soil series were named after village or geographic features near the place where a soil of that series was first observed and mapped (Office of Soil Survey, 1979). The soils in the study area fall under the Popa-Rock Land (Basalt) – Matsana soil association which are *Loamy, mixed, mesic Typic Hapludolls*. The principal soils in this association are Popa and Matsana series occupying 55% and 27% of the total area respectively. While other variants like the Fusi series may occur but the remaining area constitutes the rocklands including cliffs and bare rocks.

The Popa Series (*loamy, mixed, mesic Lithic Hapludolls*) is found on undulating to steep topography and is shallow. They occupy crest and convex upper and middle slopes of the basaltic hills and mountain association. The surface layer is typically very dark brown loam of about 400 mm thick. The underlying material is variegated brown, greyish brown and dark yellowish brown loam about 100 mm thick that grades abruptly through greyish brown weathered basaltic material to indurated basalt bedrock at a depth of approximately 500 mm. Erosion and leaching due to the high rainfall result in the shallow soils (<600 mm deep) of the summits and hills (acid *lithosols*, Lesotho Highlands Development Authority, 1998).

The Matsana series (*Fine, loamy, mixed, mesic typic Hapludolls*) is found on undulating to steep slopes and is moderately deep. They occupy crest and plane or convex upper and middle slopes of the basaltic bedrock controlled terrain. The surface layer is typically very dark brown and brown, loam and gravelly loam of about 400 mm thick. The subsoil is typically dark reddish brown and dark brown gravelly loam, gravelly clay loam and loam about 500 mm thick that grades abruptly through greyish brown weathered basaltic material to indurated basalt bedrock at a depth of approximately 900 mm. The underlying material is typically variegated brown and dark brown gravelly loam or sandy loam.

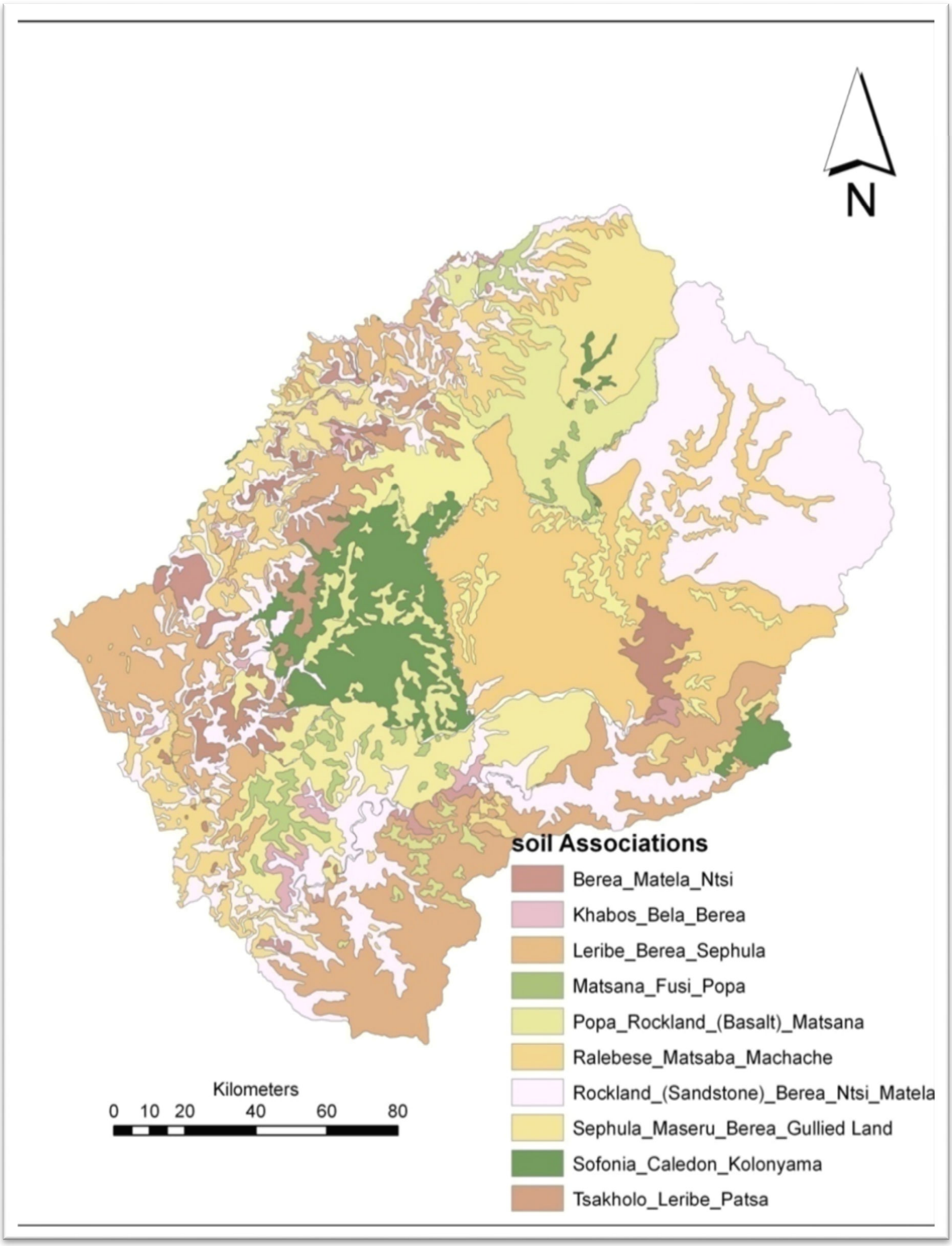

Figure 3-3 Soil associations of Lesotho (Office of Soil Survey of Lesotho, 1979).

Table 3-1 Classification of Lesotho soil series by soil taxonomy (Office of soil survey of Lesotho, 1979).

Order	Suborder	Group	Subgroup	Family	Series
Entisols	Psaments	Udipsaments	Typic Udipsaments	Sandy, mixed, mesic	Thoteng
	Fluvents	Udifluvents	Typic Udifluvents	Sandy, mixed, mesic	Caledon
				Coarse-loamy,mixed, mesic	Majara
	Orthents	Udorthents	Lithic Udorthents	loamy mixed, mesic	Ntsi
	Aquents	Haplaquents	Typic Haplaquents	Coarse-loamy, mixed, mesic	Theko
Inceptisols	Ochrepts	Dystrochrepts	Plinthicaquic Dystrochrepts	Fine-loamy, mixed, mesic	Berea
			Aquic Dystrochrepts	Coarse-loamy, mixed, mesic	Qalaheng
Vertisols	Uderts	Pelluderts	Typic, Pelluderts	Fine-montmorillonitic, mesic	Pechela
Alfisols	Udalfs	Paleudalfs	Typic Paleudalfs	Fine, mixed, mesic	Qalo
	Ustalfs	Haplustalfs	Typic Haplustalfs	Fine, mixed, mesic	Moshoeshoe
	Aqualfs	Albaqualfs	Agric Albaqualfs	Fine, mixed, mesic	Sephula
			Typic Albaqualfs	Fine, mixed, mesic	Maseru
				Fine, loamy mixed, mesic	Tsiki
		Natraqualfs	Typic Natraqualfs	Fine, mixed, mesic	Patsa
			Glossic Natraqualfs	Fine, mixed, mesic	Ts'akholo
Mollisols	Udolls	Hapludolls	Fluventic Hapludolls	Fine-loamy, mixed, mesic	Bosiu
			Typic Hapludolls	Fine-loamy, mixed, mesic	Kubu
				Fine-loamy, mixed, mesic	Leribe
				Loamy, mixed, mesic	Ralebese
				Coarse-loamy, mixed, mesic	Matela
				Fine-loamy, mixed, mesic	Matsana
			Cumulic Hapludolls	Coarse-fine, mixed, mesic	Tsenola
				Fine-loamy, mixed, mesic	Fusi
				Fine-loamy, mixed, mesic	Maliele
			Lithic Hapludolls	Loamy, mixed, mesic	Popa Lekholong
			Fluventic Hapludolls	Fine-loamy, mixed, mesic	Kolonyama
				Coarse-loamy, mixed, mesic	Sofonia
		Argiudolls	Typic Argiudolls	Fine, mixed, mesic	Machache
				Fine, mixed, mesic	Matsaba
				Fine, mixed, mesic	Khabos
				Fine-loamy, mixed, mesic	Khabos thin
				Fine, mixed, mesic	Thabana
			Aquic Argiudolls	Fine-loamy, mixed, mesic	Rama
	Ustolls	Argiustolls	Pachic Argiustolls	Fine, mixed, mesic	Seforong
			Udic Argiustolls	Fine, mixed, mesic	Nkau
	Aquolls	Argiaquolls	Typic Argiaquolls	Fine, mixed, mesic	Bela
		Haplaquolls	Cumulic Haplaquolls	Fine-loamy, mixed, mesic	Maseru-dark

The Fusi series (*Cumulic Hapludolls*) is found on gentle to moderate sloping hillsides and is deep. They occupy plane and concave middle and lower slopes of the basalt bedrock controlled terrain. The surface layer is typically very dark brown and brown, loam and gravelly loam of about 400 mm thick. The subsoil is typically dark reddish brown and dark brown gravelly loam, gravelly clay loam and loam about 500 mm thick. The underlying material is typically variegated brown and dark brown gravelly loam consisting of weathered rock material.

The Matsana, Popa and Fusi series are soils developed from the *in situ* weathered basaltic rock (Office of Soil Survey, 1979). The parent material is high in calcium, magnesium, and iron and low in silica (Lesotho Highlands Development Authority, 1998). Klug *et al.* (1991) commented on the high Ca content (in the region of 10.5% CaO), and volcanic glass that the basalt of Maloti Mountains contain. The soils therefore have naturally high fertility that favours luxurious grass growth and a high level of organic matter incorporation. The top layer is dark and very high in organic matter (6 to 16%, Office of Soil Survey of Lesotho, 1979). The low temperature has further inhibited the decomposition of this organic matter and it contributes to the dark thick surface layer.

3.1.4 Hydrology

The Bokong wetlands are the water sources for the Bokong River and Lepaqoa stream. Both drainage systems contribute to the Katse reservoir. These wetlands help to regulate the quantity of water moving through a watershed by retaining water during wet periods and releasing it during dry periods. The catchment has many smaller wetlands that provide the necessary storage capacity and are essential for the proper functioning of a watershed.

3.1.5 Vegetation and wetland types

Lesotho is mainly a grassland biome with six grassland or vegetation types influenced by mainly altitude and climate (Bredenkamp *et al*., 1996). Bokong falls in the Alpine Belt which lies between 2600 m at the upper limit of the Subalpine Belt and 3200 m as the highest point of the Alpine Belt. Therefore, the vegetation is essentially sub-alpine grassland with a number of endemic plants species. The vegetation of the Bokong wetlands falls within the Lesotho Highland Basalt Grassland (Gd 8) as described by Mucina and Rutherford (2006). Du Preez and Brown (2011) supposed that this vegetation type is one of the most endemic-rich vegetation units in the Drakensberg Alpine Centre, but only 1% of it is statutorily conserved in Lesotho. Dominant plants are tussock grasses like *Merxmuellera disticha, M.*

drankensbergenis, Festuca caprina, and short shrubs. Trees are non-existent. The grasses are used for summer grazing.

Schwabe and Nthabane (1989) used the classification and ordination to identify plant communities which characterise particular wetlands of the Maloti Mountains. The following vegetation associations were derived as influenced by moisture, soil type, and position within the wetland system: More saturated sites are dominated by sedges, *Haplocarpha nervosa* and *Isolepis angelica*. Areas with fluctuating water table are dominated by grasses like *Merxmuellera disticha*, *Anthraxia fontana,* and other plants such as *Trifolium* are intermingled. The dry vegetation association that occur in the drier parts of the wetlands include *Helichrysum, Poa annua, Koeleria capensis*. In pools, where there is free standing water two endemic and rare species of *Aponogenton* and *Carex cognata* are found. A healthy wetland is characterised by an abundance of *Carex sp., Scirpus sp.* and *Merxmullera sp* (Schwabe, 1995). Species that are found in dry areas associated with disturbance by livestock include *Senecio sp, Rumex sp.*, *Eumorphia sericea*, short sedge grasses, *Helichrysum chionosphaerum*. Photographs of selected species are presented in Appendix 1.

Three wetland types were identified following the provisional classification of wetlands in the high altitude catchments of Lesotho (Jacot, 1962; Schwabe & Nthabane, 1989; Schwabe, 1995; Marneweck & Grundling, 1999). The three wetland types were bogs, fens and hillslope seeps. Even though some researchers disputed the existence of bogs in these wetlands (Cronk & Fennessy, 2001; Du Preez & Brown, 2011), the difference observed is that fens represent an earlier successional stage of peat accumulation than bogs and tend to have organic matter content which is relatively lower in fens than bogs. Therefore, these distinctions were used in this study.

A bog is wetland that accumulates acidic peat, a deposit of dead plant material from usually mosses while fens are usually characterized by their neutral water pH (Mitsch & Gosselink, 2007). However, Schwabe (1995) described the Bokong fens as acidic and they are usually valley head fens comprising of large lawns of sedges and grasses, pools. The valley head fens were the most common wetland types in the study area. Hillslope seeps are formed due to local stratigraphy such as the impermeable layer of saprolite or hard rock, forming a perched aquifer (Marneweck & Grundling, 1999). The hillslope seeps are found mainly on concave slopes or terraces above the tributaries of Bokong River and are also referred to as seepage zones (Marneweck & Grundling, 1999). These wetlands were supplied by a shallow perched aquifer hence, the soils became dry during portions of the growing season.

3.1.6 Land use

The main use of the Maloti Mountains including the Bokong catchment is grazing of domestic animals including cattle, sheep and goats. The national rangeland inventory carried out between 1983 and 1986, estimated the Lesotho rangelands to be 75% overstocked (Range Management Division, 1988). The Lesotho Highlands Development Authority (1998) indicated that while there have been previous developments for the conservation of these sensitive areas in the Maloti Mountains through range management associations (RMAs) as recommended by Schwabe (1993) only relatively small portions are protected and the remaining portions reflect indicators of unsustainable use.

The Bokong wetlands are degraded due to anthropogenic impacts resulting in gully erosion that drains the wetlands, followed by the invasion of exotic species. The Lesotho Highlands Development Authority (1998) attributed the degradation of wetlands to trampling that damages the delicate vegetal layer of the wetlands and the exceptionally slow recovery (Lesotho Highlands Development Authority, 1998). Repeated trampling exposes the fragile organic soils that are removed easily by runoff. Marneweck and Grundling (1999) observed the elevated remnants of peat which are dry, which indicated the original peat surface which has undermined the storage capacity of the wetlands. Uncontrolled burning during the dry season is common in the mountain rangelands of Lesotho and happens in any six out of ten years (Morris *et al*., 1991). High wind speed of up to 100 km hr^{-1} increases the probability of spring fires (Lesotho Highlands Development Authority, 1998).

The protected part of the Bokong wetlands is the Bokong Nature Reserve (BNR). The BNR is used as tourist site which comprises endemic alpine flora and fauna. The fauna consists mainly of a number of birds such as bearded vulture and other bird species endemic to the afro-alpine zone. The Mountain rhebuck population is particularly high and serves a means of tourist attraction. There are peculiar colonies of the endemic ice rat (*Otomys sloggettii)* that dig tunnels in areas around the wetlands that are not waterlogged. These moles make underground tunnels around the drying parts of the wetlands which collapse and result in gullies. Other minor land uses include the harvesting of medicinal plants and grasses for crafting and thatching for livelihoods.

3.2 HYDROLOGY DETERMINATION

The study area, including the drainage patters, wetlands, and instrumentation is given in Figure 3-4. The area is approximately 13 km^2. Wetlands and drainage patterns were extracted from existing shape files (Schwabe & Whyte, 1993; Maloti-Drakensberg Trans-frontier Project, 2006), collected from small scale national data (1:250 000) on the wetlands of Lesotho. The two were overlaid on a 10 m contour map developed from a 20 m resolution DEM (Maloti Drankensberg Trans-frontier Project, 2006). The total wetland area within the study area is 23.145 ha which is about 1.7% of the study area and comprise of 54 wetlands, ranging from 0.2 to 7.5 ha in size.

3.2.1 Climatic parameters

A weather station which records rainfall, air temperature, relative humidity and soil temperature was installed at the study site (Figure 3-5). Rainfall intensity was measured using a tipping bucket rain gauge, from January 2010 to August 2011. The comparison of the rainfall intensities from January to July 2010 and 2011 are given in Figure 3-6. The 2011 rainfall was charecterised by more rainfall events with higher intensities than in 2010. The highest rainfall intensities of 7.8 mm in 5 minutes were recorded between January and July 2011, while in 2010 the highest rainfall intensity was 3.4 mm in 5 minutes.

Rueter and Bell (2003) showed the importance of seasonal variations in precipitation when evaluating the distribution of water in the landscape and its influence on pedogenesis. In this study, seasonal variations were determined by comparing the two previous year’s seasonal rainfall patterns and the twenty year seasonal means with the study period rainfall seasonal variations (Figure 3-7). The daily rainfall records between 1991 and 2011were taken from the Mphosong weather station situated at an altitude of 3090 m above sea level within the study site. Spring begins in August and summer starts in November, while winter starts in May. In all seasons rainfall for the two years prior the commencement of the study and the twenty year mean did not show much variation from the seasonal rainfall pattern observed during the study period, except for summer of the 2010/11 season. The summer rainfall recorded for the 2010/11 season was almost 40% higher than the average rainfall for all other years.

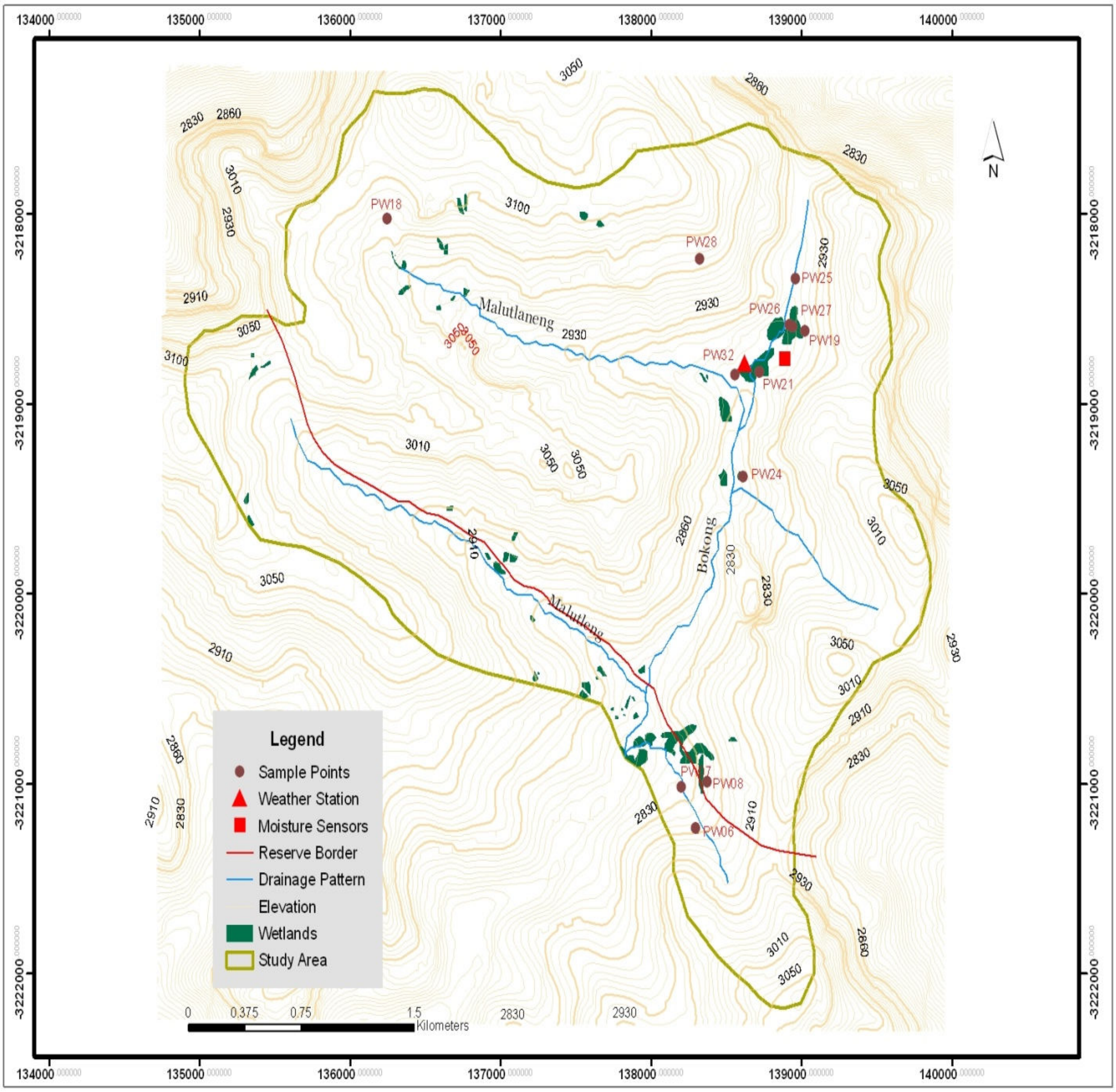

Figure 3-4 The study site showing the drainage system and sampled wetlands.

Figure 3-5 Weather station and sensors installed at Bokong in wetland PW32.

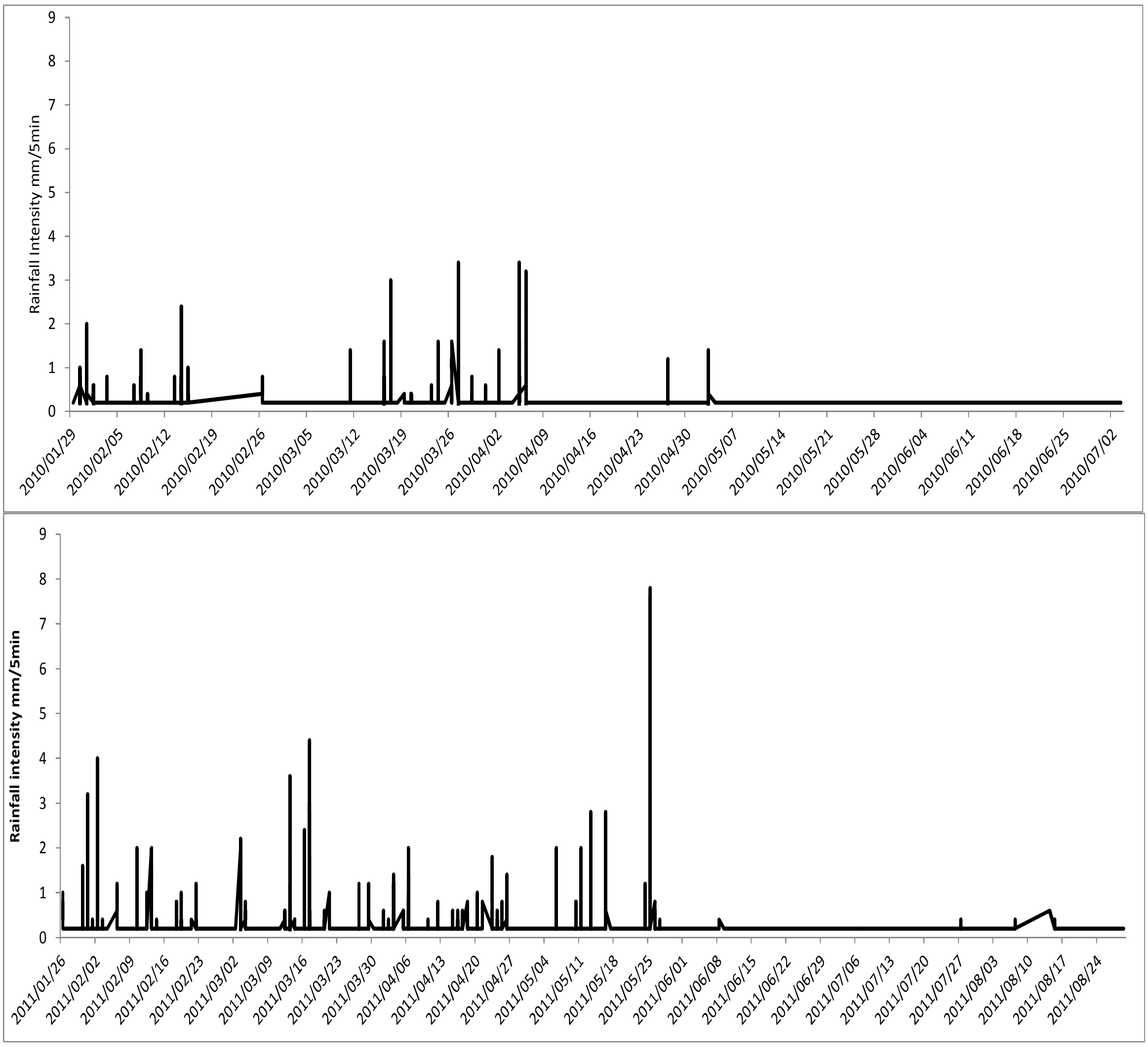

Figure 3-6 Rainfall intensity for two seasons from January to August 2010 and 2011

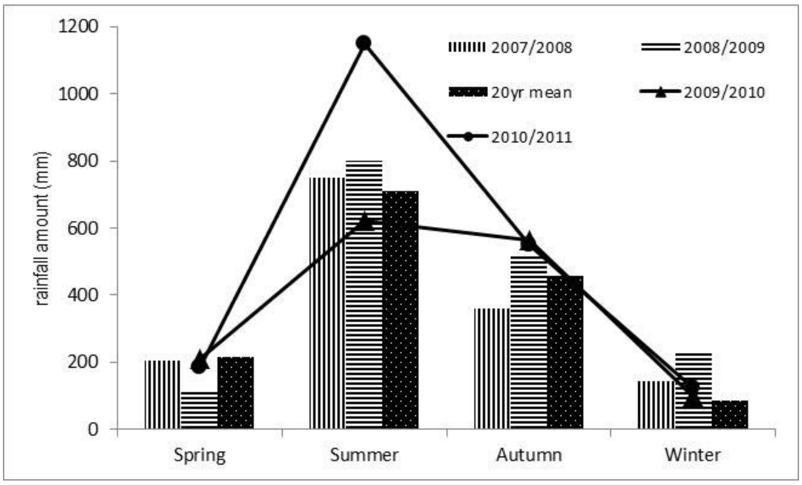

Figure 3-7 Seasonal rainfall patterns and a 20 year mean (August 1991 to July 2011).

Hydrologic parameters are naturally variable and therefore require many years (10 years) of ground water monitoring to determine whether minimum standards for water table depth, duration and frequency in wetlands are met. Because soil water table behaviour responds to daily precipitation, a two year water table dataset alone is not sufficient to represent the water table regimes of the soil. Therefore, in short-term studies, normality of precipitation during the monitoring period has to be considered. In this study the probability distribution of a time series was used to describe the probability that monthly rainfall fell into a specified range of values using quantiles and percentiles (Morgan & Stolt, 2006). Average monthly precipitation recorded from the Mphosong weather station between 1991 and 2011 were used to estimate 30 and 70% precipitation probabilities. The probabilities were calculated using the 2-parameter gamma distribution, gamfit, and gaminv (Mathworks Inc., 2000). The monthly rainfall distribution was normal within the 20 year period (Table 4-2). Nine months of the monitoring period had rainfall amounts within the 30 and 70 percentiles. The annual precipitation recorded at Mphosong weather station from September 2009 to August 2010 was 1510.7 mm and from September 2010 to August 2011 was 2030.1 mm (Table 4-2).

The mean temperatures recorded during the study period was 2°C in winter and 10°C in summer while mean relative humidity was 66% in winter and 79% in summer. Potential Evapotranspiration was calculated using the Thornthwaite equation (FAO, 1998):

$$PET_i(0) = 1.6(10Ti/J)^{\circ} \qquad (3\text{-}1)$$

This equation uses the mean monthly temperature T_i (°C) and latitude (degrees) either in the Northern or Southern Hemisphere. The highest PET is in December and January at 54.1 mm and 65.3 mm respectively and lowest in June and July at 26.6 mm and 26.3 mm respectively. This enabled the estimation of the average climatic water balance for the period 2009 to 2011, which reflected a surplus of moisture during the rainy and warmer months of November through April and a deficit of moisture during the cooler and drier months of June through September.

Table 3-2 Average precipitation recorded in Bokong between 1991 and 2011 and amount of precipitation recorded between 2009 and 2011.

Month	Precipitation (mm)				
	2009-2010	2010-2011	30% quartile	70% quartile	Average 1991-2011
September	16.0	4.4	6.7	36.1	32
October	209.0	130	42.2	96.7	153.1
November	139	329.2	52.8	116.1	225.3
December	128.9	414.9	76.3	126.1	233.2
January	353	420.3	71.5	137.6	255.2
February	147.5	147.5	48.9	99.7	172.5
March	186	180.8	51.3	105.3	183.3
April	231.9	215	22.4	55.4	125.7
May	52.9	135.4	07.2	21.4	56
June	46.5	15.4	2.3	15.1	23.8
July	0	18.2	1.1	8.4	16.7
August	0	19	5.2	29	37.7
Totals	1510.7	2030.1			1514.5

3.2.2 Soil temperature and water content

Soil temperature and water content data were collected using Decagon soil moisture probe (ECH_2O; Cobos, 2006) and Hobo XTI data-loggers (Onset Computer Corporation, 2007) placed in waterproof polycarbonate containers that were installed at five different depths (150, 300, 450, 600, and of 750 mm). The temperature and soil moisture sensors were placed on the concave west facing lower footslopes at 2897 m above sea level at 15% slope. The soil depth was approximately 1000 mm to the C horizon and it is situated immediately above the valley bottom wetlands near PD11 as was indicated in Figure 3-4. The temperature trends down the profile differed with seasons (Figure 3-8). Soil temperature ranged between 4.99°C and 8.23°C in winter (May to July) and from 10°C to 12°C in summer (November to January).

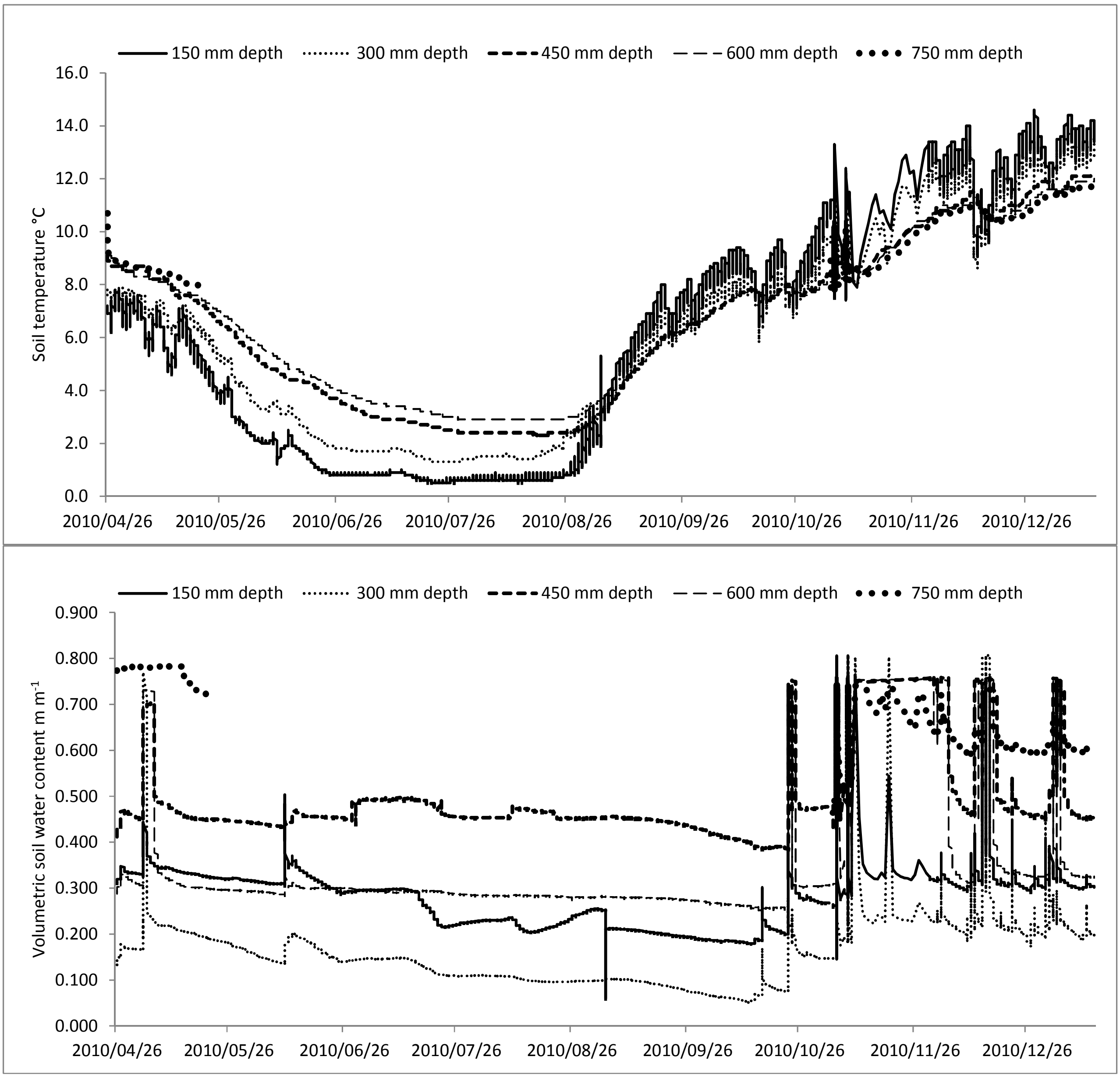

Figure 3.8. Soil temperature and soil water content at different depths from 26 April 2010 to 13 Jan 2011.

The temperatures increase with depth in winter with highest temperatures in the lower 750 mm (Figure 3-8). The lower temperatures in the top layers of the soil were due to the effect of snowfall. The depth of snow in the profile observed during winter months was 500 mm. In summer the temperature decreased with depth.

The lowest temperature recorded in the top 150 mm depth was 0.5°C and the highest was 14.6°C (std. dev. was 4.5) compared with the 750 mm depth where the difference between lowest recorded temperatures was 7.8°C (std. dev. was 1.1) between seasons. Lesotho

Highlands Development Authority (1998) indicated that the vegetation of this mountain climate provides the micro-climate which significantly reduces the wide fluctuations in temperature at the soil surface that would exist in the absence of such cover. There were only 3 months (June to August) in a year in which temperatures were below 5°C within the 500 mm depth considered to be inactive microbial period according to the growing season definition by USDA-NRCS (2010). The 5°C temperature or warmer at 500 mm depth is used to determine the growing season in soils but the threshold temperatures depend on the soil properties (Burdt *et al.*, 2005).

The soil moisture content ranged between 0.50 and 0.10 m m^{-1} in winter and 0.20 and 0.8 m m^{-1} from spring through summer seasons (Figure 3-8). There was also an indication of local stratification down the profile, where soil moisture in the 450 mm depth was higher than the underlying 600 mm layer during the dry season between May and October.

3.2.3 Water table elevations

Groundwater observations were made using piezometers which were installed in triplicate at depths of 50, 250, 500, 750, and 1000 mm (Figure 3-8) in ten representative wetlands (Figure 3-4) to determine both the soil water level and the vertical groundwater movement. The piezometers were open only at the lower portion of the riser. They were constructed from 50 mm polyvinyl chloride (PVC) pipes covered at the bottom by geotextile fabric (Fiedler & Sommer, 2004) protruding on the surface by 100 mm. They were installed in auger holes, backfilled in approximate depth sequence with soil from the auger hole, and sealed at the soil surface with bentonite to reduce sidewall flow (Morgan & Stolt, 2004). Ponding depth was measured with a steel tape (Burdt *et al*., 2005) once every two weeks. Water table data was recorded for two seasons from September 2009 to August 2011.

Figure 3-9 A number of installed piezometers at PW32 wetland sealed with bentonite and covered at the tops and the depth labelled on top of the caps.

Water table hydrographs were developed from these bi-weekly water table data for two seasons for each well. The bi-weekly water table data was also used to calculate the seasonal high water table, average seasonal high water table (ASHWT), and cumulative saturation for each horizon. The ASHWT was calculated by averaging the lowest and highest water table values (Morgan & Stolt, 2006). Cumulative frequency is the percentage time the water table was recorded at different depths (Morgan, 2002). It was calculated as the number of times the water table depth was recorded divided by the number of observations during the monitoring period.

The calculated frequencies were then extended to the determination of the cumulative saturation by multiplying the number of times each depth was recorded by 14 days, assuming that the water table maintained the same depth to obtain the number of days the water table resided in that level. This was done by sorting data in descending order and counting the number of times a specific depth appears, multiplying that amount by the recording interval (14 days), and then dividing that number by the total time of measurement (730 days) to get the percentage of time that depth was saturated. These values were then added to the previous values to obtain a cumulative saturation for that time period. The cumulative saturation was plotted against the water table depth to obtain the percentage of time the water table is present within a horizon. A horizon was considered saturated if >75% of the horizon was under the free water table (Jacobs *et al*., 2002).

3.2.4 Soil redox potential

Reducing conditions were determined by measuring the redox potential with a Platinum electrode (Hanna HI7020) calibrated using a redox standard solution of 263 mV at 25°C.

Two Pt electrodes were installed at 500 mm depth and connected to a CR-1000 Campbell Scientific Inc. logger near wetland PW32. Along with hourly recorded redox potential measurements was a Decagon soil moisture probe (ECH_2O; Cobos, 2006) recording soil water content at 500 mm every hour and used to calculate the degree of water saturation. Reduction was defined by a decrease in Eh of a soil. The degree of saturation in which Eh starts to decrease was determined by integrating both degree of saturation graph and redox potential graph and analysing the slopes of the graphs. According to Ponnamperuma (1972), the Fe^{3+} and Mn^{4+} start to reduce at 400 mV and 300 mV respectively and pH starts to increase towards neutrality. The percentage time in hours, for which Eh was less than 400 mV (onset of Fe-oxide reduction), was also determined.

3.3 SOIL CHARACTERISATION

3.3.1 Soil survey

Field exploration of the survey area was done to familiarise with landmarks, wetlands and borders of the area. The necessary routes for data collection were established based on detailed examination of 2928AB national topographic sheets at a scale of 1:50 000 (Lesotho Government, 1982). Soil survey along these routes was done through auger sampling and observation of road embankments to visualize the sequence of soil distribution in the landscape. Movement was done upslope to the top of the hill then along contours. All observations were geo-referenced with a Garmin eTrex 30 GPS with ± 10 m accuracy, mapped and labeled as Figures 3-9. The main physiographic units of the study area were firstly delimited on the topographic map and a preliminary legend for soil types was established. The preliminary legend took into account the set of features that were important to wetland functions and potentially varying within the physiographic regions. Among them were soil depth, field estimation of amount of gravel in the A horizon, presence of transitional AB horizon, presence of stoneline, and presence and depth of redoximorphic features.

Surface analysis was performed on 30 m digital elevation model (DEM) obtained from Maloti Drankensberg Trans-frontier Project (2006) using a GIS geospatial analysis extension for slope gradient, aspect (Figure 3-5, (a) and (b) respectively). These were used in the absence of aerial photographs and ortho-photographs of the area to prepare the base map. Main physiographic units were described as follows: The summits had a slope of less than 10% and found on elevations higher than 2900 m asl, midslopes had slopes higher than 20% and elevations higher than 2900 m asl, footslopes had slopes between 10 and 24% and elevations around and below 2900 m asl, while valleys had slopes less than 10% and elevations below 2900 m asl.

Soil profiles were marked along hillslope transects from the summit to the valleys. Soil profiles on the dry land were identified as permanently dry (PD) and from wetlands as permanently wet (PW). The permanently dry land did not have a water table within 500 mm of the soil surface. The terrain attributes for the thirty-two (32) profiles are given in Table 3-2. Four (4) of the profiles were on the summits, five (5) were on the midslopes, nine (9) were on the footslopes, while six (6) were in the valleys.

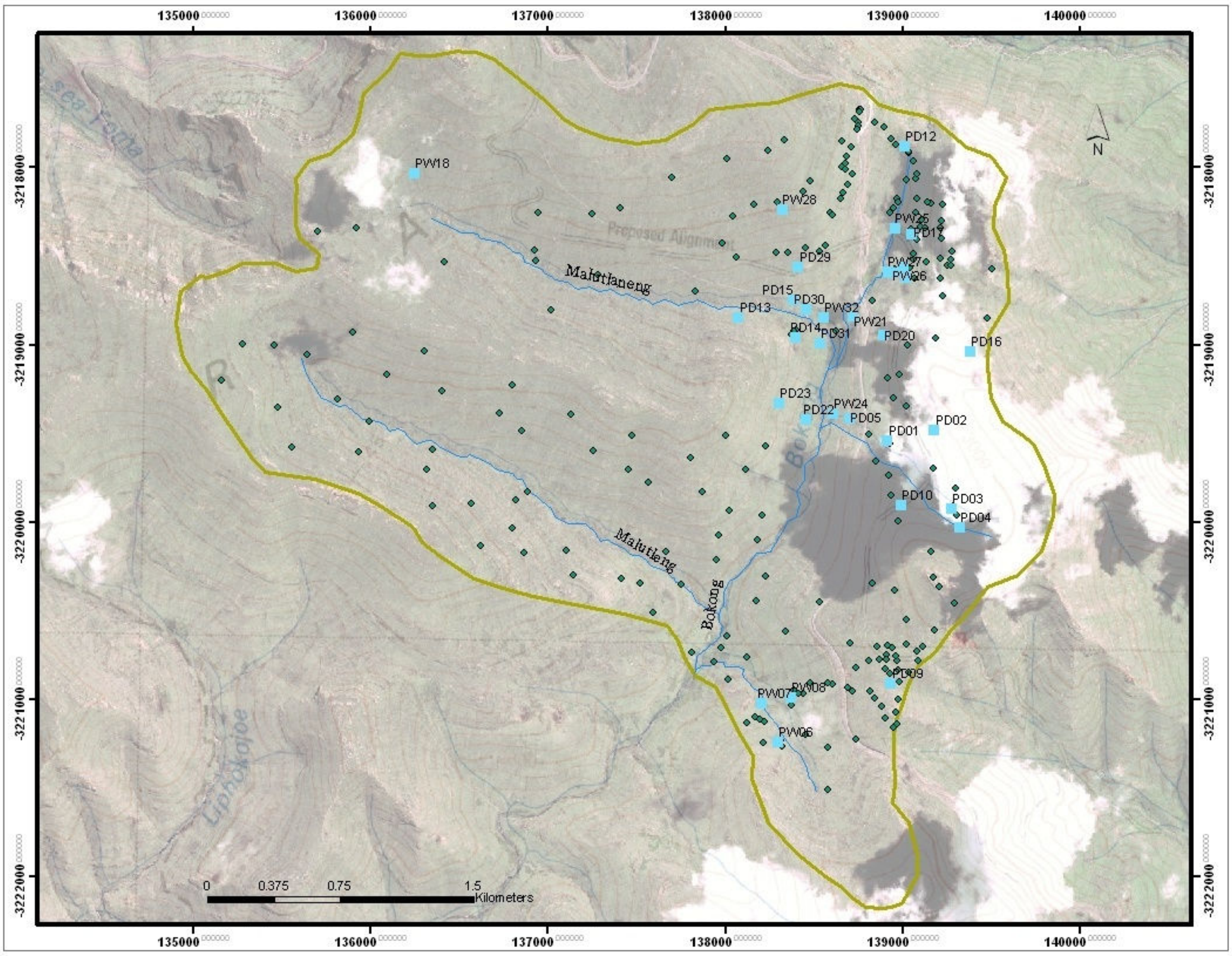

Figure 3-10 Auger observations and labeled profiles in the study area.

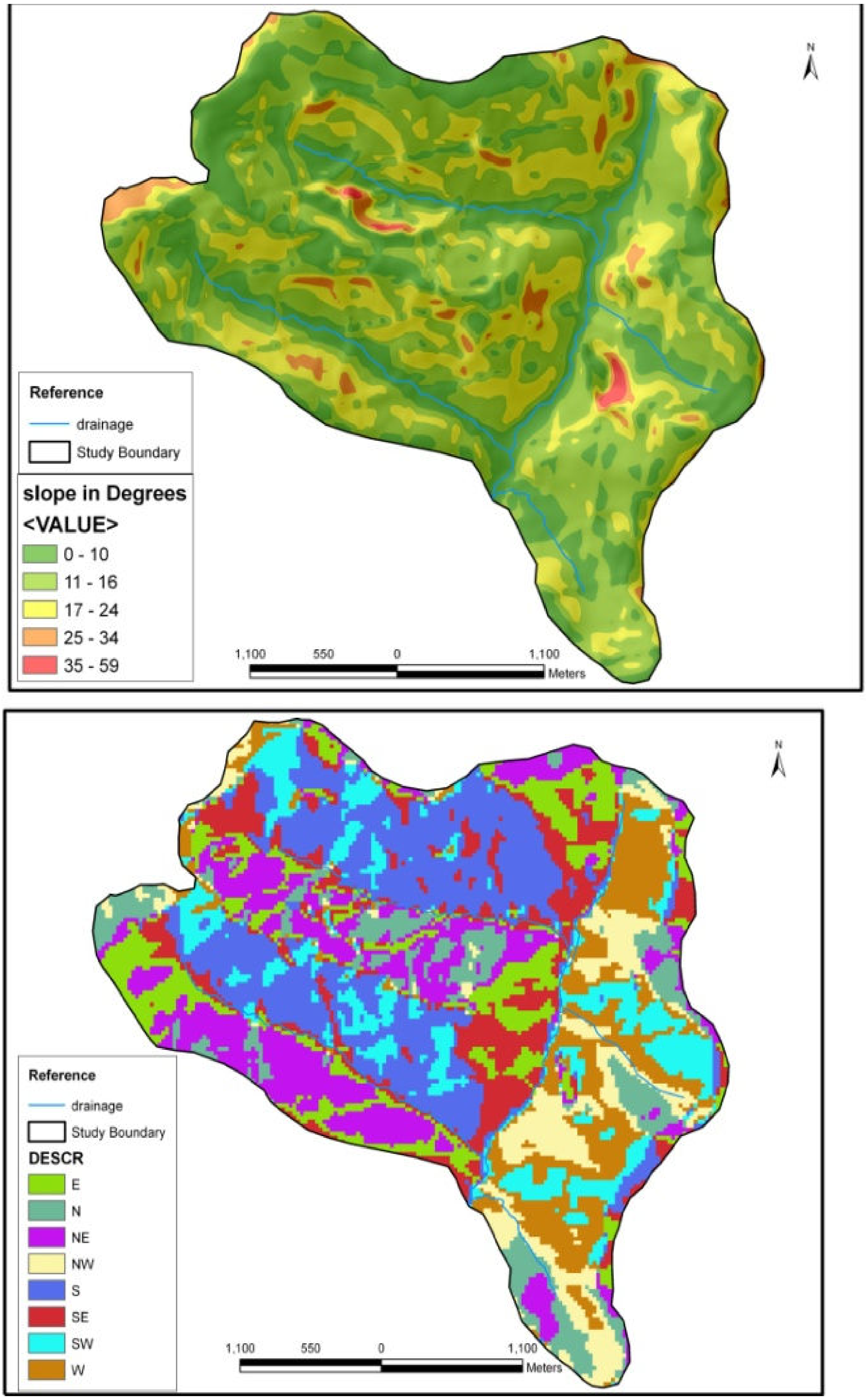

Figure 3-11 Slope and aspect analysis of the study site

Table 3-3 Distribution of profiles and some selected physical properties in different physiographic units of Bokong catchment.

Profile no.	Coordinates		Elevation	Aspect	Slope %	PU	Depth (mm)
	South	East					
PD01	-29.0874	28.4268	2903	NW	18	Footslope	900
PD02	-29.0868	28.4295	2976	SW	41	Midslope	950
PD03	-29.0908	28.4305	2961	NW	11	Summit	600
PD04	-29.0917	28.4310	2977	N	21	Midslope	810
PD05	-29.0862	28.4245	2860	W	22	Footslope	880
PW06	-29.1028	28.4206	2861	N	30	Midslope	590
PW07	-29.1008	28.4196	2828	NW	11	Footslope	1000
PW08	-29.1005	28.4213	2844	W	13	Footslope	850
PD09	-29.0997	28.4271	2963	E	8	Summit	650
PD10	-29.0907	28.4276	2959	NW	10	Summit	330
PD11	-29.0785	28.4275	2897	W	15	Footslope	1000
PD12	-29.0724	28.4275	2888	SE	5	Valley	800
PD13	-29.0812	28.4180	2913	NE	21	Midslope	600
PD14	-29.0822	28.4213	2897	NE	18	Footslope	720
PD15	-29.0803	28.4212	2898	SE	16	Footslope	800
PD16	-29.0828	28.4315	2976	N	8	Summit	420
PD17	-29.0768	28.4315	2901	W	19	Footslope	1100
PD18	-29.0740	28.3992	3062	SE	8	Summit	800
PW19	-29.0791	28.4277	2887	W	13	Footslope	850
PD20	-29.0820	28.4264	2909	W	18	Footslope	1000
PW21	-29.0810	28.4247	2862	W	4	Valley	1000
PD22	-29.0864	28.4220	2867	E	18	Footslope	1000
PD23	-29.0855	28.4204	2907	SE	39	Midslope	150
PW24	-29.0860	28.4236	2850	SW	14	Footslope	1000
PW25	-29.0766	28.4270	2883	SE	6	Valley	800
PW26	-29.0788	28.4269	2882	W	10	Valley	767
PW27	-29.0788	28.4267	2872	W	7	Valley	1000
PW28	-29.0757	28.4205	3034	S	20	Midslope	1000
PD29	-29.0786	28.4215	2926	S	23	Midslope	1000
PD30	-29.0807	28.4220	2873	SE	12	Footslope	880
PD31	-29.0825	28.4228	2865	E	14	Footslope	760
PW32	-29.0812	28.4230	2868	W	3	Valley	1000

† PU = physiographic units

Soil profiles were dug to a depth of 1 meter where possible or shallower where the rock was encountered. One side of a pit was cleaned and the different horizons demarcated. All profiles were described using the soil description form of Turner (1991), which includes features such as matrix colour, abundance, size and colour of redoximorphic features. Soil profile information was captured in MS Access program of the ARC-Institute for Soil, Climate and Water in Pretoria. The description of the profiles is given in Appendix 2.

3.3.2 Redoximorphic features

The description of redoximorphic features was done for each horizon throughout the profile to determine the hydric soil indicators and determine the relationship between redoximorphic features and hydrology. The matrix soil colour was described using the *Munsell® Soil Colour Charts* (Gretagmacbeth, Munsell®Corporation, 1998). Redoximorphic feature interpretations were made based on standard soil survey criteria and nomenclature (Turner, 1991; Soil Survey Staff, 1993; Schoeneberger *et al*., 2002) with abundance categories as few <2%, common 2 to 20%, and many >20%. Redoximorphic features were also described to the depth of 1000 mm because the soils had thick, dark surface layers, and indicators may not be easily seen within 500 mm of the surface.

Hydric soil indicators were identified using the USDA-NRCS (2010) indicators. Detailed descriptions of profiles and hydrology data described in Section 3.2 to a depth of 1000 mm were used to inform modification on these indicators.

3.3.3 Relationship between hydrology and redoximorphic features

The abundance categories for redoximorphic features were modified into indices as suggested by Galusky *et al*. (1998), and also consider the type of redoximorphic features. This study used the following indices and evaluated the relationship between the indices and water table depth and regimes:

- Few redoximorphic features index was abbreviated as *d_RMFs* (Morgan & Stolt, 2006).
- Few depletions with common redox concentrations was abbreviated as *d_conc* (Galusky *et al*., 1998; Morgan & Stolt, 2006).
- Common to many depletions with or without few redox concentrations was abbreviated as *d-depl* (Galusky *et al*., 1998; Morgan & Stolt, 2006).
- Depth to the first gleyed horizon was abbreviated as *d_gley* (Galusky *et al*., 1998).
- Depth to chroma 3 and 4 was abbreviated as *d_34* (Galusky *et al*., 1998).
- PDI and depth of black topsoil horizons (equation 2-7) were added because the of high organic matter accumulation in these landscapes (Rueter & Bell, 2003).

The cumulative saturation of each horizon from all the described profiles with one of the indices was determined. Only twelve profiles had at least one of the indices and water table within 1000 mm. This was deemed the percentage time in a year required for saturation to develop each type of redoximorphic features. The correlation coefficient of cumulative saturation percentage and lower depth of the horizon with an index was determined to evaluate whether redoximorphic features explained the hydrology of the site. The high correlation would mean that redoximorphic feature index represent the depth to which the water table commonly rises and remained there for a critical period.

3.3.4 Soil laboratory analysis

Following detailed descriptions of the profiles, representative soil samples were taken with a hammer starting from the lowest horizon and then upwards to the top horizon, to avoid contamination. The horizons were sampled at several locations along the pit faces. Soil samples were then placed in sampling bags, sealed, labeled both inside and outside, and transported to the laboratory for chemical and physical analyses.

The soil samples collected were air-dried, weighed, crushed, and passed through a 2 mm sieve and some to pass through a 0.5 mm sieve. The samples screened through a 2 mm sieve were used for the determination of particle-size analysis, pH, total N, available P, basic cations (Ca, Mg, Na, and K), and Fe, Mn, and Al. Those that passed through a 0.5 mm sieve were used for the determination of organic carbon. The soil that remained in the 2 mm sieve was used for the determination of the gravel content. The soil clods were broken and washed off. The remaining stones were dried in an oven and weighed as gravel. All the chemical soil properties were analysed using the methods described by The Non-Affiliated Soil Analysis Working Committee (1990).

Brief details of the soil analyses and methods are given below:

(a) Particle size analysis (PSA) was determined by fractionation and the pipette method (Gee & Bauder, 1986). The soil was pre-treated with hydrogen peroxide to remove organic matter. Seven particles size classes including coarse sand, medium sand, fine sand, very fine sand, coarse silt, fine silt, and clay were determined.

(b) Soil pH was determined in a 1:2.5 soil: water ratio and 1 M KCl (McLean, 1982).

(c) Organic C was determined by the wet digestion method (Walkley & Black, 1934) and total C by dry combustion using a LECO Carbon/Nitrogen determinator (LECO, 2008). Dry combustion mean recovery was higher (Appendix 4) and since the study soils were carbonate free, and organic carbon should equal to total carbon (Fiedler & Sommers, 2004), dry combustion results were used for further analysis.

(d) Phosphorus was determined using the method of Bray and Kurtz (1945).

(e) Exchangeable and soluble cations (Ca, Mg, Na, and K) and cation exchange capacity were determined by leaching with 1 N NH_4OAc at pH 7. The CEC was determined by saturating ammonium acetate leached soil with Na acetate and leaching again with 1 N NH_4OAc at pH 7. Soluble cations were determined by atomic absorption spectrophotometry (Schollenberger & Simon, 1945).

(f) Iron, Al and Mn oxides were extracted by dithionite citrate bicarbonate (DCB; Mehra & Jackson, 1960) and determined with atomic absorption spectrophotometry (Varian SpectrAA-200).

Bulk density of each horizon in representative profiles was determined with the core method (Blake & Hartge, 1986). A core sample was taken by inserting a cylindrical core sampler of a known volume (0.00080 m^3) with a core driver into the soil (Figure 3-11a). The surface of the soil area to be sampled was first cleaned. Once the sampler was driven deep enough to be covered by soil on the top, it was removed carefully using a spade (Figure 3-11b). Both ends of the core were then leveled with a field knife, covered with boards, tightened with tape and placed into a sealed plastic bag (Figure 3-11c). Three replicate samples were taken per horizon. The core samples were weighed and put in an oven to dry for 24 hours at 105°C, after which they were reweighed (excluding the weight of core samplers and boards).

Figure 3-12 Bulk density samples collection

3.4 STATISTICAL ANALYSIS

The soil properties spatial variability was measured by coefficient of variation. One-way analysis of variance was used to test whether there were significant differences in soil properties between different slope positions (SAS Institute, 1999). Correlation matrix was performed to analyse the level of relationships between soil properties. All the absolute values of correlation coefficient less than 0.217 were indicating no statistical significant relationship between soil properties at $P > 0.05$ as controlled by the sample size (Steel & Torrie, 1986). The principal component analysis (PCA) was used to analyse the cause of soil variation and establish the spatial patterns of soil properties. PRINCOMP procedure was used to computation of principal components (SAS Institute, 1999).

Relationships between horizons with each of the redoximorphic features index and depth to the average seasonal high water table (ASHWT) and cumulative saturation were evaluated using simple regression analysis (Microsoft Corporation, 2010). Analysis of variance and Turkey's multiple comparison tests were used to determine differences between mean cumulative saturation of different indices (SAS Institute, 1999). A comparison of cumulative saturation means for redoximorphic features indices were evaluated using box plots showing percentiles, minimum, maximum and mean (Ott & Longnecker, 2001).

The statistical difference between dithionite citrate bicarbonate extractable Fe, Mn and Al levels and masses and soil organic carbon stock for hydric and non-hydric soils were determined using the t-test. Analysis of Variance was used to establish the difference in organic carbon pools from the three wetland types with depth (bogs, fens and hillslope seeps). Means separation was done using Duncan multiple range test (SAS Institute, 1999).

CHAPTER 4

SOIL PROPERTIES, HYDRIC SOIL INDICATORS AND SPATIAL VARIABILITY IN THE TOPOSEQUENCES.

4.1 INTRODUCTION

A catchment is the central unit of planning where all sustainable development activities are based. Hence, the catchment requires detailed characterization and inventory of soil resources. Soil information in Lesotho is very sparse. Those available on detailed scale of 1:10 000 are only for a few areas. There is also not such information on the wetlands, hence strengthening the need for soil information. Stolt *et al.* (2001) reported that detailed soil information is needed for assessing soil spatial variability. In small catchments where geology is uniform, soil spatial variability is influenced by the microclimate and the topography (Boul *et al*., 2003; Tsui *et al*., 2004). The aspect, slope and elevation control movement of water and material in a hillslope which in turn contributes to spatial differences in soil properties (Tsui *et al.,* 2004). Slope and aspect affect the soil moisture content in the landscape while elevation controls the temperature. The soil moisture and temperature regimes have been reported to influence the pedogenic processes (Boul *et al*., 2003). In addition, Ceddia *et al*. (2009) reported a strong correlation between of relief and soil spatial variability; however, each soil property exhibits spatial variation depending on the predominant factors that cause the variability.

In this study the spatial difference was evaluated by grouping the landscape into different physiographic units called slope positions. Slope positions are geographic objects with a fuzzy boundary, which reflect the regional terrain attributes as well as local attributes (Qin *et al*., 2009). Two areas with the same topographic attributes may belong to different slope positions and be associated with different geomorphic processes. Geologically, summits and valleys can have the same slope gradient, but their geographic context and operating geomorphic processes are completely different hence different pedogenic processes. Variability in soil properties is expected due to movement of soils down slope, and differences in pedogenic processes as influenced by moisture variation along the slope (Tsui *et al.,* 2004). Hence, the purpose of this investigation was to determine the spatial variability between soil properties and hydric indicators in the toposequences.

4.2 SOIL PROPERTIES IN DIFFERENT PHYSIOGRAPHIC UNITS

4.2.1 Soil morphological properties

Soil depth varied between 467 mm on the summits and 900 mm on the footslopes (Figure 4-1). Lesotho Highlands Development Authority (1998), associated the thinner soils of the summits and thicker soil on the lower slope positions to aeolian and colluvium erosion and deposition deposits. The soils of the summits showed minimum degree of profile development and lacked transitional horizons, while the lower slope position soils had a developed profile with A1, A2, AB, BA or B1, B, C, C1, G1, and G horizons (Figure 4-1). The soils at the upper part of the toposequence are usually shallow because they undergo a net loss due to erosion, while accumulations occur on the footslopes (Carroll & Bascomb, 1967; Binnie & Partners, 1972; Office of Soil Survey, 1979; Schmitz & Rooyani, 1987; Klug *et al.*, 1991; Lesotho Highlands Water Authority, 1998).

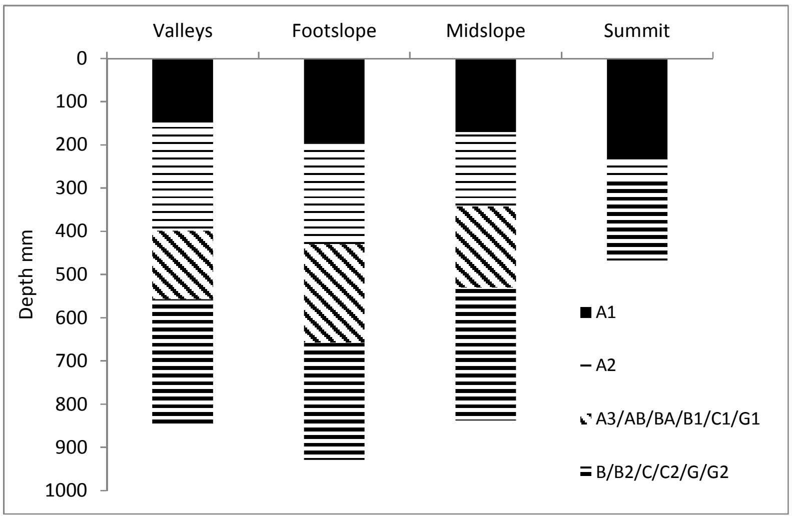

Figure 4-1 Horizon lower boundaries at the different slope positions.

The colour of the surface horizons for all landscapes positions were dominantly yellow red (10YR) with value of 2 and chroma 2 to 1. The value was associated with high organic carbon content (>1.8%) in all profiles, especially in the topsoil (Tripathi *et al.*, 2006). The subsurface horizon chroma on the upper slope position ranged from 3 to 4, while the subsurface horizons on the lower slopes were characterised by low chroma. Calero *et al.* (2008) and Díaz *et al.* (2010) associated the high chroma of the subsurface horizons with low organic carbon content and good soil drainage.

The structure of the surface horizons in all slope positions varied from strong to moderate medium granular except in the valleys where wetland plant roots formed a mat layer that makes horizons structureless. The intermediate subsurface horizons (AB) were weak to moderate, medium granular structure. The consistence of the surface horizons was loose, friable when dry, non-sticky and non-plastic when wet.

4.2.2. Spatial soil variability

Variability between soil properties represented by both horizontal and vertical variability (along the toposequence and with depth) is given in Table 4-1. Minimum and maximum values observed between soil properties, which reflected a very large range and variation in most properties. The soil pHwater ranged from 4.5 to 6.1 and pH KCl ranged from 3.8 to 5.5 indicating very strong acid to medium acidity (Table 4-1). This is a reflection of leaching characteristic of high rainfall areas. Similar soil pH levels were reported by the Office of Soil Survey (1979) for the three soil series that occur in association in the toposequence of the mountain soils, which are *Matsana*, *Fusi* and *Popa* soil series (Chapter 3). According to Wilding and Dress (1978) coefficient of variation classification, soil pH is the least variable property in this landscape (Table 4-1). Akinbola *et al*. (2006) also observed least variability of soil pH irrespective of depth, different slope positions or toposequences, while other properties vary significantly between toposequences.

Moderately variable properties were soil particle sizes, bulk density and cation exchange capacity (Table 4-1), suggesting the relatively medium dynamic nature of the properties (Boul *et al*., 2003). The mean contents of the soil particle sizes reflect a clay loamy texture. Bulk density ranged from 0.26 to 1.1 g cm^{-3} (Table 4-1). Most soils have a bulk density between 1.0 and 1.6 g cm^{-3}. The low bulk density observed in the study area was explained by high organic matter content of the topsoil. According to Fey (2010) exceptionally low bulk density can be expected where organic matter content and micro-aggregating effects of iron and aluminium oxides are high. The CEC ranged between 9 and 45 $cmol_c$ kg^{-1} with a mean of 26 $cmol_c$ kg^{-1} (Table 4-1).

All other properties were highly variable. The mean distribution of exchangeable bases were in order of Ca > Mg > K > Na on the exchange complex (Table 4-1). Exchangeable Ca occupied almost 26% of the exchange complex and contributed 70% of base saturation percentage. Manganese had the highest CV of 89% and low standard error of the mean. Manganese is a very mobile element and its distribution is affected by among others the soil moisture status (Bohn *et al*., 2001). Most variable properties are important for management of the site.

Table 4-1 Descriptive statistics of soil properties at Bokong, Lesotho.

Variable	N	Max	Min	Range	Mean	Std. Dev.	Std. Error	CV %
Soil pH KCl	88	5.5	3.8	1.7	4.6	0.30	0.03	6
Soil pHwater	88	6.1	4.5	1.6	5.5	0.36	0.03	6
Clay %	81	42	15	27	30	4.99	0.55	16
Silt %	81	51	16	35	33	7.75	0.86	23
Sand %	81	67	8	59	37	10.53	1.17	28
CEC cmol$_c$ kg^{-1}	88	45	9	36	26	8.63	0.92	32
Bulk density kg m^{-3}	88	1.1	0.26	0.84	0.68	0.23	0.025	34
Al$_d$ g kg^{-1}	88	84.4	10.6	73	42	16.7	1.79	39
Base Sat. %	88	84	11	73	35	17.35	1.85	48
Avail. P mg kg^{-1}	88	2.046	0.218	1.828	0.7	0.37	0.04	50
Exch. Na cmol$_c$ kg^{-1}	88	0.91	0.10	0.82	0.26	0.13	0.01	52
Exch. Ca cmol$_c$ kg^{-1}	88	23.9	1.59	22.31	6.78	3.78	0.40	55
Fe$_d$ g kg^{-1}	88	181	24	157	93	53	5.66	56
Exch. Mg cmol$_c$ kg^{-1}	88	5.67	0.28	5.38	1.58	1.03	0.11	64
Total N %	88	2.1	0.04	2.06	0.52	0.38	0.04	77
Organic C %	88	14.9	0.18	14.7	3.4	2.71	0.28	78
Exch. K cmol$_c$ kg^{-1}	88	3.54	0.15	3.39	0.48	0.40	0.04	84
Mn$_d$ g kg^{-1}	88	14	0.1	14	2.1	1.8	0.20	89

† pHwater – soil pH in water, pH KCl soil pH by KCl, Exch. are exchangeable cations, Base Sat. – base saturation

‡ Fe$_d$, Mn$_d$ and Al$_d$ are dithionite citrate extractable iron, manganese and aluminium respectively.

†† N is the number of observations analysed, Max and Min are the highest value observed in each parameter respectively, Std. Dev. is the standard deviation, Std. error is the standard error and CV is the coefficient of variation.

CV%: <15 – Least variable, 15 – 35 – Moderately variable, >35 – Most variable (Wilding & Dress, 1978)

4.2.3. Physical and chemical soil properties

The analysis of variance showed a significant difference between slope positions for silt, clay, bulk density, soil pH KCl, exchangeable Na, base saturation and manganese and no significant difference between slope positions and other properties (Table 4-2). All properties were significantly lower in the valleys except for clay, which was rather significantly high. There were no significant difference observed between different horizons in exchangeable bases, base saturation and the dithionite extractable oxides.

Table 4-2 Soil properties at different landscape positions and at different depths.

										Exchangeable bases									
SLP	N	Sand	Silt	clay	Bulk density	pH water	pH KCl	OC	TN	Ca	K	Mg	Na	P	BS	CEC	Fe$_d$	Mn$_d$	Al$_d$
		%			g cm^{-3}			%		mg kg^{-1}					%	c mol kg^{-1}	g kg^{-1}		
Summits	9	28^a	44^a	27^b	0.72^a	5.5^a	4.7^a	3.3^a	0.44^a	1204^a	138^b	240^a	36^b	0.87^a	28^a	28^a	76^a	2.8^a	37^a
Midslope	19	30^a	36^b	34^a	0.63^b	5.6^a	4.7^a	3.7^a	0.51^a	1483^a	162^b	221^a	74^a	0.65^a	36^a	27^a	86^a	2.4^a	41^a
Footslope	38	30^a	36^b	33^a	0.72^a	5.4^a	4.6^a	3.4^a	0.47^a	1392^a	186^b	174^a	59^a	0.68^a	27^a	26^a	104^a	2.3^b	43^a
Valleys	22	30^a	34^b	35^a	0.56^b	5.5^a	4.4^b	3.4^a	0.49^a	1244^a	243^a	155^a	56^b	0.86^a	23^b	23^a	87^a	1.1^b	40^a
Horizon																			
A1	22	30^b	37^a	33^a	0.52^b	5.3^c	4.5^b	6.2^a	0.86^a	1445^a	208^a	231^a	59^a	0.89^a	38^a	31^a	90^a	2.8^a	47^a
A2	24	38^a	31^b	30^a	0.61^b	5.4^b	4.5^b	3.9^b	0.52^b	1462^a	200^a	210^a	58^a	0.74^b	36^a	28^a	98^a	2.1^a	42^a
AB/BA/B 1/C1/G1	22	40^a	30^b	28^a	0.79^a	5.5^b	4.6^b	2.1^c	0.31^c	1243^a	179^a	155^a	57^a	0.68^b	34^a	23^b	90^a	1.7^a	39^a
B/B2/C/C 2/G/G2	20	38^a	33^b	27^b	0.80^a	5.7^a	4.7^a	1.3^c	0.21^c	1252^a	171^a	142^a	64^a	0.63^b	33^a	21^b	94^a	1.6^a	39^a
Source of Variation	df									ANALYSIS OF VARIANCE									
slope	3	ns	*	*	*	ns	*	ns	ns	ns	**	ns	**	ns	*	ns	ns	**	ns
horizon	3	**	**	**	**	**	**	**	**	ns	ns	ns	ns	*	ns	**	ns	ns	ns

* Significant at the 0.05 probability level

** Significant at the 0.01 probability level

ns - non-significant at the 0.05 probability level

df – degree of freedom

† Means followed by the same letter within columns, are not significantly different according to Duncan Multiple Range test (α = 0.05).

‡ SLP – Slope positions; Gr –gravel content and it was analysed for the A1 horizon only.

†† pH water – soil pH in water, pH KCl soil pH by KCl OC – organic carbon, TN - total nitrogen, P – available phosphorus, BS – base saturation, CEC – cation exchange capacity, Fe$_d$, Mn$_d$ and Al$_d$ are dithionite extractable iron, manganese and aluminium respectively..

The sand content was relatively uniform between slope positions. Summits had significantly higher silt content and significantly lower clay content. Clay content decreased with depth and it was significantly lower in the B2 horizon than overlying horizon (Table 4-2). Similar trends of clay content with depth were observed by Office of Soil Survey (1979) for mountain soils of Lesotho. The clay content in these soils ranged from 20 to 26% in the 300 mm of the soil surface and decreased to 13% in the B2 and 4% in the AC horizon. The soils developed from the weathered basaltic rock (Office of Soil Survey, 1979) and the influence of the parent material is evident in the lower horizons. The valleys and midslopes had the lowest bulk density while the footslopes and summits had significantly higher bulk densities (Table 4-2). The topsoil bulk density was also significantly lower than the subsoil. The increase in bulk density with depth may be caused related to less weathering and removal of minerals in the subsoil (Thangasamy *et al.,* 2005).

The soil pH KCl was significantly lower in the valleys than other slope positions. The pH is also significantly higher in the B2 horizon than the overlying horizons. Soil organic carbon (SOC) and total nitrogen (TN) levels ranged from 3.7 and 0.51% in the midslopes to 3.3 and 0.44% in the summits respectively (Table 4-2). Schmitz and Rooyani (1987) attributed the high levels of organic matter in the mountain soils of Lesotho to the lower temperatures and evaporation. Walter *et al*. (2006) reported SOC levels of 6.9% from Oxbow marshes and 4.4% from hillslope seeps in the Drakensberg Mountains with a temperature range of 16 C° and -2 C°. Nkheloane *et al* (2012) reported very high means of soil organic carbon of 17.2% from the upper 500 mm of the soil surface in the mountain rangelands of Thaba-putsoa Lesotho. Cold temperatures lower the rates of decomposition of organic matter and result in high accumulations that are reflected on the organic carbon levels of the surface horizons with a mean of 6.2% (Table 4.2).

The Carbon/Nitrogen (C/N) ratio was relatively uniform in all slope positions (Figure 4-2) with a mean of 6.9 indicating comparable decomposition rate between slopes positions (Yang *et al*., 2010). The C/N ratio of soil organic matter is related to the patterns of nitrogen immobilization and mineralization during organic matter decomposition by micro-organisms. The C/N ratio of most arable soils is 8:1 and higher C/N is observed under grassland (Tisdale *et al.,* 1993). The C/N ratio of the topsoil in the study area ranged from 7:1 to 8:1, while in the subsoil it ranged between 5:1 and 7:1 (Figure 4-2). The lower C/N ratio in the subsoil reflects a greater degree of breakdown and development of the humus stored in the subsoil (Batjes, 2002). Lower C/N in the subsoil may also means more leaching of N relative to C (Tisdale *et al.,* 1993).

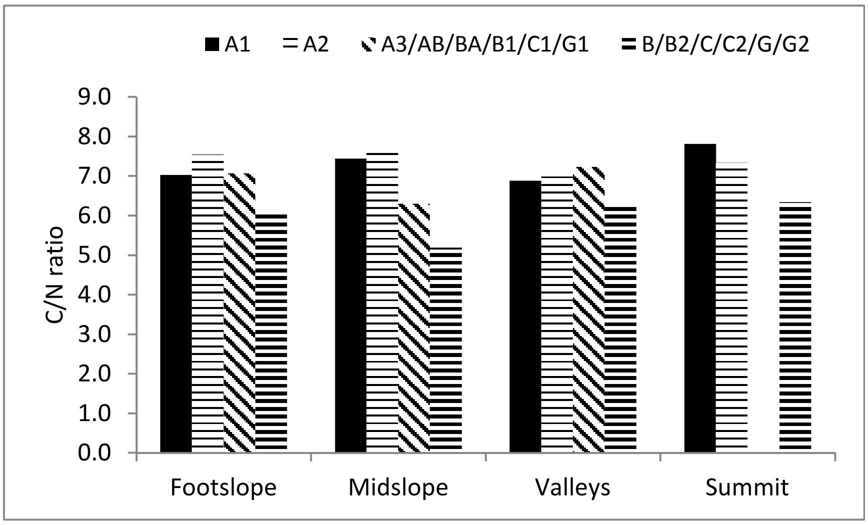

Figure 4-2 Soil organic carbon (OC) and total nitrogen (TN) ratio (C/N ratio) for each horizon in the four slope positions.

There were no significant differences in exchangeable Ca, Mg and CEC in terms of slope positions (Table 4-2). However, the CEC was higher on the summits, which may be attributed to the nature of the parent material. According to Schmitz and Rooyani (1987), the clay mineralogy of the basalt in the Maloti Mountains is montmorillonite or interstratified montmorillonite and illite with or without vermiculite. Bell and Haskins (1997) also found that Plagioclase is the major mineral of the basalt rocks of the Katse Dam catchments. Van der Merwe (2000) also observed that smectites are dominant clay minerals in South African soils with dark topsoil. These soils are non-expanding because they are saturated with divalent cations particularly Ca, which stabilises the swelling clays. Exchangeable Na was significantly lower in the summits and valleys, K was highest in the valleys and base saturation was significantly lower in the valleys (Table 4-2). Available P was not significantly different between slope positions (Table 4-2). The mean levels of available P ranged between 0.65 and 0.87 mg kg^{-1} in a toposequence. The low contents of available P may be attributed to high contents of Al and Fe-oxides coupled with a low pH.

Dithionite citrate bicarbonate extractable elements were very high in this landscape (Table 4-2). The Fe_d content ranged between 24 and 181 g kg^{-1} (2.4 and 18.1%) while Mn_d levels ranged between 0.1 and 14 g kg^{-1} respectively. This was also attributed to the nature of the parent material. According to Duncan *et al* (1983) the contents of $F_{e2}O_3$ and MnO in the Lesotho Basalt is 10.96% and 0.16% respectively. Jokova and Filcheva (2003) stated that the high contents of dithionite forms show that intensive modern weathering processes have occurred. Hidayat *et al*. (2002) reported Fe_d content of 12.03% from highly weathered oxisols in India. Trakoonyingcharoen *et al*. (2006) reported iron oxides contents ranging from 5 to 134 g kg^{-1} in the red soils of the tropics also suggesting highly weathered environments. Dithionite extractable elements have been widely considered to differentiate soil types, indicate pedogenic environments, and determine soil age or degree of soil development by other researchers (McKeague & Day, 1966; Blume & Schwertmann, 1969; Olaleye *et al*., 2008; Enya *et al*., 2011). The Mn_d was significantly higher in the summits and midslopes (Table 4-2). The lower contents of Mn_d in the valleys were attributed to Mn being lost under longer saturated anaerobic conditions and high Mn was observed in aerobic environments (Fieldler & Sommers, 2004). The Fe_d and Al_d were not significantly different between slope positions (Table 4-2).

4.3 CORRELATION ANALYSIS

The correlation between OC and TN, exchangeable Ca and Mg and base saturation, bulk density and OC and clay are typical and these were observed in this landscape (Table 4-3). Particle sizes did not show any relationships with other properties except poor correlation between clay, bulk density and CEC. Furthermore, dithionite citrate extractable elements were not correlated with other properties. Poor correlation was observed between soil pH and Mn_d.

Principal component analysis had eigenvalues of eight (8) components between 5.06 (PC1) and 0.80 (PC8) that contributed 82.8% of the total contribution (Table 4-4). It is important to note the components that were significant were PC1, 2, 3, 4 and 5, which contributed about 23, 15, 11, 10 and 7% respectively to the cumulative contribution and accounted for 67.9% variability in soil properties (Table 4-4). The factor pattern that characterised the derived principal components is given for the first five principal components (Table 4-5). In the first principal component (PC1) high coefficients were given to organic carbon and total nitrogen. These variables were related to organic matter turnover in the soil. Hence, PC1 was considered to determine organic matter input which was favoured by luxuriant vegetation growth in this environment and uniform C/N ratio along the toposequences and with depth.

Table 4-3 Correlation coefficients between soil properties and slope

	Sand	Silt	clay	Bulk	OC	TN	pHk	Ca	K	Mg	Na	P	BS	CEC	Fe_d	Mn_d	Al_d
Sand	1.00																
Silt	-0.90	1.00															
Clay	-0.67	0.41	1.00														
BulkD	0.25	-0.18	-0.41*	1.00													
OC	-0.14	0.05	0.30	-0.50*	1.00												
TN	-0.16	0.08	0.29	-0.49	0.91*	1.00											
pHk	0.17	-0.15	-0.08	0.03	-0.01	-0.06	1.00										
Ca	-0.07	0.01	0.12	-0.05	0.20	0.14	0.01	1.00									
K	-0.00	-0.03	0.12	-0.25	0.32	0.33	0.06	0.59	1.00								
Mg	-0.12	0.01	0.11	-0.05	0.11	0.07	-0.17	0.85*	0.42	1.00							
Na	0.09	-0.16	0.03	0.04	0.02	0.03	-0.01	0.50	0.44	0.40	1.00						
P	0.12	-0.06	-0.17	-0.14	0.21	0.19	-0.07	-0.22	0.04	-0.11	0.03	1.00					
BS	0.05	-0.07	-0.00	0.11	-0.14	-0.18	-0.01	0.75*	0.26	0.73*	0.45	-0.24	1.00				
CEC	-0.28	0.19	0.24	-0.24	0.56*	0.55	-0.04	0.35	0.38	0.26	0.01	0.00	-0.26	1.00			
Fe_d	0.03	-0.04	0.09	0.07	0.01	0.01	-0.15	0.26	-0.08	0.31	0.06	-0.19	0.01	0.18	1.00		
Mn_d	0.01	-0.09	0.14	-0.03	0.35	0.33	0.36	0.18	-0.01	0.11	-0.07	-0.12	0.26	0.12	0.23	1.00	
Al_d	0.01	-0.09	0.14	-0.03	0.35	0.33	0.36	0.18	-0.01	0.11	-0.35	-0.12	-0.02	0.30	0.07	0.33	1.00

* Significant at the 0.05 probability level

ns - non-significant at the 0.05 probability level

n = 88

† BulkD - bulk density, OC – organic carbon, TN - total nitrogen, pHk – soil pH in KCl, P – soluble phosphorus, BS – base saturation, CEC – cation exchange capacity, Fe_d, Mn_d and Al_d are dithionite citrate extractable iron, manganese and aluminium respectively.

Table 4-4 The first eight eigenvalues and proportion of variance for each the principal components

Principal component	Eigenvalue	Proportion	Cumulative
PC 1	5.06628093	0.2303	0.2303
PC 2	3.36581558	0.1530	0.3833
PC 3	2.47740315	0.1126	0.4959
PC 4	2.34160826	0.1064	0.6023
PC 5	1.69236889	0.0769	0.6792
PC 6	1.31891700	0.0600	0.7392
PC 7	1.14882694	0.0522	0.7914
PC 8	0.80810352	0.0367	0.8282

† PC – Principal components

Table 4-5 Factor pattern for the first five principal components

PC	PC1	PC2	PC3	PC4	PC5
Sand	0.181416	0.083464	0.140866	**0.524212**	-0.123019
Silt	0.124014	-0.104941	-0.114473	**-0.500809**	0.092631
Clay	0.233129	-0.061842	-0.151045	-0.312875	0.247220
BulkD	-0.267891	0.136798	0.087848	-0.022078	-0.176098
OC	**0.391676**	-0.100660	0.079892	0.184319	0.043306
TN	**0.382927**	-0.110523	0.087909	0.154376	0.010662
pHwater	0.190364	-0.002988	0.345513	-0.058830	**0.362513**
pH KCl	-0.064598	0.029094	**0.420223**	0.077882	0.434067
Ca	0.182587	**0.470681**	-0.008795	-0.023320	0.064992
K	0.217465	0.254109	-0.004113	0.141908	0.054539
Mg	0.146310	**0.438521**	-0.099555	-0.073635	-0.056374
Na	0.063252	0.330596	-0.186953	0.201620	0.088408
P	0.058526	-0.181995	-0.090871	0.287751	-0.139857
BS	-0.000949	**0.440184**	-0.189889	0.004824	0.242654
CEC	0.307732	0.057636	0.248242	-0.110168	-0.350186
$\mathrm{Fe_d}$	0.051411	0.193981	0.033651	-0.139214	-0.254109
$\mathrm{Mn_d}$	0.138700	0.054060	**0.420131**	-0.025124	0.099815
$\mathrm{Al_d}$	0.044835	0.016167	0.332882	-0.274667	-0.129548

† PC – Principal components n = 88
‡BulkD – bulk density; OC – organic carbon, pHw ater– soil pH in water; pH KCl – soil pH in KCl; Ca, K, Mg, Na, exchange bases; P – available P; BS – base saturation percentage; CEC – cation exchange capacity; $\mathrm{Fe_d}$, $\mathrm{Mn_d}$, $\mathrm{Al_d}$, - are dithionite citrate extractable Fe, Mn and Al.

The PC2 variables with high correlation were Ca, Mg and base saturation (Table 4-5). These were variables related to the nature of the parent material and hence determine the inherent soil fertility. The PC3 showed high correlations in soil pH-KCl and Mnd which determine the soil acidity. The PC4 was more related to soil texture (sand and silt particles).

4.4 SOIL CLASSIFICATION AND MAPPING

4.4.1 Soil forms of Bokong

Selected soil properties of the sampled profiles used in the classification are given in Table 4-6. The surface horizon of the study area had dark moist and dry colours to qualify as a melanic A (Soil Classification Working Group, 1991). In addition, exchangeable cations (Ca, Mg, K, Na) per kg clay for every one percent of organic carbon must be greater than 4 cmol_c kg^{-1}. Where the topsoil fails to meet all the requirements of melanic A, the horizon was classified as orthic A (Soil Classification Working Group, 1991). Some soils had the sum of exchangeable cations requirements less than 4 cmol_c kg^{-1}, and then these surface horizons were classified as Humic A. The organic O was also observed in few profiles. The underlying material was either yellow-brown apedal B horizon, G horizon or unspecified material with or without signs of wetness. The three main soil forms (Soil Classification Working Group, 1991) that were found in Bokong were Mayo on the summits, Inhoek in the midslopes and footslope and Willowbrook in the valleys (Figure 4-3).

4.4.2 Correlations with FAO/WRB and USDA taxonomy

All profiles previously classified in the South African soil classification (Soil Classification Working Group, 1991) were further correlated with FAO/WRB (FAO, 2006), USDA soil taxonomy (Soil Survey Staff, 2010) and the local Lesotho soil series where possible (Table 4-7). According to the FAO/WRB (FAO, 2006), the two major soil types of the study area were Stagnosols and Umbrisols with Phaeozems and Histisols in small localised areas. The Haplic Stagnosols (Dystric, chromic) mainly occurred in the valleys and concave midslopes, and Haplic Umbrisol (Humic), were found both on footslopes and midslopes while Leptic Umbrisol (Humic) occurred on the summits. Stagnic Umbrisol (Humic) and Haplic Phaeozems also occur on the midslopes and footslopes. Umbrisols are described as soils which have accumulated organic matter in the mineral soil with low base saturation and it is associated with Phaeozems where base saturation is higher (FAO, 2006). The Stagnosols were mainly in the wetlands and classified as Haplic Stagnosols (Dystric chromic). Sapric Histisols (Dystric) were also observed in few wetlands which have developed peat.

Table 4-6 Diagnostic horizons selected soil properties and hydric soil indicators for pedons sampled at Bokong.

Prof.	**SA**	**L D**	**Matrix colour**		**CEC**	**EC***	**BS**	**SOC**	**Clay**	**RMFs****	**RMFs****	**Hydric**
Id.	**DH**	**mm**	**Moist**	**Dry**	**cmolc kg^{-1}**		**%**	**%**	**%**	**Conc.**	**Depletions**	**Indicators**
PD01	me	180	10YR2/1	10YR3/1	27.0	7	46	5.9	29	none	None	none
	me	360	10YR2/1	10YR3/2	30.1	10	33	3.7	27	none	None	none
	ye	580	10YR3/1	10YR3/2	33.7	8	25	3.2	31	none	None	none
	ye	900	7.5YR4/6	10YR5/4	21.8	35	25	0.6	27	none	None	none
PD02	me	260	10YR2/1	10YR3/1	17.7	8	69	5.0	30	none	None	none
	me	390	10YR2/2	10YR3/2	38.0	6	27	5.8	29	none	None	none
	ye	530	10YR3/3	10YR4/2	40.2	11	24	3.3	26	m/c/rusty/pores	None	none
	ye	950	10YR4/6	10YR5/4	20.7	41	30	0.7	23	none	None	none
PD03	ot	280	10YR2/1	10YR3/1	40.2	3	17	7.2	36	none	None	none
	me	440	10YR3/2	10YR3/1	22.6	7	35	3.4	36	none	None	none
	ye	600	10YR3/3	10YR3/2	28.4	7	22	3.1	30	m/m/rusty/pores	None	none
	ye	1000	10YR4/6	10YR5/6	24.5	20	30	1.5	26	none	None	none
PD04	me	170	10YR2/1	10YR3/2	34.8	4	26	6.8	36	none	None	none
	ot	340	10YR2/2	10YR3/2	24.3	3	27	5.1	37	none	None	none
	me	510	10YR3/2	10YR3/1	19.7	6	27	3.1	31	none	None	none
	ye	810	10YR3/4	10YR4/3	16.5	26	33	0.7	29	none	None	none
PD05	me	250	10YR2/1	10YR3/1	27.7	8	62	6.4	35	none	None	none
	me	540	10YR2/1	10YR3/1	26.8	8	52	4.7	35	none	None	none
	ye	630	10YR3/4	10YR3/3	17.5	20	76	2.9	23	none	None	none
	ye	880	10YR3/6	10YR4/3	22.9	14	20	1.5	21	none	None	none
PW06	ot	70	10YR2/1	10YR3/2	35.9	2	24	12.6	38	none	None	**F13**
	me	190	10YR2/1	10YR3/2	44.6	16	74	6.6	32	none	None	none
	ye	410	5YR4/4	5YR5/4	17.9	121	84	0.5	27	c/f/red/distnct	m/c/blc/pores	none
	ye	590	5YR4/6	10YR6/8	25.7	262	69	0.3	26	c/f/red/distnct	m/c/rusty pores	none
PW07	oo	210	10YR2/1	N2.5/0	42.4	4	49	14.9	33	none	None	**A2**
	ot	400	10YR2/2	10YR4/4	44.6	3	17	5.9	39	f/f/orng/distnct	None	**F6**
	ye	540	7.5YR4/4	7.5YR5/6	20.4	22	49	1.3	35	f/f/orng/distnct	f/f/bl-grn/distnct	none
	ye	1000	10YR5/6	10YR5/4	17.6	93	77	0.5	28	none	c/f/bl-grn/distct	none
PW08	me	70	10YR2/1	10YR3/2	40.2	7	19	3.8	27	none	None	**F13**
	me	200	10YR2/1	10YR3/2	23.0	13	46	3.4	25	f/f/red/promt	None	**F8**
	on	750	10YR2/2	5YR5/4	31.5	14	30	2.3	30	f/f/red/distnct	None	none
	on	850	2.5YR5/6	2.5YR6/4	28.2	319	75	0.2	34	m/c/yel/distnct	m/c/gry/promt	
PD09	me	200	10YR2/1	10YR3/2	40.2	4	18	6.2	27	none	None	none
	ot	250	10YR2/2	7.5YR4/4	32.6	8	28	3.5	32	f/fblc/pores	None	none
	li	650	10YR3/3	10YR5/4	28.4	56	55	1.1	24	c/f/ry/distnct	None	none

† SA DH – South African Soil Classification diagnostic horizons (Soil Classification Working Group, 1991): me – Melanic A; ot – Orthic A; oo – Organic O; ye – Yellow-brown apedal, gh – G horizon; on – Unspecified and li – Llithocutanic.

‡ LD – lower depth, CEC – cation exchange capacity; BS – base saturation; SOC – soil organic carbon; conc. - concetrations

†† EC* – exchangeable cations per kg clay for every one per cent of organic carbon (Soil Classification Working Group, 1991)

‡‡ RMFs** – redoximorphic feature. Horizons where.RMFs were not given indicate that they were not observed. The RMFs descriptions include abundance, size, colour and contrast in the order separated by forward slash (/) (Turner, 1991; Soil Survey Staff, 1993; Schoeneberger *et al*., 2002)

Abudance- f- few (< 2%), c – common (2 to 20%), m – many (> 20%)
Size: f- fine, m – medium, c – course
Colour; orng – orange,yel – yellow, bl-grn – bluish green, gry – grey, blc - bleached.
Contrast: promt – prominent, distinct – distinct.

§ Missing values of CEC, EC, BS, SOC, and clay results were either omitted because of high or too low values observed or samples spilled off from storage.

n/a is for a peat soil where texture of peat was determined by feel method as a sapric material.

Hydric soil indicators (USDA-NRCS, 2010): **A1** Histisols, **A2** Histic epipedon, **A12** Thick dark surfaces, **F2** Loamy gleyed matrix, **F6** redox dark surfaces, **F7** Depleted dark surfaces, **F8** Redox depressions, **F13** Umbric surface.

Table 4-6 continues.

Prof.	SA	L D	Matrix colour		CEC	EC*	BS	SOC	Clay	RMFs**	RMFs**	Hydric Indicators
Id.	DH	Mm	Moist	Dry	cmol kg^{-1}		%	%	%	Conc.	Depletions	
PD10	me	200	10YR2/1	10YR3/2	22.8	7	29	3.7	28	none	None	none
	me	250	10YR2/2	10YR3/2	26.7	8	23	2.5	30	none	None	none
	li	330	10YR3/4	10YR3/4	26.4	16	30	2.1	23	none	None	none
PD11	me	170	10YR2/1	10YR4/1	38.0	6	29	7.0	28	none	None	none
	me	410	10YR2/2	10YR3/2	40.2	11	27	2.9	33	none	None	none
	on	800	10YR2/2	10YR3/2	33.7	14	34	3.6	23	none	None	none
	on	1000	7.5YR3/4	10YR3/4	30.4	13	29	2.5	28	none	None	none
PD12	me	200	10YR2/1	10YR3/2	26.3	10	49	3.9	32	none	None	none
	me	330	10YR2/1	10YR3/2	28.3	18	44	2.7	27	none	None	none
	me	500	10YR2/2	10YR3/2	24.9	16	59	2.6	35	none	None	none
	on	700	10YR3/2	10YR4/2	30.3	18	47	2.1	37	none	None	none
	on	800	10YR3/3	10YR4/3	19.6	23	59	1.5	33	m/c/rusty pores	None	none
PD13	me	200	10YR2/1	10YR3/2	30.8	5	22	4.5	29	none	None	none
	ot	340	10YR3/3	10YR3/3	42.4	6	21	4.9	32	none	None	none
	ye	600	10YR3/4	10YR4/5	19.1	17	24	0.9	29	none	None	none
PD14	me	300	10YR2/1	10YR3/1	32.6	4	19	4.5	31	none	None	none
	me	550	10YR2/2	10YR3/2	33.7	38	31	1.1	26	none	None	none
	ye	720	10YR3/4	10YR3/2	§	§	§	§	§	none	None	none
	ye	810	10YR4/4	10YR4/4	30.1	51	19	0.3	30	none	None	none
PD16	me	300	10YR2/1	10YR3/1	29.7	4	28	7.4	30	none	None	none
	me	350	10YR2/1	10YR3/2	29.3	7	37	3.4	28	none	None	none
	li	420	10YR4/3	10YR4/2	19.5	73	19	0.2	28	none	None	none
PW19	me	450	10YR2/1	10YR3/2	18.4	6	38	3.4	34	none	None	**F13**
	gh	600	10YR3/4	10YR3/2	14.9	6	40	2.6	37	none	None	none
	gh	850	10YR5/1	10YR6/1	16.3	14	31	1.3	27	none	Gley	none
PD20	me	450	10YR2/1	10YR2/1	35.9	5	20	6.0	27	none	None	none
	ye	600	10YR3/3	10YR3/3	20.0	9	32	2.7	27	none	None	none
	ye	1000	10YR4/4	10YR4/4	18.8	13	42	1.7	37	none	None	none
PW21	ot	220	5B4/1	10YR4/2	27.4	5	27	3.6	42	none	None	**F2**
	ot	480	7.5YR 4/2	7.5YR 4/2	22.8	57	80	1.5	32	c/f/orng/distnct	None	none
	ye	700	7.5YR 4/4	7.5YR 6/4	29.6	86	55	0.7	27	f/f/orng/distnct	None	none
	ye	1000	10YR4/4	10YR6/4	§	§	§	§	§	m/c/orng/distnct	f/m/yel/faint	none

† SA DH – South African Soil Classification diagnostic horizons (SCWG, 1991): me – Melanic A; ot – Orthic A; ye – Yellow-brown apedal, gh – G horizon; on – Unspecified and li – Llithocutanic.

‡ LD – lower depth, CEC – cation exchange capacity; BS – base saturation; SOC – soil organic carbon; conc. - concetrations

†† EC* – exchangeable cations per kg clay for every one per cent of organic carbon (SCWG, 1991)

‡‡ RMFs** – redoximorphic feature. Horizons where.RMFs were not given indicate that they were not observed. The RMFs descriptions include abundance, size, colour and contrast in the order separated by forward slash (/) (Turner, 1991; Soil Survey Staff, 1993; Schoeneberger *et al.*, 2002)

Abudance- f- few (< 2%), c – common (2 to 20%), m – many (> 20%)
Size: f- fine, m – medium, c – course
Colour; orng – orange,yel – yellow, bl-grn – bluish green, gry – grey, blc - bleached.
Contrast: promt – prominent, distinct – distinct.

§ Missing values of CEC, EC, BS, SOC, and clay results were either omitted because of high or too low values observed or samples spilled off from storage.

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Hydric soil indicators (USDA-NRCS, 2010): **A1** Histisols, **A2** Histic epipedon, **A12** Thick dark surfaces, **F2** Loamy gleyed matrix, **F6** redox dark surfaces, **F7** Depleted dark surfaces, **F8** Redox depressions, **F13** Umbric surface.

Table 4-6 continues

Prof.	SA	L D	Matrix colour		CEC	EC*	BS	SOC	Clay	RMFs**	RMFs**	Hydric
Id.	DH	mm	Moist	Dry	cmol kg^{-1}		%	%	%	Conc.	depletions	Indic.
PW24	ot	110	10YR3/3	10YR4/3	28.3	8	35	2.9	41	none	None	none
	ot	490	10YR2/1	10YR4/1	29.0	3	22	5.9	32	none	c/f/ blc/pores	**F7**
	gh	750	5Y4/1	5Y4/1	17.6	9	43	3.7	22	none	m/c/ blc/pores	**A12**
	gh	1000	5Y5/1	5Y5/1	12.0	50	30	0.3	23	none	m/c/ blc/pores	
PW25	me	150	10YR2/1	10YR3/2	9.8	6	63	3.5	28	c/f/orng/dist	None	**F8**
	me	350	10YR2/1	10YR3/1	17.7	5	23	2.9	30	c/f/orng/dist	None	
	gh	600	G2/N	10YR4/2	9.3	9	36	1.4	26	m/m/orng/promt	c/m/bl-gn/distnct	**A12**
	gh	800	G1.5/N	10YR4/2	8.8	§	39	0.9	§	m/m/orng/promt	c/m/bl-gn/distnct	**A12**
PW26	me	120	10YR2.5/1	10YR2/1	39	§	56	58	§	none	None	
	ye	450	10YR3/1	10YR3/2	25	16	45	4.7	15	none	c/m/blc/pores	**F7**
	on	767	10YR5/1	10YR5/4	34	§	22	1.4	§	none	m/c/blc/pores	
PW27	oo	150	2.5Y2.5/1	2.5Y2.5/1	37.0	§	11	12.4	n/a	Peat	None	**A1**
	on	500	2.5Y2.5/1	2.5Y 2.5/1	27.0	§	26	5.6	n/a	Peat	None	
	on	1000	2.5Y2.5/1	2.5Y 2.5/1	28.2	§	16	7.3	n/a	Peat	None	
PW28	ot	150	10YR2/2	10YR4/3	25.0	4	33	5.0	38	none	None	none
	ot	450	10YR2/1	10YR4/3	13.9	16	43	1.4	28	none	None	none
	ye	600	10YR3/3	10YR5/4	15.3	9	35	2.1	29	none	None	none
	on	1000	10YR3/3	10YR5/4	15.3	24	28	0.8	22	m/f/rusty pores	f/f/yel/faint	none
PW32	ot	100	10YR2/2	10YR3/2	30.4	3	16	4.1	43	none	None	
	ot	280	10YR3/1	10YR4/2	17.5	3	16	3.3	25	f/f/orng/faint	None	none
	ot	370	10YR3/1	10YR3/2	17.5	7	16	2.1	25	c/m/orng/dstnct	f/m/bl-grn/faint	none
	gh	550	10YR4/2	2.5YR7/2	17.6	§	23	2.3	§	c/m/orng/dstnct	f/m/bl-grn/faint	**F7**
	gh	940	10YR5/1	10YR5/1	13.0	14	23	0.9	23	m/c/orng/promt	c/c/bl-grn/distnct	

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‡ LD – lower depth, CEC – cation exchange capacity; BS – base saturation; SOC – soil organic carbon; conc. - concetrations

†† EC* – exchangeable cations per kg clay for every one per cent of organic carbon (SCWG, 1991)

‡‡ RMFs** – redoximorphic feature. Horizons where.RMFs were not given indicate that they were not observed. The RMFs descriptions include abundance, size, colour and contrast in the order separated by forward slash (/) (Turner, 1991; Soil Survey Staff, 1993; Schoeneberger *et al*., 2002)

Abudance- f- few (< 2%), c – common (2 to 20%), m – many (> 20%)
Size: f- fine, m – medium, c – course
Colour; orng – orange,yel – yellow, bl-grn – bluish green, gry – grey, blc - bleached.
Contrast: promt – prominent, distinct – distinct.

§ Missing values of CEC, EC, BS, SOC, and clay results were either omitted because of high or too low values observed or samples spilled off from storage.

n/a is for a peat soil where texture of peat was determined by feel method as a sapric material.

Hydric soil indicators (USDA-NRCS, 2010): **A1** Histisols, **A2** Histic epipedon, **A12** Thick dark surfaces, **F2** Loamy gleyed matrix, **F6** redox dark surfaces, **F7** Depleted dark surfaces, **F8** Redox depressions, **F13** Umbric surface.

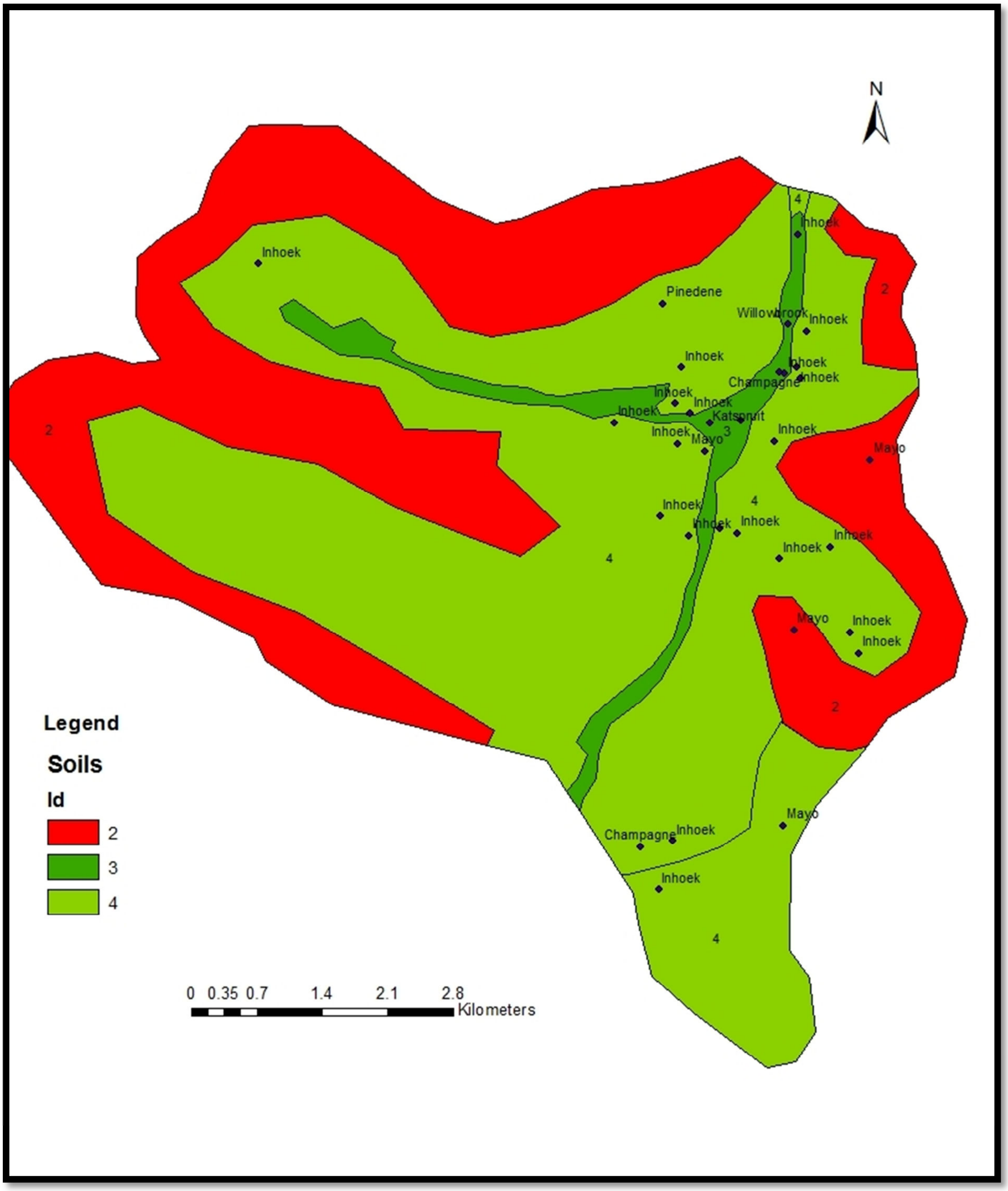


Figure 4-3 Soil map of the study site: (Soil forms; 2 Mayo, 3 Wilowbrook, 4 Inhoek).

Table 4-7 Soil correlations between the South Africa Soil Forms (Soil Classification Working Group, 1991) and FAO/WRB (FAO, 2006), and USDA Soil Taxonomy (Soil Survey Staff, 2010).

Prof.	SLP	SA Soil Form	FAO/WRB	USDA Soil Taxonomy
PD01	Footslope	Inhoek	Haplic Umbrisol (Humic)	Humic Dystrudepts
PD02	Midslope	Inhoek	Haplic Umbrisol (Humic)	Humic Dystrudepts
PD03	Summit	Inhoek	Haplic Umbrisol (Humic)	Humic Dystrudepts
PD04	Midslope	Inhoek	Haplic Umbrisol (Humic)	Humic Pachic Dystrudepts
PD05	Footslope	Inhoek	Haplic Phaeozems	Typic Hapludolls
PW06	Midslope	Inhoek	Haplic Stagnosols (Eutric, chromic)	Aeric Humaquepts
PW07	Footslope	Champagne	Sapric Histosols (Dystric)	Typic Haplosapists
PW08	Footslope	Inhoek	Haplic Stagnosols (Dystric, chromic)	Aeric Humaquepts
PD09	Summit	Mayo	Leptic Umbrisol (Humic)	Humic Lithic Dystrudepts
PD10	Summit	Mayo	Leptic Umbrisol (Humic)	Humic Lithic Dystrudepts
PD11	Footslope	Inhoek	Haplic Umbrisol (Humic)	Humic Pachic Dystrudepts
PD12	Valley	Inhoek	Haplic Umbrisol (Humic)	Humic Pachic Dystrudepts
PD13	Midslope	Inhoek	Haplic Umbrisol (Humic)	Humic Dystrudepts
PD14	Footslope	Inhoek	Haplic Umbrisol (Humic)	Humic Pachic Dystrudepts
PD16	Summit	Mayo	Leptic Umbrisol (Humic)	Humic Lithic Dystrudepts
PW19	Footslope	Willowbrook	Stagnic Umbrisol (Humic)	Cumilic Humaquepts
PD20	Footslope	Inhoek	Haplic Umbrisol (Humic)	Humic Dystrudepts
PW21	Summit	Pinedene	Haplic Stagnosols (Dystric, drainic)	Aeric Humaquepts
PW24	Footslope	Katspruit	Haplic Stagnosols (Dystric, chromic)	Cumilic Humaquepts
PW25	Valley	Willowbrook	Haplic Stagnosols (Dystric, chromic)	Cumilic Humaquepts
PW26	Valley	Pinedene	Haplic Stagnosols (Dystric, chromic)	Cumilic Humaquepts
PW27	Valley	Champagne	Sapric Histosols (Dystric)	Typic Haplosapists
PW28	Midslope	Pinedene	Haplic Umbrisol (Humic)	Humic Pachic Dystrudepts
PW32	Valley	Kartspruit	Haplic Stagnosols (Dystric, chromic)	Cumilic Humaquepts

† Prof – profile identity
‡ SLP - Terrain morphological unit
†† SA - South Africa Soil Form (Soil Classification Working Group, 1991)
‡‡ FAO/WRB (FAO, 2006)
# USDA soil taxonomy (Soil Survey Staff, 2010)

Lesotho has classified its soils using the USDA soil taxonomy (Soil Survey Staff, 2010). In this study the soils of Bokong were classified as Inceptisols with either an udic and or an aquic moisture regime. Soils of Bokong with high base saturation are Typic Hapludolls (PD05), and a similar classification was made by the Office of Survey (1979) for the Matsana soil series. The Fusi soil series is also expected on the same landscape. Ironically, the Office of Survey (1979) classified the Fusi soil series as Cumulic Hapludolls while their soil characterisation reflected a base saturation lower than 50% throughout the horizon of this soil. The rather similar soils as the Fusi series were observed in Bokong with a cambic horizon and low base status and they were classified as Humic Dystrudepts or Humic Pachic Dystrudepts on the footslopes where the humic layer was thicker. The Aquic suborders were observed in the wetlands and classified as Cumulic Humaquepts. The USDA soil taxonomy uses the histic epipedon to classify Histisols hence all Histisols are hydric except those which occur over the bedrock (Mausbach & Parker, 2001). Two subgroups, Fluvaquentic Haplosaprists and Typic Haplosaprists were observed (PW07 and PW27 respectively). PW27 had organic carbon content (by weight) of more than 12 per cent with no mineral horizons throughout the depth to greater than 1000 mm, while PW07 had a mineral horizon below the histic epipedon.

4.4.3 Hydric soils indicators of Bokong

The main idea of characterizing and classifying the Bokong wetland soils was to identify hydric soils. The definition of hydric soils is met only when hydric soil indicators are present (Hurt & Carlisle, 2001). The hydric soil indicators identified in the Bokong wetlands, with reference to USDA-NRCS (2010) hydric soil field indicators are described in Table 4-8. The histisols (A1) indicator was observed only in profile PW27 and a histic epipedon was observed in profile PW07. Umbric surfaces (F13) were common and were observed in profiles PW06, PW08 and PW19 which occur on the midslopes and footslopes. The histisols, histic epipedon and umbric surfaces are formed as a result of slower organic matter decomposition and formation of peat (USDA-NRCS, 2010). Indicators with prominent concentrations were not common.

Some profiles had the redoximorphic features occurring deeper than that required by the USDA-NRCS (2010) indicators and hence could not meet the listed field indicators. The gleyed matrix observed in PW19 occurred at 600 mm depth from the surface. A gley matrix colours observed in PW24 and PW25 are used for indicator testing only and are not yet confirmed as hydric indicators. Profiles PD02, PD03, PD09, PD12 and PW28 had few concentrations or rust streaks below 500 mm depth (Table 4-7). This suggested that not all wetlands found in Bokong were hydric according to USDA-NRCS (2010), therefore, proper characterisation and classification of soils is required to identify hydric soils.

The FAO/WRB classification was able to differentiate the hydric soil from non-hydric because Histisols and all stagnosols found in Bokong were hydric soils, and profile PW19 was classified as Stagnic Umbrisol (Humic). The non-hydric soils were Haplic or Leptic Umbrisols. USDA soil taxonomy classified all hydric soils as Aeric or Cumilic Humaquepts including profile PW19 and Haplosapists. The two soil classification systems satisfactory identifying hydric soils of Bokong. The South African soil classification system soil forms that confirm a wetland existence (DWAF, 2005) found in Bokong were Champagne, Katspruit, Willowbrook soil forms and other hydric soils required classification at family level to separate them from non-hydric soils (Kotze *et al*., 1994).

Table 4-8 Description of hydric soil field indicators identified in the wetlands of Bokong (USDA-NRCS, 2010).

Indicator	Description
Histisol (A1)	A layer 400 mm or more within the upper 800 mm of soil surface is the organic material (12% or more organic carbon).
Histic Epipedon (A2)	A histic epipedon underlain by mineral soil material with chroma of 2 or less.
Thick dark surfaces (A12)	A layer at least 150 mm thick or more with a depleted or gleyed matrix below 300 mm of the surface and the overlaying layer must have value of 2.5 or less and chroma of 1 or less.
Redox dark surfaces (F6)	A layer at least 100 mm thick, is entirely within the upper 300 mm of the soil surface with matrix value of 3 or less and chroma 2 with few to many prominent redox concentration
Depleted dark surfaces (F7)	A layer at least 100 mm thick with matrix colour of value 3 or less and chroma of 1 or 2 with common or more redox depletions within the upper 300 mm of the mineral soil.
Redox depression (F8)	A layer 50 mm thick or more with few or more distinct or prominent redox concentrations within the 150 mm of the soil surface
Loamy gleyed matrix (F2)	A layer 100 mm thick or more with matrix colour value of 4 and chroma of 1 within 25 cm of the soil surface
Umbric surface (F13)	A layer 150 mm thick or more from the soil surface with matrix colour value of 3 or less and chroma of 1 and the lower 100 mm has same colours with chroma of 2 or less. Umbric surfaces in the higher landscape positions, dominated by Humic Dystrudepts, are excluded.

4.5 CONCLUSIONS

The topography had influenced the spatial variation of soil. Soil pH, sand, silt and clay content, bulk density, and CEC were least to moderately dynamic. Relatively stable (static) soil properties tend to have a regular spatial structure. Summits had relatively high pH and CEC and significantly high silt content and bulk density. The valleys had relatively lower pH and CEC and significantly low silt content and bulk density. Soil pH, sand and bulk density were increasing with depth, while silt, clay and CEC decreased with depth. All other properties were dynamic and they gave different spatial patterns. The dynamic properties were decreasing with depth, except for exchangeable Ca and Na and Fe_d, which showed irregular trends, probably due to Fe mobility under different moisture regimes suggesting intra and inter pedon translocation as the soil water fluctuates. The dynamic properties were supposed to be more influenced by soil water regimes and above ground inputs into the soil and they were important in pedogenic processes. The PCA showed that soil factors that are contributing more to the spatial variation were organic matter, inherent fertility, acidity and textural variation and can be used to group soils along a toposequence.

The soil types of Bokong are Umbrisols and Stagnosols (FAO, 2006). The hydric soils of the study were mainly Haplic Stagnosols (Dystric, chromic). Histisols (PW07 and PW27) and Stagnic Umbrisol (Humic) in the hillslopes wetlands on the midslopes (PW19) also occur. However, indicators that relate to the histic nature of the soil were more frequently observed than iron and manganese based morphological features. Therefore the research focus should be on developing more indicators for proper characterisation and classification of soils is required to identify hydric soils. .

CHAPTER 5

RELATIONSHIP BETWEEN SOIL HYDROLOGY, REDOX POTENTIAL AND HYDRIC SOIL INDICES

5.1 INTRODUCTION

Wetland hydrology is defined as the water table depth, duration, and frequency required for wetland ecosystem functioning (Mitsch & Gosselink, 2007). The relationship between hydrology and redoximorphic features (RMFs) is site specific. Some conditions may, however, alter this usual relationship. This is because redoximorphic features are not only directly related to the period of saturation, but also through interaction of the redox processes and soil environmental conditions (Faulkner & Patrick, 1992). Hence, it is useful to calibrate RMFs by monitoring the water table and evaluating the presence of reducing conditions. The objective of this chapter was therefore to determine the relationship between redox potential, RMFs and soil water regimes in the Bokong catchment.

5.2 HYDROLOGY OF BOKONG WETLANDS

5.2.1 Water table hydrographs

Water table hydrographs were developed from bi-weekly water table data using five different depths from September 2009 to August 2011 in twelve representative wetlands (Figure 5-1). Daily precipitation data was also added to bi-weekly rainfall data to compare it with the developed bi-weekly water table hydrographs. The seasonal patterns were in response to rainfall. The falling of the water table was characterised by falling peaks, which were more defined during the winter months of May to October due to lack of precipitation. In most piezometers, the groundwater table (GWT) rose rapidly following a precipitation event, reaching a maximum level during longer rainfall storms except for small precipitations events (i.e. ≤ 10 mm). In the same way lack of precipitation events within the two weeks led to water table falling to different levels observed between September 2009 and April 2010 (Figure 5-1). In cases where precipitation did not occur for a month, the water table level fell below the piezometers, which were 1000 mm deep.

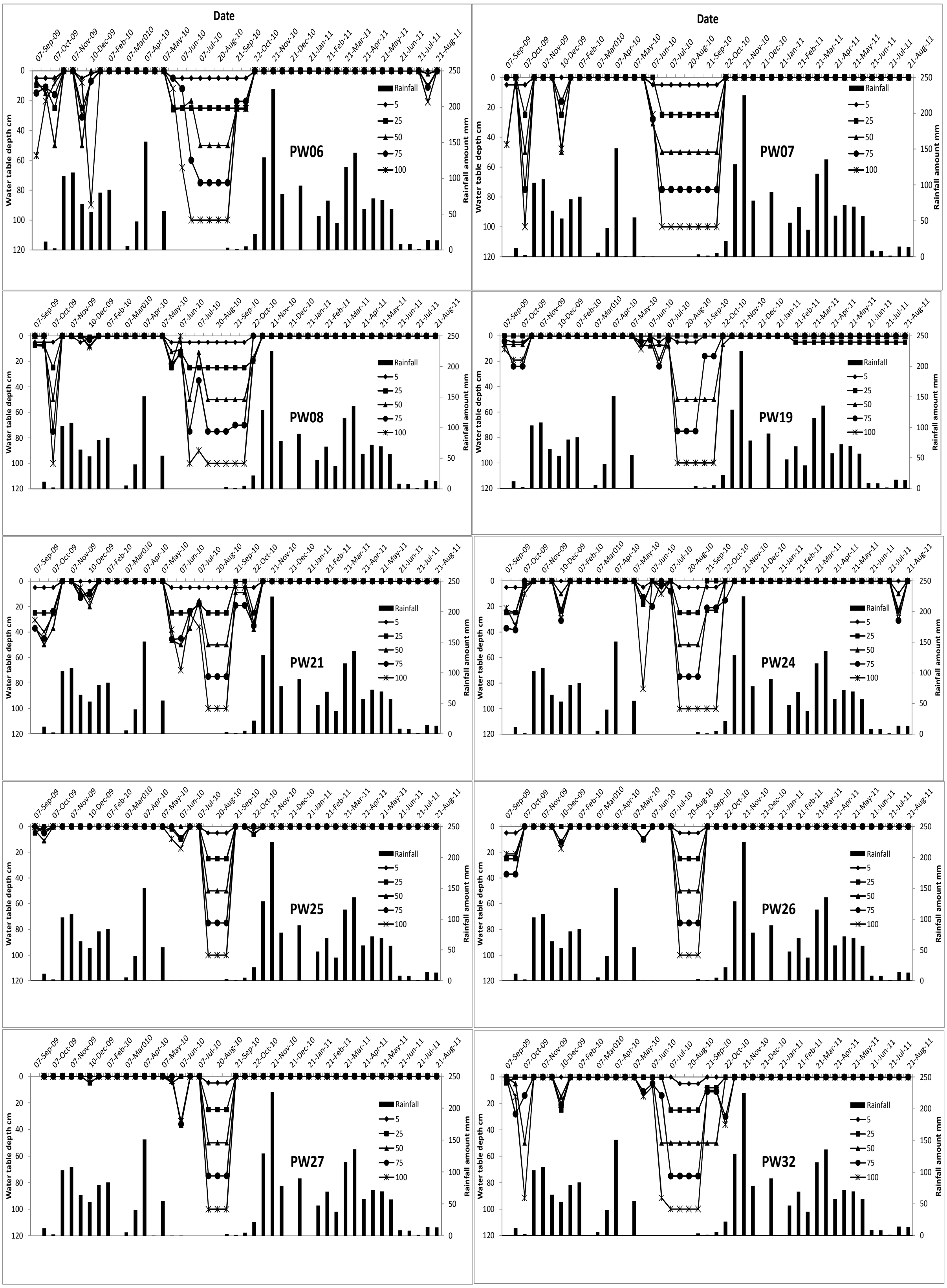


Figure 5-1 Water table hydrographs at different depths of representative wetlands at Bokong from September 2009 to August 2011.

The response to lack of precipitation events differs between wetlands, with deeper GWT observed in wetlands on the midslopes and footslopes (PW06, PW07, and PW08), while in the valley bottom, the GWT was much shallower (PW25, PW26, and PW27) (Figure 5-1). The 2010/11 season which started in September 2010 and ended in August 2011 was characterised by more rainfall events of high intensities and had 35% more annual rainfall than in 2009/10 (Chapter 3). It can therefore be inferred that seasonal water table fluctuations observed in 2010/11 were in response to short interval precipitation events observed during this season.

5.2.2 Groundwater flows

The piezometers were installed at different depths. The low rainfall during the dry period, beginning in May and ending in July, resulted in higher hydraulic head at the shallower piezometer suggesting recharge flow. However, during the rainy season (November to March), longer rainstorms caused the GWT to rise in all piezometers leading to an equal piezometric head in all depth. Lateral flows were observed for three months in PW06 and for about eight months in PW27 in 2009/10 season, while during 2010/11 season, almost the whole season all wetlands were flooded for 10 months (Figure 5-1). The functional relationship should be predominantly based on groundwater discharge. However, longer dry spells due to low rainfall during the winter months (May to July) resulted in low GWT, hence desiccation of the wetlands.

5.2.3 Cumulative saturation

The water table parameters commonly used to relate water table to soil redoximorphic features are cumulative saturation and average seasonal high water table (Galusky *et al.*, 1998; Szogi & Hundall, 1998; Rueter & Bell, 2003; Fiedler & Sommer, 2004; Morgan & Stolt, 2006). The water table data for wetland profiles (PW) was transformed into a cumulative saturation (Figure 5-2). All piezometers indicated that for more than 80% of monitoring time the water table resided within the 0-500 mm moisture control section, except for wetlands PW06, PW08 and PW21. The shorter duration of saturation of PW06 and PW08 wetlands was associated with disturbance due to grazing since the wetlands were near the grazed cattle posts, while other wetlands were protected from grazing by domestic animals. PW21 was on the wetland previously affected by road construction that traverses through the wetland (Marneweck & Grundling, 1999). It was identified as “Wetland 2” in the study by Marneweck and Grundling (1999).

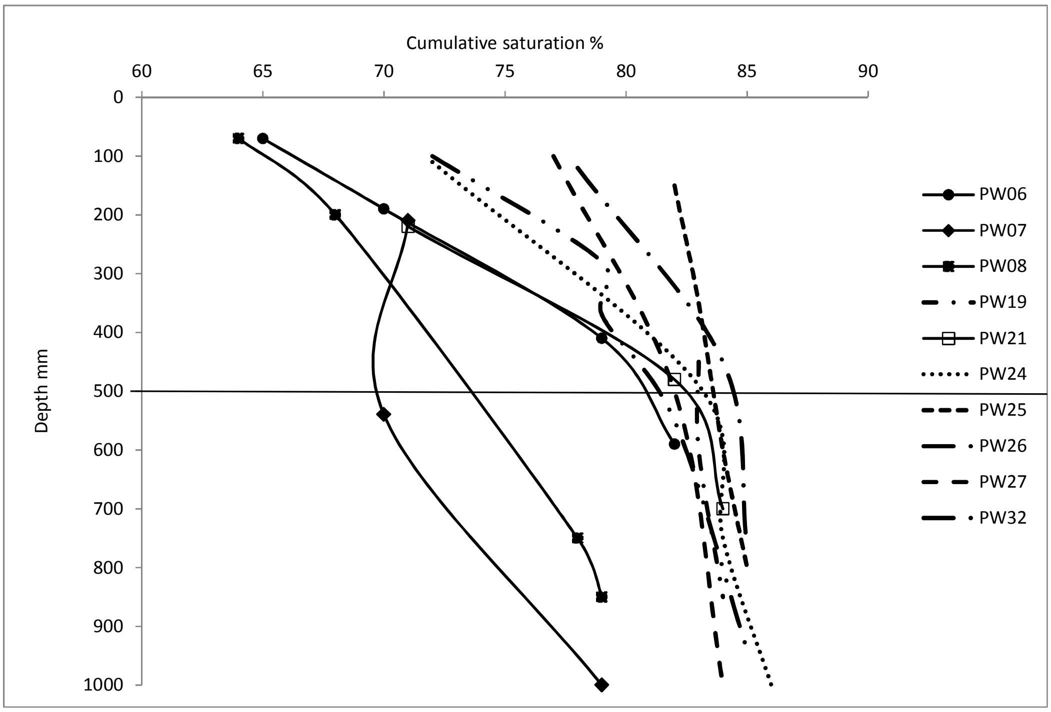


Figure 5-2 Cumulative saturation graphs of the ten piezometers in Bokong.

5.2.4 Soil water content

Soil water content data were not continuous throughout the 2010 to 2011 because of technical instrumentation problems. However, soil water content was measured during highest rainy and dry period of the 2010/11 season. The soil moisture graph and degree of saturation at 500 mm in profile PW32 indicated a similar trend to the water table levels measured in the piezometers, with low soil water content from April 2010 to October (dry period) and high soil water levels (above 0.8 m m^{-1}) from November 2010 to January 2011 (rainy period, Figure 5.3). The higher soil water content in November 2010 until January 2011 was in response to high precipitation during this summer season (Figure 5-3). The degree of saturation at and above 450 mm in Profile PD11 was also above 80%. The degree of saturation was calculated by multiplying soil water content values with the bulk density (Hillel, 1980; Van Huyssteen *et al.*, 2005; Jennings, 2008; Kuenene, 2008; Smith & Van Huyssteen, 2011). The measurement of soil water at each depth was an average to the next depth, hence the bulk density used to calculate the degree of saturation was determined from the four horizons in profile PD11 and the G2 horizon for profile PW32 (Table 5-1).

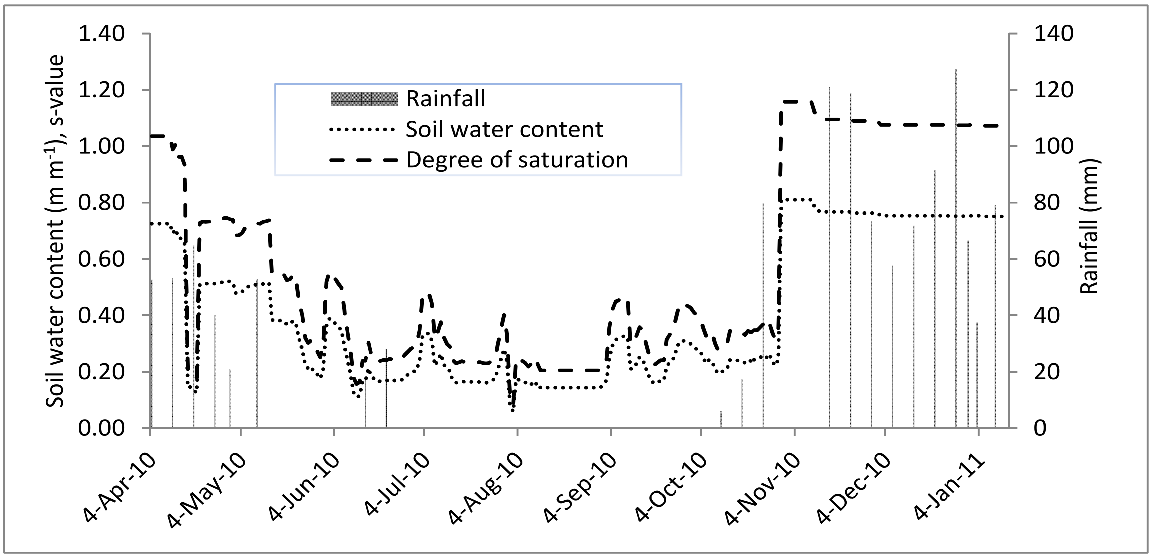


Figure 5-3 Daily soil water content (m m^{-1}), degree of saturation (s-value) at 500 mm depth and daily rainfall for PW32 from April 2010 to January 2011.

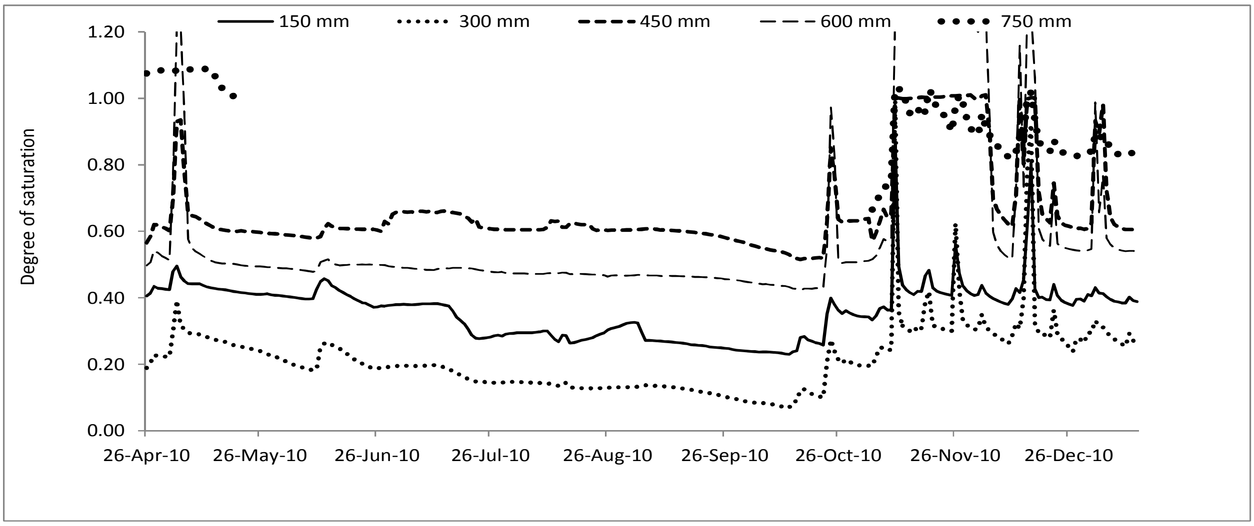


Figure 5-4 Degree of saturation at different depths at PD11 from April 2010 to January 2011.

Table 5-1 Bulk density at each depth in PD11 and at 500 mm depth for profile PW32 between 26th April 2010 and 13th January 2011

Horizon	Lower depth	Bulk density	Porosity
PD11	mm	Mg m^{-3}	%
A1	170	0.57	78
A2	410	0.65	75
AB	800	1.01	60
B	1000	0.72	72
PW32 (G2)	550	0.78	70

5.2.5 Redox potential and degree of saturation

Redoximorphic features are indicators of the water saturation and reducing conditions in wetlands. Therefore, determination of reducing conditions is important in hydrology. The soil moisture content and redox potential (Eh) measured at PW32 were analysed to confirm reducing conditions in the soil. The hourly recorded redox potential at 500 mm depth at wetland PW32 during high rainfall months from November, 2010 to January 2011 showed that Eh was negative throughout the three months at a mean of -2 mV suggesting reducing conditions (Figure 5-5). The redox potential (Eh) in April to August, 2011 were showing fluctuations between 100 mV and 340 mV indicating continuing reducing conditions until May and started to increase above 400 mV in June (Figure 5-6).

An increase in Eh above 400 mV was observed from the intersect of the redox potential and the soil degree of saturation graphs from reduced to oxidized condition (Figure 5-6). The degree of water saturation at this point when reduction ceased as given by intercept of the slope was 0.80. A higher degree of saturation (s value = 0.80) was attributed to the high porosity of the soil. Hillel (1980) determined field soil saturation at 90% of porosity. The first approximation of the degree of saturation in which reduction is expected to occur given by Van Huyssteen *et al*. (2005), for yellow brown apedal B (Soil Classification Working Group, 1991) in South Africa was 0.70 ($S_{0.7}$) and Jennings (2008) approximation on the same soil was 0.78 ($S_{0.78}$) under laboratory conditions. However, Smith and Van Huyssteen (2011) on the same soils observed that Mn^{2+} and Fe^{2+} concentrations remain relatively stable at lower degree of saturation (S = 0.6 to 0.8) while redox potential changes, hence other factors may be assumed to have delayed the reduction of Fe and Mn.

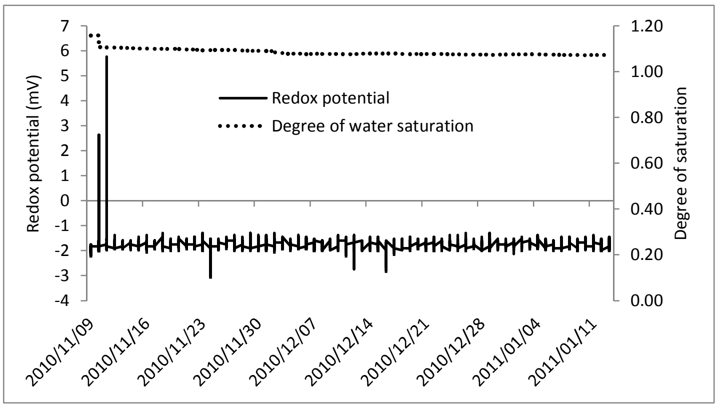


Figure 5-5 Hourly recorded redox potential and degree of saturation at PW32 from November 2010 to January 2011

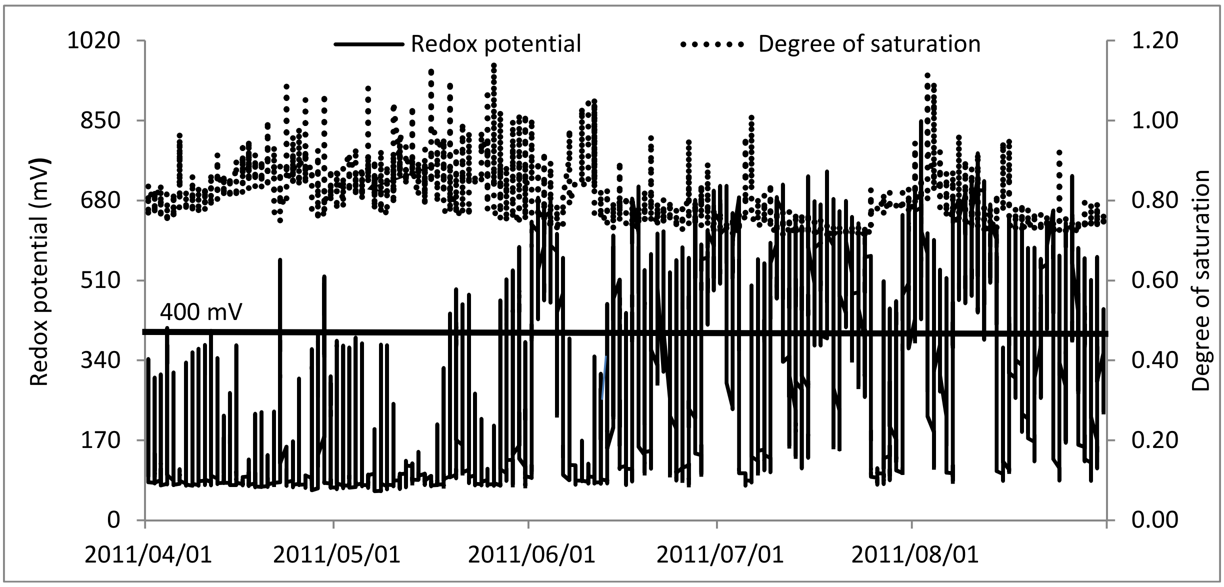


Figure 5-6 Hourly recorded redox potential and degree of saturation at 500 mm depth PW32 from April to August 2011.

5.2.6 Duration of reduced conditions

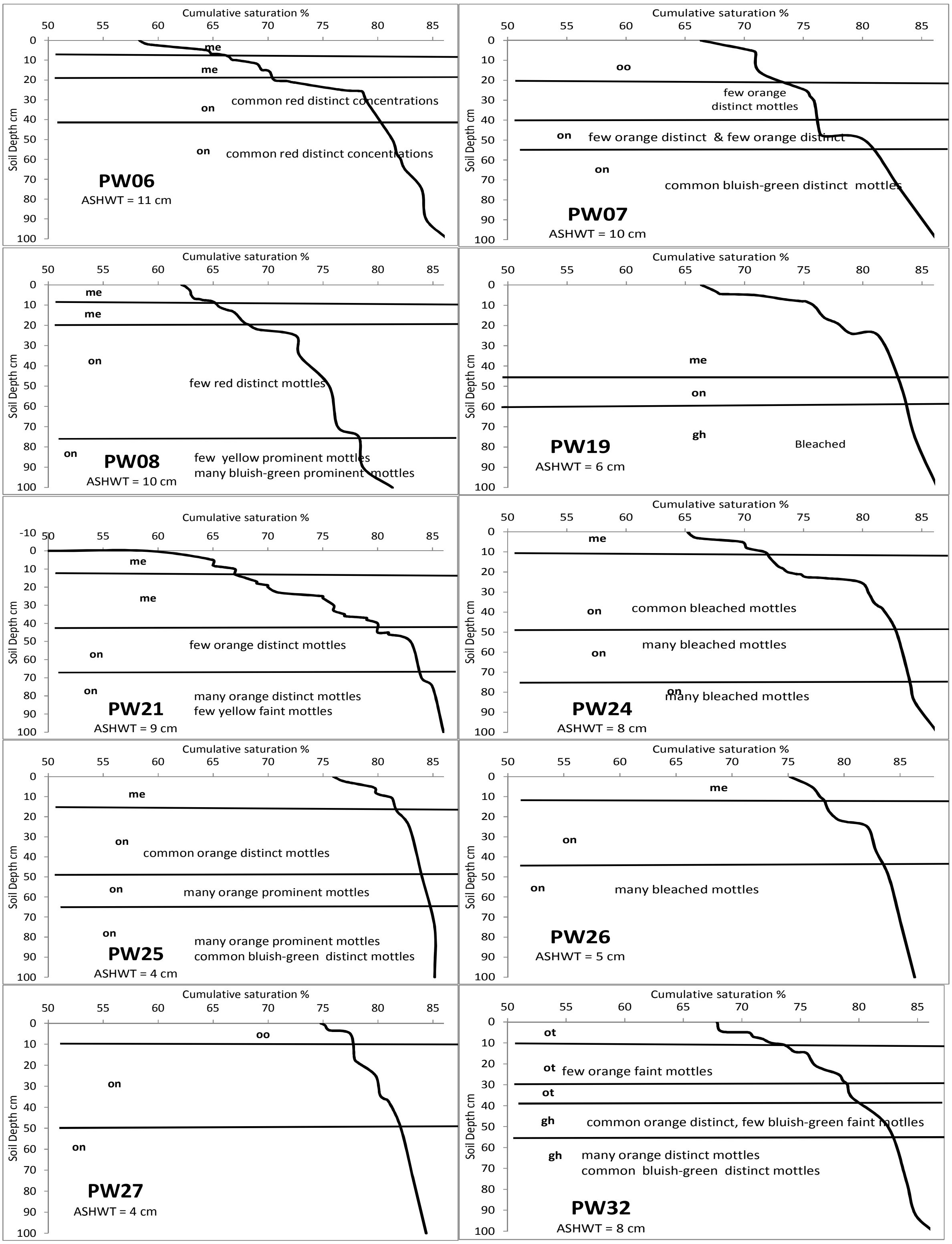
The estimated degree of saturation (s-value) at which reduction occurs was determined for the soil and environmental conditions of Bokong to be 0.80. The duration of saturation under which reduction occurred ($AD_{s>0.80}$) at PD11 was determined as 0, 0, 31, 37, and 51 days of the monitoring time from 26th April 2010 to 13th January 2011 for 150, 300, 450, 600, and 750 mm depth respectively. Aerobic conditions were prevailing within the 300 mm depth from the surface of profile PD11 throughout the monitoring period, since there were no days observed with the s-value above 0.8. Reducing conditions were expected in profile PD11 for only 37 days in 266 days (13% of the time) at the 500 mm depth from the soil surface. In PW32, the soil was expected to be reducing for 170 days out of 266 days (64%) of the monitoring period in the G2 horizon, at 500 mm depth from the soil surface. Van Huyssteen *et al*. (2010) reported a duration of saturation ($AD_{s>0.70}$) of 239 to 357 days per year (65-100%) in the G horizons of soils of South Africa. The observed cumulative saturation in 500 mm in PW32 was 82% (Figure 5-2).

5.3 RELATIONSHIP BETWEEN REDOXIMORPHIC FEATURES AND HYDROLOGY

The cumulative saturation curves indicating redoximorphic features observed in each horizon for wetland profiles are shown in Figure 5-7. The average seasonal water table is also indicated. Redoximorphic features were not observed in most surface horizons in many wetlands profiles. This was due to the black soil colour of the surface horizons that could have masked the appearance of redoximorphic features. O'Geen *et al.* (2007) associated the absence of redoximorphic features at the summit profile in the Redding catena to a lack of capillary rise extending into the topsoil. The thickness of the capillary fringe depends on the pore size distribution of the soil and it determines the depth of the redoximorphic features. O'Geen *et al.* (2007) explained the reason of thin capillary fringe to be due to the high sand content. The sandy soil texture of the Bokong soils may also restrict the capillary fringe from developing to the surface. Bioturbation by gophers can also explain the lack of hydric soil indicators/redoximorphic feature (O'Geen *et al*., 2007). Rodents (ice rats) were active on the drier edges of the Bokong wetlands (Schwabe, 1995); this may destroy evidence of hydric soil features especially at the edges of the wetland with shorter duration of standing water. PW27 did not have any redoximorphic features because of peat formation throughout its depth (Figure 5-7).

The six morphological indices of redoximorphic features identified from each horizon and cumulative saturation percentage are given in Table 5-2. Regression coefficients for each redoximorphic index indicate a significant positive correlation between cumulative saturation and redoximorphic indices, however, poor correlations were observed between average seasonal water table and redoximorphic indices (Table 5-3). Higher correlations were observed between the depth to the gley matrix and depth to chroma 3 and 4 and percentage saturation (Table 5-3). The results were in agreement with Gulasky *et al.* (1998) results, which show a higher correlation between cumulative saturation and depth to first gley horizon and depth to first partially gleyed/pale horizon indices only. The correlations between morphological indices and the cumulative saturation suggested that the duration of water table can be inferred from the redoximorphic features in Bokong.

The poor correlation between morphological indices and the depth of saturation has also been observed by other researchers (He *et al*., 2002; He *et al*., 2003; Vepraskas & Caldwell, 2008). He *et al.* (2003) ascertained that redox features do not necessarily determine the water table depth but the duration and frequency of water table at that depth. Furthermore redoximorphic features are expected to occur higher in the profile than average seasonal water table (Fiedler *et al*., 2004; Dear & Svensson, 2007; Severson *et al*., 2008).



†Diagnostic Horizons South African Soil Classification: horizons (Soil Classification Working Group, 1991): me – Melanic A; ot – Orthic A; oo – Organic O, ye – Yellow-brown apedal, gh – G horizon; on – Unspecified and li – Llithocutanic.
‡ASHWT: Average seasonal high water table.

Figure 5-7 Cumulative saturation graphs of the ten piezometers in Bokong indicating the redoximorphic features of each horizon.

Table 5-2 Soil profile description, identified morphological indices, and cumulative saturation for the ten representative wetlands.

Profile id.	Diagnostic horizons	Depth mm	Moist colours	Concentrations % & size	Concentrations Col/contr	Depletions % & size	Depletions Col/contr	Morphological Indices*	Cumulative Saturation %
PW06	ot	0 -70	10YR2/1	none	none	none	none	none	65
	me	70 -190	10YR2/1	none	none	none	none	none	70
	ye	190 - 410	5YR4/4	com/fin	red/distnct	man	bleach pore	*d_34*	79
	ye	410 - 590	5YR4/6	com/fin	red/distnct	none		*d_conc*	82
PW07	oo	0 -210	10YR2/1	none	none	none	none	none	71
	ot	210 - 400	10YR2/2	few/fin	orng/distnt	none	none	*d_rmfs*	70
	ye	400 - 540	7.5YR4/4	few/fin	orng/distnt	few/fi	bl-grn/distnct	*d_34*	79
	ye	540 - 1000	10YR5/6	none	none	com/fin	bl/grn/distct	*d_depl*	82
PW08	me	0 - 70	10YR2/1	none	none	none	none	none	64
	me	70 - 200	10YR2/1	few/fin	red/distnct	none	none	*d_rmfs*	68
	on	200 - 750	10YR2/2	few/fin	red/distnct	none	none	*d_rmfs*	78
	on	750 - 800	2.5YR5/6	mny/co	yel/promt	mny/co	gry/promt	*d_depl*	79
PW19	me	0 - 450	10YR2/1	none	none	none	none	none	83
	gh	450 - 600	10YR3/4	none	none	none	none	*d-34*	83
	gh	600 - 850	10YR5/1	none	none	none	gley	*d_gley*	84
PW21	ot	0 - 220	5B4/1	none	none	none	none	none	71
	ot	220 - 480	7.5YR 4/2	com/fi	orng/dist	none	none	*d_conc*	82
	ye	480 - 700	7.5YR 4/4	few/fi	orng/dist	none	none	*d_34*	84
	ye	700 - 1000	10YR4/4	mny/co	orng/dist	few/med	yel/faint	*d_34*	86
PW24	ot	0 - 110	10YR4/4	none	none	none	none	none	72
	ot	110 - 490	10YR2/1	none	none	com/me	bleached	*d_depl*	83
	gh	490 - 750	5Y4/1	none	none	mny/co	bleached	*d_gley*	84
	gh	750 - 1000	5Y5/1	none	none	mny/co	bleached	*d_gley*	86
PW25	me	0 - 150	10YR4/4	com/fi	orng/dist	none	none	d_34	82
	me	150 - 350	10YR2/1	com/fi	orng/dist	none	none	*d_conc*	83
	gh	350 - 600	G2/N	mny/med	orng/promt	com/med	bl-gn/distnct	*d_gley*	84
	gh	600 - 800	G1.5/N	mny/med	orng/promt	com/med	bl-gn/distnct	*d_gley*	85
PW26	me	0 - 120	10YR 2.5/1	none	none	none	none	none	78
	ye	120 - 450	10YR 3/1	none	none	com/me	bleached	*d_depl*	84
	on	450 - 767	10YR 5/1	none	none	mny/co	bleached	*d_depl*	85
PW27	oo	0 - 100	2.5Y 2.5/1	none	none	none	none	Peat**	77
	on	100 - 500	2.5Y 2.5/1	none	none	none	none	Peat**	82
	on	500 - 1000	2.5Y 2.5/1	none	none	none	none	Peat**	84
PW32	ot	0 - 100	10YR2/2	none	none	none	none	none	72
	ot	100 - 280	10YR3/1	few/fin	orng/faint	none	none	*d_rmfs*	79
	ot	280 - 370	10YR3/1	com/med	orng/dstnct	few/med	bl-grn/faint	*d_conc*	79
	gh	370 - 550	10YR4/2	com/med	orng/dstnct	few/med	bl-grn/faint	*d_conc*	82
	gh	550 - 940	10YR5/1	mny/co	orng/promt	com/co	bl-grn/distnct	*d_depl*	85

† Diagnostic horizons: South Africa soil classification system (Soil Classification Working Group, 1991): me – Melanic A; ot – Orthic A; oo – Organic O, ye – Yellow-brown apedal, gh – G horizon; on – Unspecified and li – Llithocutanic.

‡ Concentration % and size, Depletion % and size: (Turner, 1991; Soil Survey Staff, 1993; Schoeneberger *et al*., 2002)
Abudance- few (< 2%), com – common (2 to 20%), mny – many (> 20%)
Size: fin- fine, med – medium, co – course

†† Concentration col/contr, Depletion col/contr: col/contr – colour contrast: (Turner, 1991; Soil Survey Staff, 1993; Schoeneberger *et al*., 2002)
Colour; orng – orange, yel – yellow, bl-grn – bluish green, gry – grey, blc - bleached.
Contrast: promt – prominent, distinct – distinct.

‡‡ Morphological indices*:
d_rmfs – depth to few redoximorphic features, *d_34* – depth to chroma 3 or 4, d_conc depth common concentrations, *d_depl* – depth to common and many depletions, d_gley – depth to gleyed horizon.

§ Peat** with no redoximorphic features observed

Table 5-3 Linear Regression coefficients for cumulative saturation and average seasonal high water table (ASHWT) versus the depth to soil morphological indices.

Morphological indices	**Cumulative saturation**	**ASHWT**
d_34chr	0.77	0.17
d_gley	0.74	0.36
d_conc	0.67	0.01
d_depl	0.58	0.19
d_RMFs	0.50	0.05
Average		

†Morphological indices:
d_34 – depth to chroma 3 or 4
d_gley – depth to gleyed horizon
d_conc depth common concentrations
d_depl – depth to common and many depletions
d_RMFs – depth to few redoximorphic features

Table 5-4 shows the profile darkening index (PDI) and depth of the black layer with corresponding soil water saturation percentages for each profile at 500 mm depth. Thompson and Bell (2001) suggest the use of PDI to indicate degree of wetness than redoximorphic features where surface horizon have dark thick layer due to organic matter accumulation. The PDI and black layer had a good correlation with both soil water characteristics (Figure 5-8). The higher PDI index indicated that higher organic carbon accumulations had occurred due to prolonged saturation.

Table 5-4 Average seasonal high water table (ASHWT), profile index (PDI calculated from equation 2-7), depth of the black layer (mm, value ≤ 2, chroma ≤ 1) and cumulative saturation at 500 mm.

Profile no.	ASHWT (mm)	PDI	Depth of black layer	Cumulative saturation % at 500 mm depth
PW06	110	6.3	190	79
PW07	110	13.3	400	79
PW08	100	9.3	200	72
PW19	60	0	450	83
PW21	90	0	0	82
PW24	80	0	0	83
PW25	40	0	0	84
PW26	50	11.7	450	84
PW32	80	8.7	370	82
PW27	40	28.5	1000	82

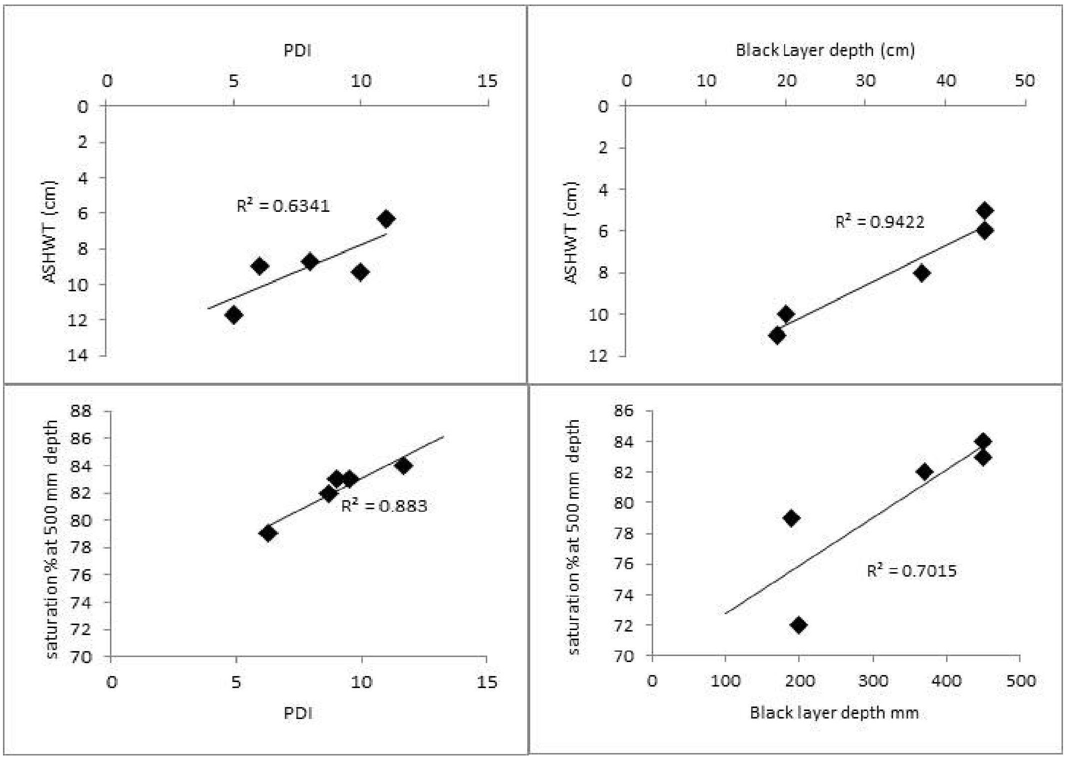
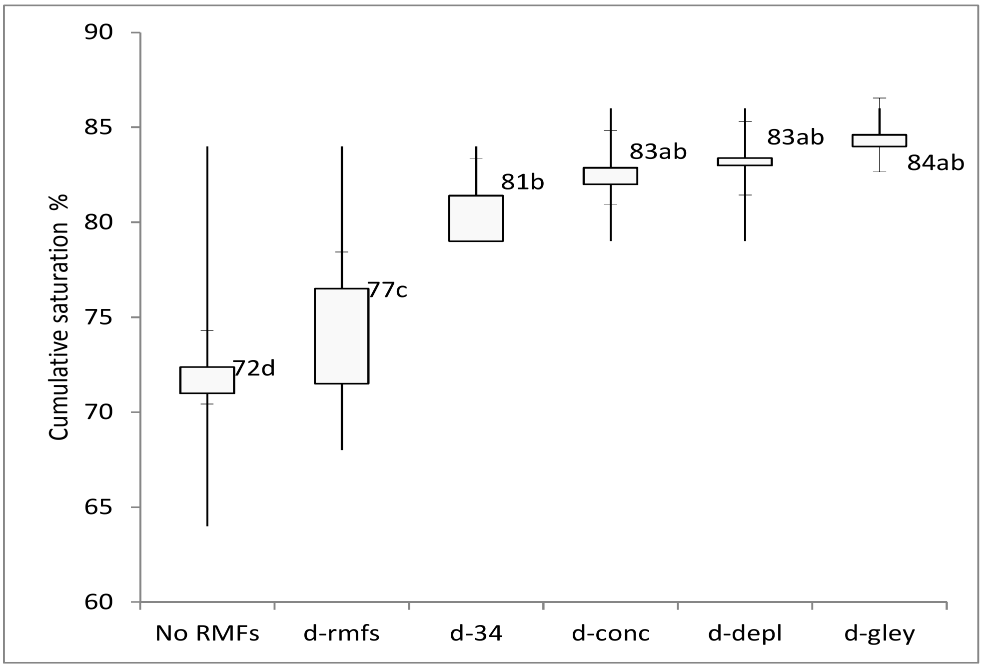


Figure 5-8 Linear correlation coefficients for average seasonal water table and cumulative saturation versus the depth to soil morphological indices.

Thompson and Bell (1996) report a significant correlation between PDI and duration of saturation at 50 cm (R^2 = 0.48, α = 0.05), while Rueter and Bell (2003) observe that thickness of the black layer is better correlated with duration of saturation than PDI (R^2 = 0.81 and 0.77).

Boxplots representing variability between morphological indices are given in Figure 5-9. There was a significant difference in cumulative saturation percentage between morphological indices, with longer duration required to form a gley matrix (*d_gley*) than the time required to develop all other redox indices (Figure 5-9). Lindbo *et al*. (2006) also observed that redox concentrations correlate to approximately 15% annual water saturation, but 2 chroma depletions correlate to approximately 80% annual water saturation. West *et al.* (1998) also observe that low chroma Fe depletions represent considerable cumulative saturation, while few depletions with common concentrations can develop with 19% cumulative frequency in loamy soils. The mean separation showed that the time required to develop *d_34, d_conc* and *d-depl* was not significantly different from time required to form gley matrix, however, the range in cumulative saturation (indicated by the height of the box) was narrow with *d_gley* and *d_depl*. The lower saturation percentage for *d_34* than *d_conc*, was assumed to be because of the abundance categories used which separated few concentrations (*d_RMFs*) from common to many.

Galusky *et al*. (1998) reported similar results on the indices, where the *d-34* index was highly correlated with average monthly water table levels derived from a first order auto-regressive model. The correlation was highest in March when seasonal water tables were highest. The gleyed matrix also had higher correlations during the same rainy season. Galusky *et al*. (1998) observed low to poor correlations or no correlations with the d-depl and d-conc respectively. The *d_conc* and *d_depl* indices indicate a fluctuating water table (Franzmeier *et al*., 1983; Zobeck & Ritchie, 1984; Evans & Franzmeier, 1986; Vepraskas & Caldwell, 2008).



† Means with different letters are significantly different at the 0.05 level.
‡ The lower line of the box represents the minimum cumulative saturation percentage (25th percentile) and the end of the upper line is the maximum cumulative saturation percentage (75th percentile) observed under every RMFs. The cross bar on whisker line above the box represents the highest observed value and on the lower whisker is the lowest observed value.
†† Morphological index: PDI - profile darkening index, No RMFs – no redoximorphic features observed, *d_RMFs* –few *d_34* – depth to chroma 3 or 4, *d_gley* – depth to gleyed horizon, *d_conc* depth common concentrations, *d_depl* – depth to common and many depletions

Figure 5-9 Box plots showing the mean difference in cumulative saturation between the abundance of redoximorphic features for the 24 months study period from 10 profiles at Bokong.

Redoximorphic features were not identified under a wide range of cumulative saturation percentage and this was associated with the dark surface horizon which masks the pigmentation of Fe. The minimum duration of saturation required for Bokong soils to develop redoximorphic features was 77% of the year. Redoximorphic features were not observed with cumulative saturation of 72% (Figure 5-9). This was supported by lack of redox features in the subsoil of permanently dry profile (PD11) with duration of reducing conditions of at least 20% of the year (Section 5.2.5). Longer saturation required to develop redox features could also be linked with low temperatures in this landscape. Vaughan *et al*. (2009) also observed that longer duration is required for Fe of ferrihydrite to be reduced as temperature decreased. However, soil temperatures at Bokong within the 500 mm of the soil surface was higher than 5°C for at least nine months in a year especially during periods of higher soil water content.

The good correlation observed between the indices and cumulative saturation percentage suggested that these indices can be used to determine the duration and frequency of the water table in this landscape. The hydric field indicators identified that were related to *d_gley* and *d_34* indices were thick dark surface (A12) and loamy gleyed matrix (F2). The hydric soil field indicators that were related to the PDI index were histisols (A1), histic epipedon (A2) and umbric surfaces (F13). The indicators that were represented by the indices that had poor correlations with the cumulative saturation (*d-conc* and *d-depl*) were redox dark surfaces (F6), depleted dark surfaces (F7) and redox depression (F8) (Table 5-5).

Table 5-5 Hydric soil field indicators proposed to infer duration and frequency of saturation of Bokong wetlands.

Hydric Indicator	**Morphological index**	**Cumulative saturation %**
Histisols (A1) Histic epipedon (A2) Umbric surfaces (F13)	PDI	79
Thick dark surfaces (A12)	*d_gley*	84
Loamy gleyed matrix (F2)	*d_34*	81
Redox depression (F8) Redox dark surfaces (F6)	*d_conc*	83
Depleted dark surfaces (F7)	*d_depl*	83

†Morphological index:

PDI - profile darkening index, *d_34* – depth to chroma 3 or 4, *d_gley* – depth to gleyed horizon, *d_conc* depth common concentrations, *d_depl* – depth to common and many depletions

5.4 CONCLUSIONS

There is a significant positive correlation between cumulative saturation and some redoximorphic indices. However, poor correlations were observed between average seasonal water table and all redoximorphic indices suggesting that the depth to average seasonal water table cannot be associated with redoximorphic features. Strong correlations were observed between the depth to the gleyed matrix and depth to chroma 3 and 4 and cumulative saturation. However, the percentage time required to form a gleyed matrix was not significantly different from time required to develop *d-34, d-conc* and *d_depl*. Therefore *d_34* and a gleyed matrix need to be used with other indicators to confirm the presence of wetland hydrology. None of the indices however, can be used to determine the depth of seasonal high water table. Field indicators such as histisols, histic epipedon, umbric surfaces, represented by PDI and thick dark surfaces and loamy gleyed matrix represented by *d-34* and thick dark surface represented by *d_gley* can be used to determine the duration and frequency of the water table in the landscape studied, hence can be used to delineate wetlands. Other field indicators represented by indices with weak correlations with cumulative saturation (*d_conc* and *d_depl*) may be used with other indicators.

CHAPTER 6

THE DISTRIBUTION OF SELECTED SOIL ELEMENTS IN HYDRIC AND NON-HYDRIC SOILS

6.1 INTRODUCTION

Soil properties distribution in a profile is influenced by soil water regime. The leaching soil water regimes dominate in freely drained soils, however, wetland ecosystems are dominated by saturated soil water regimes and redox gradients control the properties' distribution. Linkages between soil water regimes and soil properties' distribution are important to the understanding of the dominant soil processes in the soil and their ecological impact (Fiedler & Sommers, 2004), such as element transformation and pollutant retention in soils (Enya *et al*., 2011). Freely drained soils have short duration of standing water. This is indicated by minimal evidence of pedogenesis and result in uniform distribution of secondary Fe and Mn oxides with depth (O'Geen *et al*., 2007). Fluctuating water table in wetland ecosystems favours the formation of secondary Fe and Mn which result in concentrations and depletions in different depths. Free Fe and Mn oxides can be estimated by citrate-bicarbonate-dithionate (CBD) extraction (McKeague *et al*., 1971). The ratio of dithionite extractable Mn and Fe (Mn_d/Fe_d) has been used as a pedochemical indicator of water movement (Bartlett, 1986; McDaniel & Buol, 1991; McDaniel *et al*., 1992, Khan & Fenton, 1996; Jien *et al*., 2010). The objective of this chapter was to investigate the influence of soil water saturation on the distribution of secondary Fe, Mn, oxides, available P, and cations in the Bokong wetlands.

6.2 IRON AND MANGANESE OXIDES

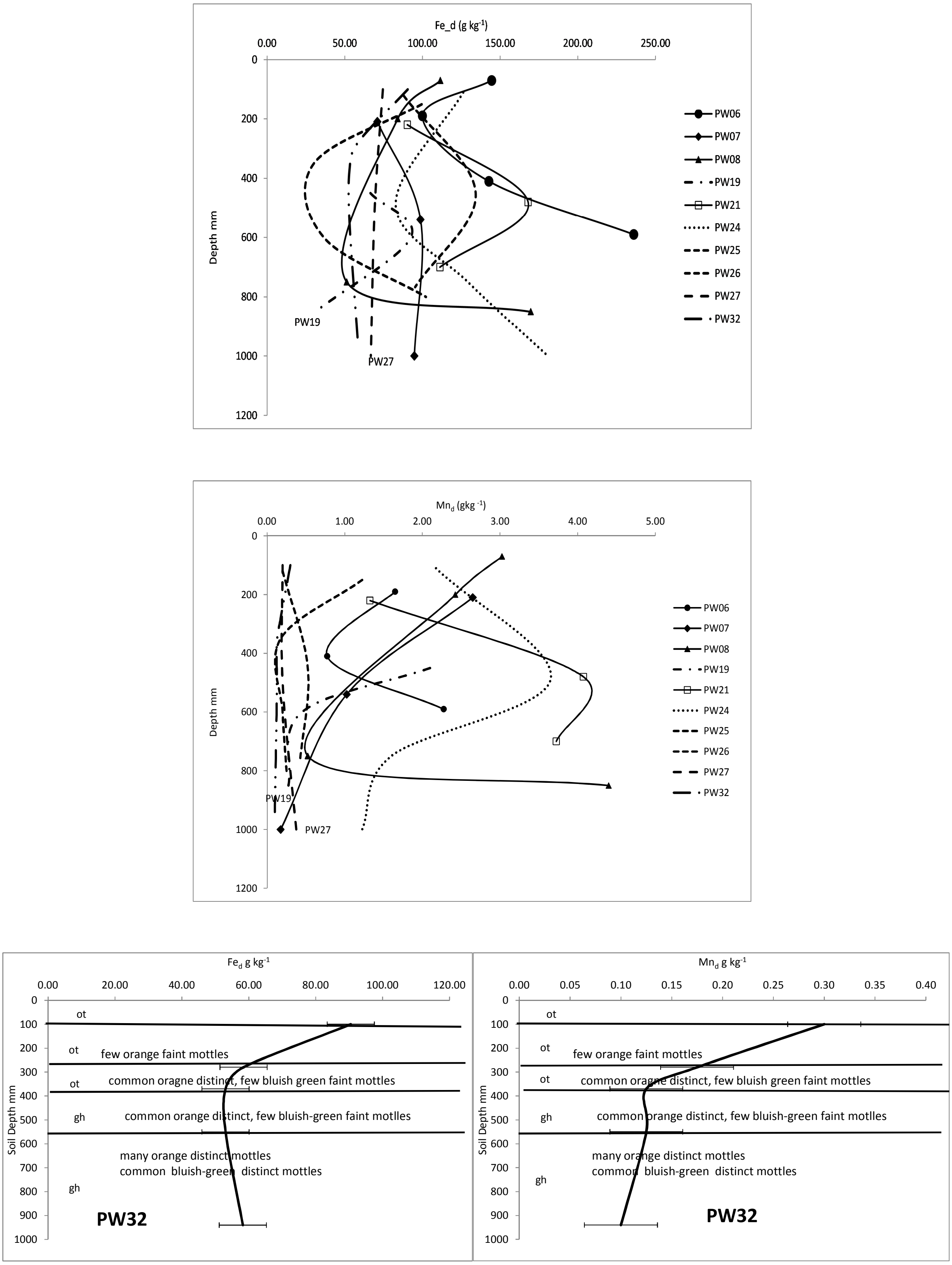
6.2.1 Distribution of Fe and Mn in hydric and non-hydric soils

There was no obvious regular pattern in the distribution of both oxides in the profiles (Figure 6-1). Generally, it could not be established which horizons have higher levels of Fe_d or Mn_d. However, both oxides showed similar trends with depth in most profiles (Figure 6-1). For example, profile PW32 had lower concentrations of Mn_d and Fe_d in the transitional horizons and higher accumulations were observed in the A1 horizons (Figure 6-1). Horizons with high accumulations of Mn_d and Fe_d are associated with highly variable redox conditions (Fiedler & Sommers, 2004). O'Geen *et al*. (2007) also associated the formation of poorly crystalline Fe (ferrihydrite) to the fluctuating water table and redox.

The horizon that had the lowest Fe content (31 g Fe_d kg^{-1}) was the G horizon in profile PW19 (Figure 6-1). This horizon had gley colours without redox concentrations, suggesting the solubility and loss of Fe due to longer duration of saturation. Increased solubility of Fe and Mn was also observed by Jennings (2008) under laboratory conditions, where an increase in degree of saturation caused a decrease in pe (Eh) and an increase in the soluble Fe^{2+} and Mn^{2+} concentration. Anaerobiosis leads to the reduction of Fe^{3+} and thus to a high release of soluble Fe^{2+} (Dethier *et al*., 2012). Moore (2006) also observed pronounced losses of dithionite-extractable Fe and Mn from gleyed horizons. Khan and Fenton (1996) observed a pronounced decrease in total Fe as the duration of saturation increased. Eger *et al*. (2011) reported the lowest concentrations of 0.34 mg kg^{-1} Fe_d under super humid New Zealand conditions where podsolization is dominant.

However, in cases where the G horizon had redox concentrations, the Mn_d and Fe_d concentrations were highest in the profile (Figure 6-1), suggesting increased localised solubility and accumulation of Fe and Mn due to periodic water saturation (Jennings *et al*., 2008). The presence of redox concentrations in the G horizon suggested that accumulations of re-oxidised Fe and Mn also occur. According to Le Roux *et al*. (1999), G horizons develop when interflow drains laterally as bedrock flow, forming a phreatic water table. However, this phreatic water table responds to seasonal changes in precipitation (Jennings *et al*., 2008). Thus, Fe^{2+} that has been lost from the upper horizon accumulates when oxidised conditions prevail in the G horizon leading to higher concentrations of Fe_d and Mn_d. Jien *et al.* (2010) observed the greatest quantities of iron nodules of 492 g kg^{-1} in plinthic horizons with reducing conditions duration of 47% of a year. The concentrations of Fe_d and Mn_d in profile PW27 were uniform throughout the profile. O'Geen *et al*. (2007) associated the similarities in extractable Fe with depth to minimal pedogenesis. Profile PW27 had developed peat throughout the depth of 1000 mm without a mineral soil.

The Mn_d and Fe_d levels in non-hydric soils were either higher in the transitional horizons such as in profile PD11 or were lowest (Figure 6-2). The higher concentrations were assumed to be a result of capillary rise from the water table. The capillary fringe concept was supported by Richardson *et al*. (2001); Fiedler *et al.* (2004); and Dear and Svensson (2007).



† Diagnostic horizons: South Africa soil classification system (Soil Classification Working Group, 1991): ot – Orthic A; gh – G horizon.

Figure 6-1 Dithionite citrate bicarbonate extractable iron (Fe_d) and manganese (Mn_d) distribution with depth hydric soils.

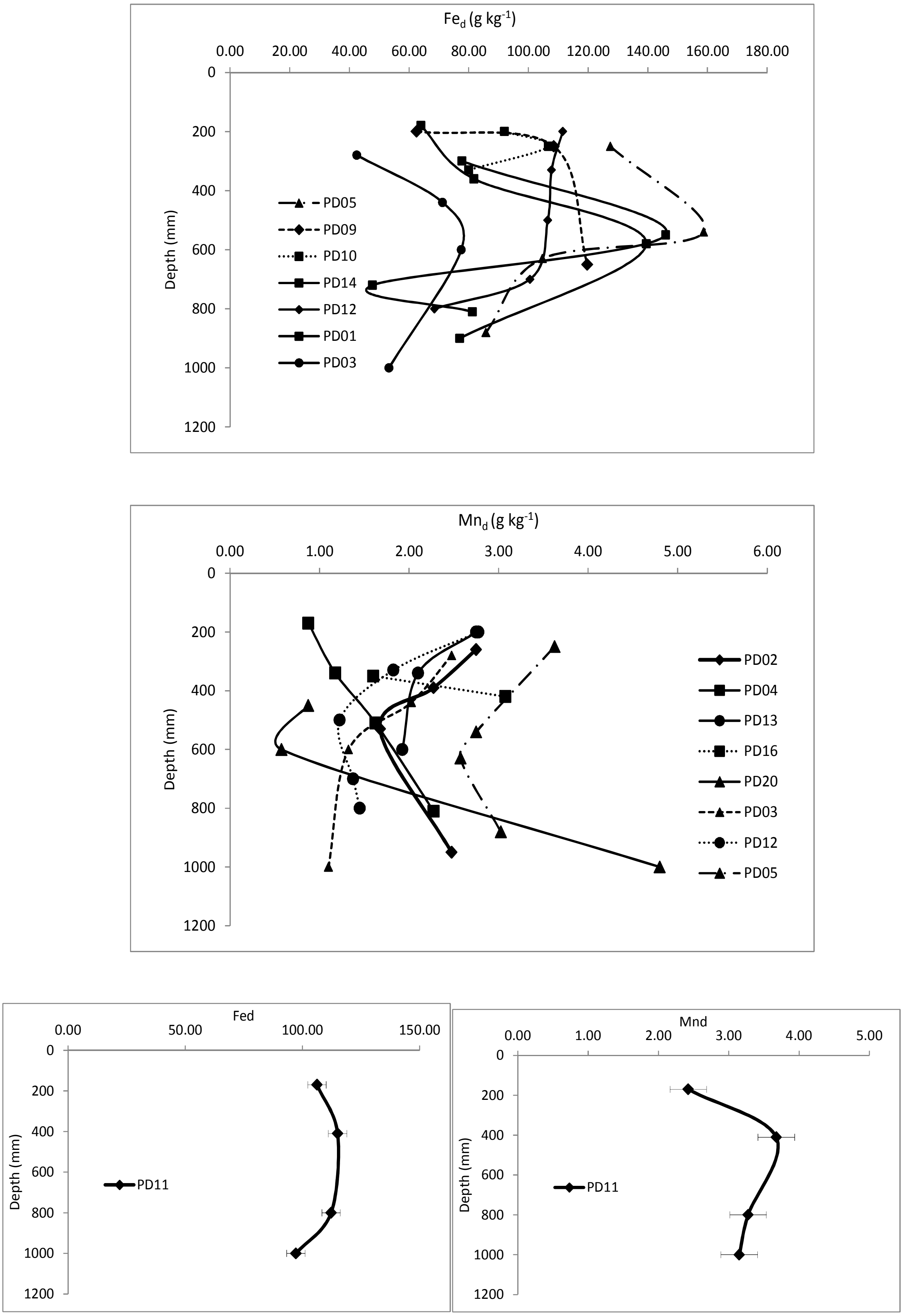


Figure 6-2 Dithionite citrate bicarbonate extractable iron (Fe_d) and manganese (Mn_d) distribution with depth non-hydric soils.

6.2.2 Pedochemical indicators

Iron oxide had a possible influence on the distribution of manganese oxide. In this landscape both oxides seemed to follow the same distribution patterns in most profiles. The correlation coefficient of the two pedogenic oxides in the hydric soils was R^2 = 0.41 and in non-hydric soils was R^2 = 0.46 (Figure 6-3). Enya *et al*. (2011) associated the co-migration of the Fe and Mn oxides with the parent material, geomorphic and physicochemical processes.

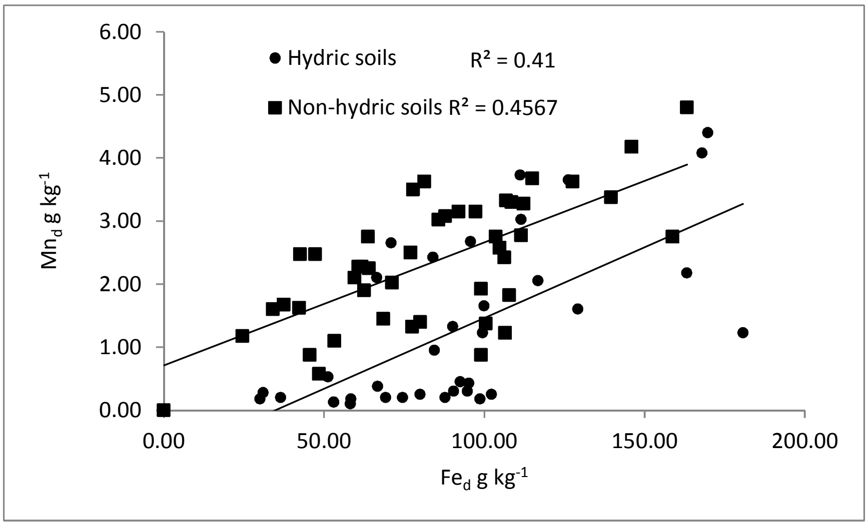


Figure 6-3 The correlation between Mn_d and Fe_d in hydric and non-hydric soils.

The Mn_d/Fe_d ratio was very low ranging from 0.002 to 0.037 in permanently wet (PW) profiles and higher values ranging from 0.009 to 0.076 in permanently dry (PD) profiles (Figure 6-4). All permanently wet profiles had Mn_d/Fe_d ratio lower than 0.01 except for PW06 and PW21 (Figure 6-4). The higher Mn_d/Fe_d ratios in both PW08 and PW21 were attributed to the anthropogenic effects on drainage of the profiles (Section 5.2.3). Jien *et al.* (2010) found that Mn_d/Fe_d in nodules is a good indicator for determining the depth of fluctuating water table. The use of the Mn_d/Fe_d ratio has also been used as a good pedochemical indicator to assess water movement in the profile (Van Huyssteen *et al.*, 2005). The low ratio in hydric soils showed the loss of Mn out of the profile to the ground water.

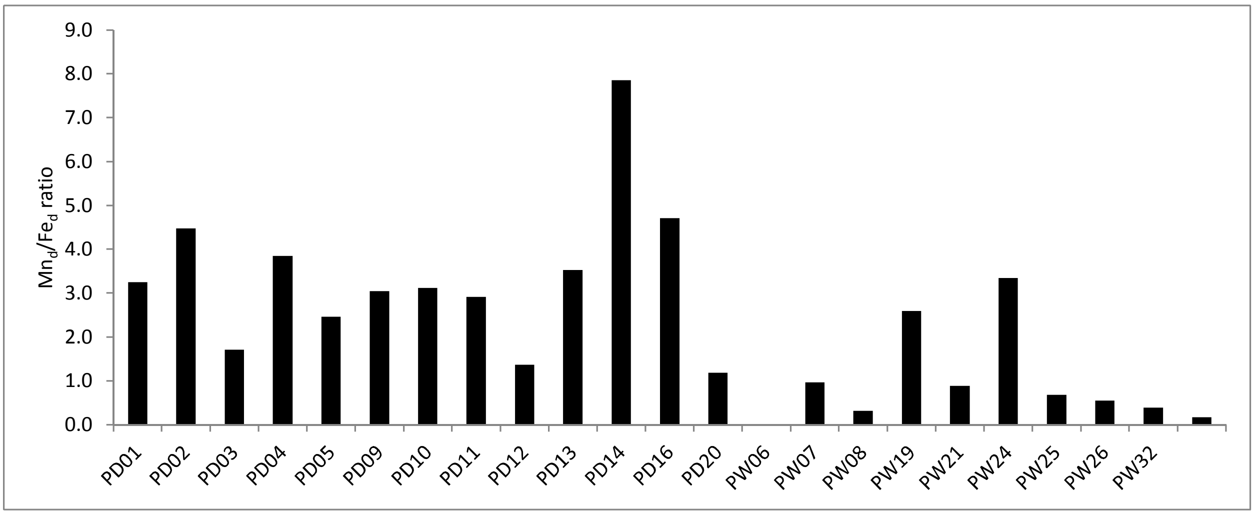


Figure 6-4 The Mn_d/Fe_d ratios in non-hydric permanently dry (PD) and hydric permanently wet (PW) soils.

6.2 3 Elemental masses

The elemental mass had more influence on the morphology of the soil than the concentrations (Fiedler & Sommers, 2004). The extracted element masses and clay masses were calculated as (Fiedler *et al.*, 2004);

$$M_x = \sum_{i=1}^{n} \left(x_i \; X \; \rho_{\beta i} \; X \; y_i \; X \; \frac{100 - cf}{10000} \right)$$

Where M_x is mass of Fe_d, Mn_d or clay in the pedon (kg m^{-2} profile $depth^{-1}$), x_i is Fe_d, Mn_d or clay content in horizon i (g kg^{-1}); n is the number of horizons to profile depth; ρ_β is bulk density (Mg m^{-3}); y_i is the thickness of the horizon $_i$ (cm); cf_i is the coarse fractions >2 mm of the horizon $_i$ (Vol. %). Selected soil properties were also discussed in relation to drainage. The mass of Fe_d and clay were not significantly different between hydric and non-hydric soils (Table 6-1). The elemental mass for Mn_d was significantly higher in non-hydric soils. This was also the case with Mn_d levels.

Table 6-1 Total Fe_d and Mn_d Masses per profile and the element mass/clay ratio for each profile

Profiles	Fe_d	Mn_d	Clay	Fe_d/clay	Mn_d/clay
	-------------------kg m^{-2}---------------------				
			Non-hydric soils		
PD01	34.32	1.15	10.67	3.22	0.357
PD02	35.66	1.54	16.53	2.16	0.713
PD03	47.48	1.42	22.97	2.07	0.689
PD04	13.10	0.42	10.36	1.26	0.334
PD05	50.55	1.25	11.83	4.27	0.293
PD09	53.69	1.62	12.99	4.13	0.392
PD10	23.89	0.94	5.72	4.17	0.226
PD11	64.43	1.83	15.64	4.12	0.444
PD12	16.50	0.35	5.09	3.24	0.108
PD13	22.92	0.64	9.44	2.43	0.265
PD14	31.40	1.05	9.63	3.26	0.322
PD16	10.73	0.48	5.08	2.11	0.228
PD20	33.44	0.80	13.61	2.46	0.327
mean	33.70 ± 16.5^a	1.04 ± 0.48^a	11.50 ± 11.5^a	2.99	0.36
			Hydric soils		
PW06	34.50	0.41	5.42	6.36	0.064
PW07	77.90	0.33	16.85	4.62	0.071
PW08	42.26	0.79	17.32	2.44	0.325
PW19	26.84	0.43	14.70	1.83	0.233
PW21	47.59	1.30	11.83	4.02	0.322
PW24	87.53	1.24	16.78	5.22	0.238
PW25	20.44	0.10	5.77	3.54	0.028
PW26	13.72	0.05	1.33	10.33	0.005
PW32	26.77	0.06	9.97	2.69	0.022
mean	41.95 ± 25.4^a	0.52 ± 0.52^b	11.11 ± 5.8^a	4.56	0.15
t-test (P=0.005)	0.18	0.01	0.43		

† Means of each element followed the different letters were significantly different between hydric and non-hydric soils at P = 0.005.

The Fe_d/clay ratio was higher in hydric soils, while the Mn_d/clay ratio was higher in non-hydric soils (Table 6-1). McDaniel *et al.* (1992) used the element/clay ratio as a pedochemical indicator of element accumulation. The Mn_d/clay masses correlated well with clay masses (Figure 6-5), while Fe_d/clay masses did not have any correlation with clay masses indicating the total independence of Fe_d movement from clay. However, the high correlation between Mn_d masses and clay in non-hydric soils (R^2 = 0.81) were assumed to be due to clay decreases with depth in this landscape. The Mn_d accumulated in the higher horizons that were freely draining and decreased with depth in wetter horizons. Therefore, the relationship of clay and Mn_d was not associated with the co-migration of the two properties (clay and Mn_d). The redistribution of both Mn_d and Fe_d was more influenced by hydraulic and redox gradients (Fiedler *et al.*, 2004).

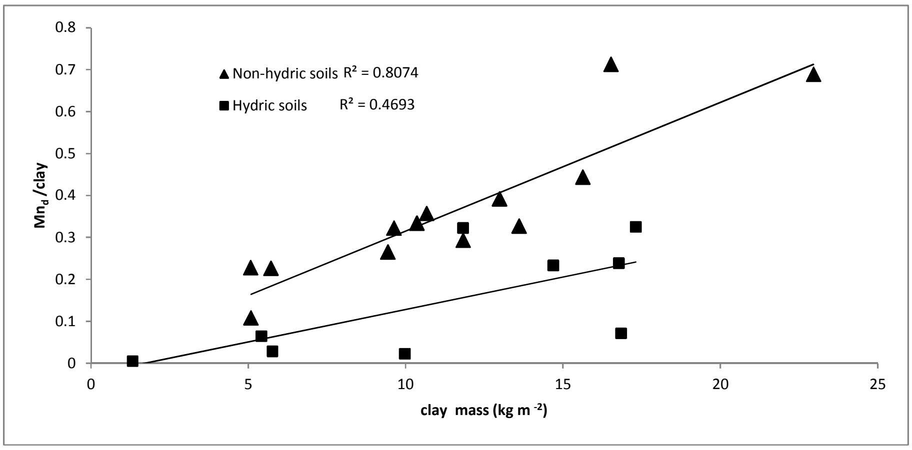


Figure 6-5 The relationship between Mn$_d$/clay ratio and clay mass in non-hydric and hydric soils.

6.3 DISTRIBUTION OF SELECTED PROPERTIES AS AFFECTED BY SOIL WATER SATURATION

The means of selected soil properties in different horizons in hydric and non-hydric soils are given in Table 6-2. A paired t test indicated that soil pH, exchangeable Mg and Na, dithionite extractable Fe and Al were significantly different between hydric and non-hydric soils. Hydric soils had significantly higher Mg, Na and Fe content, and significantly low soil pH and Al content. Generally it appeared that soluble phosphorus, Fe and exchangeable bases accumulated in hydric soils, while the soil pH and Al content decreased.

The mean dithionite extractable iron and manganese (Fe$_d$ and Mn$_d$) contents in hydric soils were of 104 g Fe$_d$ kg^{-1} and 1.5 g Mn$_d$ kg^{-1} while in non-hydric soils it were 83 g Fe$_d$ kg^{-1} and 2.5 g Mn$_d$ kg^{-1} (Table 6-2). The significantly higher Fe$_d$ in hydric soils may be due the fluctuating water-table in the G horizon that can cause the movement of Fe within the profile. When the horizon is saturated, the Fe is reduced and moves up with the water table and as the water table drops the Fe is oxidised and precipitates. However, the Fe$_d$ might also accumulate in subsoil where higher electron potential and pH conditions prevail.

Table 6-2 Comparison of selected soil properties between hydric and non-hydric soils.

Horizons	**pH**	**pH**	**Ca**	**K**	**Mg**	**Na**	**P**	**Fed**	**Mnd**	**Al-d**
	water	KCl	--------------------mg kg^{-1}--------------------					--------g kg^{-1}--------		
					Hydric soil					
A1	5.3	4.5	1384	223	253	75	0.87	98	2.9	43.9
A2	5.3	4.5	1552	244	240	81	0.88	123	1.5	35.5
AB/BA/B1/C1/G1	5.5	4.5	1045	108	175	72	0.78	83	0.5	29.4
B/B2/C/G/C2/G2	5.7	4.6	1342	136	222	74	0.68	113	1.3	35.0
Profile means	5.4^{b}	4.5^{b}	1329^{a}	177^{a}	222^{a}	76^{a}	0.80^{a}	104^{a}	1.5^{a}	35.7^{b}
					Non-hydric soil					
A1	5.3	4.6	1491	246	174	48	0.91	74.7	2.4	46.0
A2	5.4	4.6	1440	220	197	53	0.80	87.0	2.6	46.0
AB/BA/B1/C1	5.6	4.7	1340	165	166	46	0.60	84.8	2.4	48.6
B/B2/C/C2	5.8	4.9	1162	174	137	54	0.57	83.5	2.6	47.2
Profile means	5.6^{a}	4.7^{a}	1365^{a}	195^{a}	165^{b}	47^{b}	0.68^{a}	83^{b}	2.5^{a}	47.4^{a}
T-test $_{(P<0.05)}$	0.03	0.01	0.40	0.13	0.02	0.00	0.07	0.03	0.08	0.02

† Profile means of each soil property with different letters are significantly different between hydric and non-hydric soil at the 0.05 level.

‡ BulkD - bulk density, pHwater– soil pH in water, pH KCl soil pH by KCl, P – available phosphorus, Fe_d, Mn_d and Al_d are dithionite extractable iron, manganese and aluminium respectively.

Manganese preferentially accumulated in non-hydric soils. Similar observations were made by Fiedler and Sommers (2004) in Inceptisols under a temperate humid climate, who observed higher amounts of Mn_d in well drained soils and lower levels that ranged between 0.11 and 0.48 g Mn_d kg^{-1} in reducing conditions. The low concentration of Mn_d in the hydric soils suggested a loss of Mn to local groundwater flow (McDaniel *et al*., 1992). Bartlett (1986) explained that in well-drained soil profiles secondary Mn can be found at deeper depths than Fe because it remains in a reduced, soluble form longer than Fe, with increasing redox potential.

The significantly higher contents of Mg^{2+} and Na^+ in hydric soils were similarly associated with the fluctuating water table that regulates the availability and mobility of nutrients (Kolka and Thompson, 2006). Brinkman (1970) proposed the term ferrolysis to describe redox reactions in hydromorphic soils. Le Roux *et al*. (2005) associated redoximorphic features observed in E and G horizons in the soil of South Africa to ferrolysis. The repeated cycles of oxidation and reduction of Fe and Mn result in depletions and accumulations of the oxides in different horizons (Le Roux, *et al*., 2005; O'Geen *et al.,* 2007). Ferrolysis also lead to redistribution of other elements, such that during reduction, Fe^{2+} and Mn^{2+} are formed and displace basic cations, which are then leached through lateral flow and accumulate at the depth of leaching (Van Ranst & De Conink, 2002; Le Roux, *et al*., 2005; O'Geen *et al.,* 2007). Fiedler *et al.* (2004) indicated that in hydric soils leaching is expected to be extensive, but the process of lessivage and thus argillic horizon formation is retarded, probably because the soils do not undergo frequent desiccation. The significantly low soil pH in hydric soils (Table 6-2) was associated with H^+ dissociation from organic acids during aerobic phase of ferrolysis (Webster & McLaughlin, 2010).

Soil phosphorus exists in forms of organic P, fixed P, and ortho-P. Transformation of fixed P into soluble ortho-P is controlled by redox. Available P decreased with depth both in hydric and non-hydric soils. Under reduced conditions P is mobilised and accumulates above the water table (Fiedler *et al*., 2004). This is as a result of increased solubility of Fe upon reduction, thereby releasing higher concentrations of adsorbed and precipitated P to the soil solution. In hydric soil the highest P in the surface horizon and Fe_d content was relatively lower (Table 6-2).

The variable concentrations of elements among genetically similar horizons reflected that redistribution of elements is not influenced by weathering alone (McDaniel *et al.* 1992).

Fiedler and Sommers (2004) described the redistribution of the pedogenic oxides of this nature typical of gleyzation processes reflected by development of redoximorphic features.

6.4 CONCLUSIONS

The distribution of dithionite citrate bicarbonate oxides was reflected on the redoximorphic properties suggesting inter pedon translocations due to hydraulic and redox gradients. Presence of grey matrices was marked by relatively low contents of both Fe_d and Mn_d in PW19 while occurrences of redox concentrations were reflected by higher concentrations of Fe_d and Mn_d. However, there was no obvious regular pattern in the distribution of the Fe_d and Mn_d in the profiles. The Mn_d/Fe_d ratio was a good pedochemical indicator to assess redistribution of Fe and Mn in the profile and hence, the soil water regimes. The Mn_d/Fe_d ratio was higher ratios in non-hydric soils reflecting the affinity of Mn to precipitate at higher electron potentials, while lower ratios were observed under hydric soils. The possible losses of Mn to the groundwater table in reduced soils may have led to its lower contents in hydric soils. Iron and Mn oxide distribution was not following any genetic horizon development patterns and their movement was independent of clay movement. Significantly higher Fe_d, Mg^{2+}, Na^{+} contents were observed in hydric soils, while soil pH and Al_d were significantly lower.

CHAPTER 7

SOIL ORGANIC CARBON DISTRIBUTION AND STORAGE IN HYDRIC AND NON-HYDRIC SOILS OF BOKONG.

7.1 INTRODUCTION

The soil is the World's third biggest carbon reservoir (Chesworth, 2004). The soil carbon in the world is estimated at 1500 Gt C, which is three times more than C contained in vegetation (FAO, 2004). In wetland ecosystems, carbon is reserved in peats (Roulet, 2000). Peat is a soil material high in organic C composed of root exudates, microbial byproducts, and dead organic matter at various stages of decay (Webster & McLaughlin, 2010). The prolonged soil water saturation and anaerobic environments are the primary factor affecting organic matter dynamics and most biogeochemical functions in peats (Asada & Warner, 2005). Changes in soil water saturation accompanied by redox gradients may lead to increase in loss of carbon in wetlands (Chesworth, 2004; Yang *et al*., 2010). However, the effect is not direct since it depends also on the response of vegetation and microbes to changes in the water balance yield. Furthermore, the above and below ground allocation of organic matter is a principal factor controlling the carbon balance (Post & Kwon, 2000).

Soil as carbon sinks have different carbon accumulation patterns (Asada & Warner, 2005). Research had tried to quantify the differences in soil organic carbon stock by observing the vertical distribution of organic carbon since they reflect allocations of organic carbon in the soil (Esteban & Jackson, 2000; Chi *et al*., 2010; Yang *et al*., 2010). It is important to understand the vertical patterns of carbon pools of different wetland types which can be used to predict consequences of changing hydrology on carbon sequestration in wetlands. The objectives of this chapter were to evaluate the vertical distribution of soil organic carbon in hydric and non-hydric soils, and to estimate the soil organic carbon stock of Bokong to 1000 mm depth or to the depth of the C horizon.

7.2 VERTICAL DISTRIBUTION OF SOIL ORGANIC CARBON

7.2.1 Hydric soils organic carbon levels

The permanently wet (PW) soils profiles had hydric soil indicators. The soil organic carbon of profile PW32 decreased with depth, while the bulk density increased (Figure 7-1). Results also showed that profile PW32 had significantly higher organic carbon in the surface horizon than the all the subsoil horizons (Figure 7-1). The high organic carbon in the topsoil was associated with partial decomposition of organic material due to anaerobic conditions that slow down the decomposition rate leading to accumulations and formation of peat (SSSA, 1997; Kolka & Thompson, 2006). This is because reduction of Fe and Mn oxides facilitates the anaerobic oxidation of organic matter, which yields less energy for microbial decomposition. The permanently wet (PW) soils had developed peat in the topsoil (SSSA, 1997). The mineral soil underlying the peat had very low carbon content that ranged between 0.5 and 3% (Figure 7-2).

All permanently wet (PW) profiles generally showed vertical distributions of organic carbon and bulk density similar to profile PW32 except for profile PW24, which had higher soil organic carbon levels in the transitional horizon than in the underlying and the overlying horizons (Figure 7-2). The general decreasing trend of organic carbon content in hydric soils with depth was drastic from the topsoil into the subsoil suggesting the accumulation of organic matter from above ground litter and roots and little distribution into the subsoil. The profiles PW06 and PW07 had the highest organic carbon especially in the surface horizon, but it decreases drastically in the subsoil (Figure 7-2). The high organic carbon content may be attributed to the addition of animal manure from livestock grazing since the two wetlands were the only grazed wetlands in the study area.

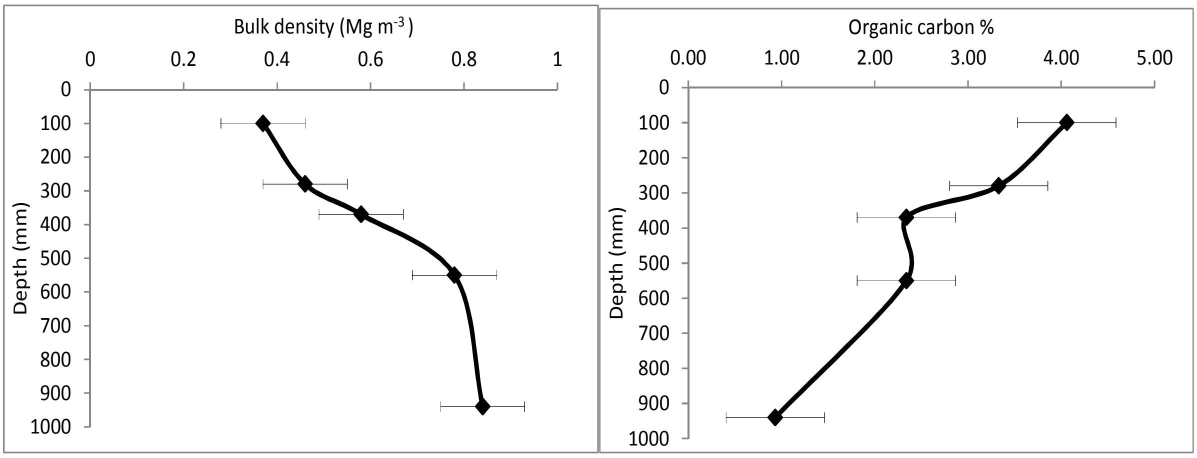
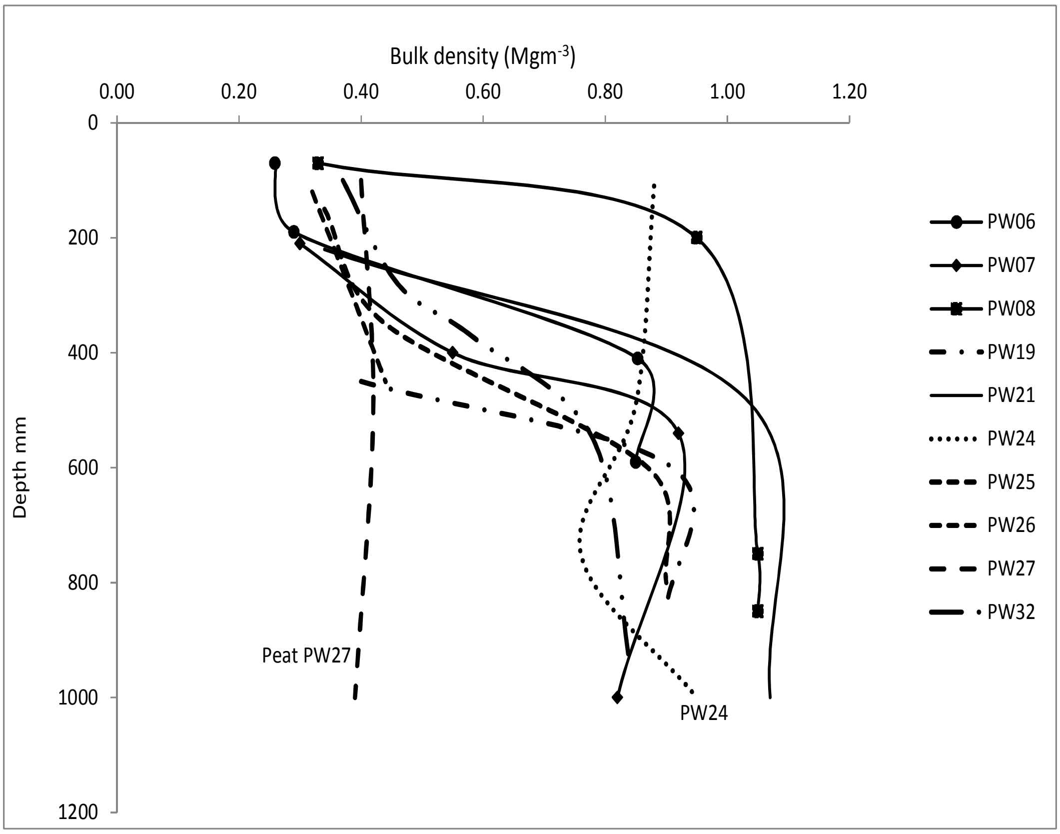


Figure 7-1 Bulk density and soil organic carbon profiles in PW32.



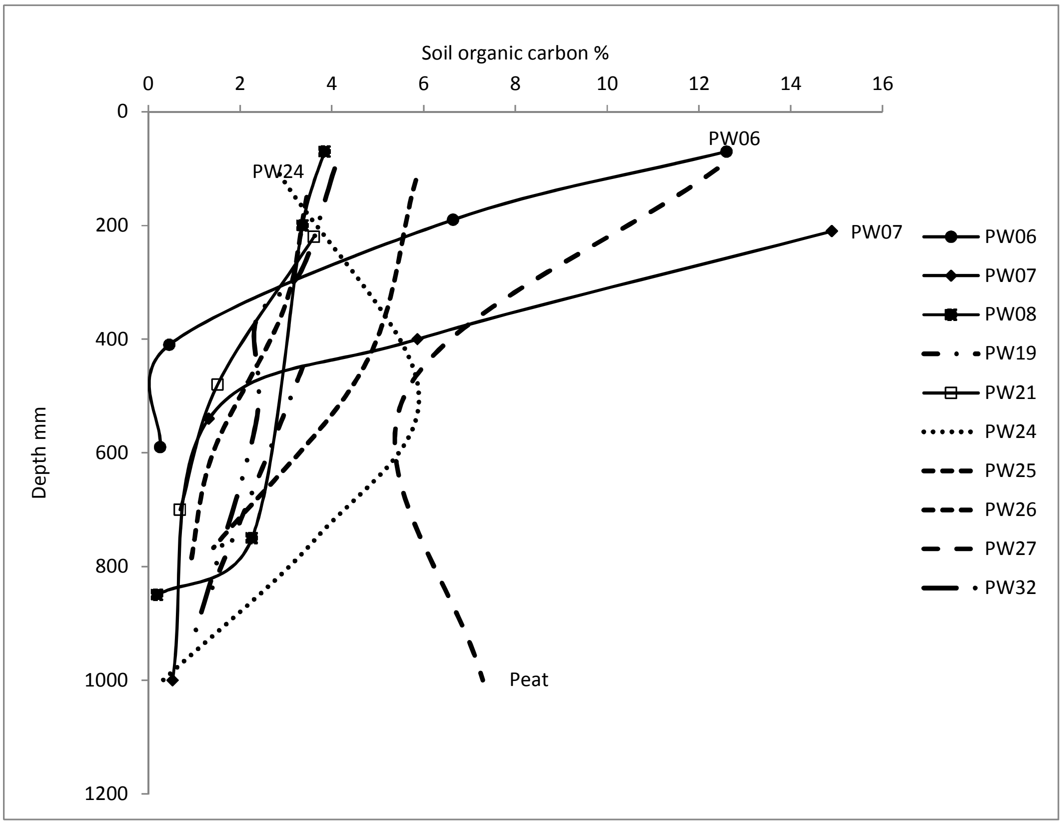


Figure 7-2 Bulk density (Mg m^{-3}) and organic carbon profiles in permanently wet (PW) soils.

7.2.2 Non-hydric soils organic carbon levels

Soil organic carbon steadily decreased with depth in soil profile PD11, while the bulk density decreased (Figure 7-3). Results also showed that soil organic carbon was significantly higher in the top horizon and very low in the subsoil as was the case with the permanently wet soils (Figure 7-3). Similar trends of organic carbon down the profile were observed in other profiles (Figure 7-4). However bulk density distributions gave irregular trends. Higher bulk densities were observed in topsoil horizons than in the underlying horizons of some soils (Figure 7-4). The aboveground or root litter and exudates are responsible for higher accumulations of soil organic carbon input in the topsoil. The low soil organic carbon in the subsoil was attributed to limited root distribution in the subsoil due to massive soil structure (Esteban & Jackson, 2000; Lorenz & Lal, 2005; Rumpel & Knabner, 2011). Rantoa (2009) reported organic carbon content in the master horizons of soils of South Africa ranged between 0.3 in the C horizons and 16% in the O horizon. However, the subsoil organic carbon is about 1.2%. Rantoa (2009) also observed that organic carbon content in these soils is weakly positively correlated with rainfall and aridity index.

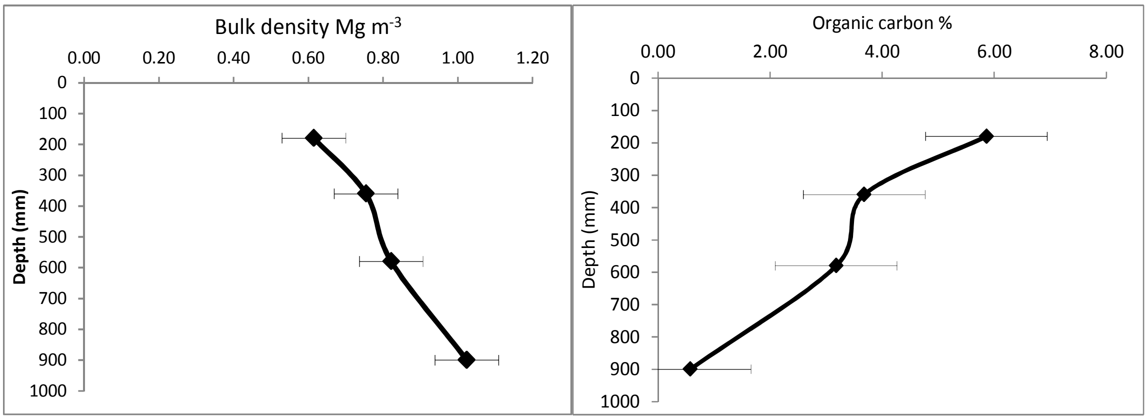


Figure 7-3 Bulk density and organic carbon profiles in PD11.

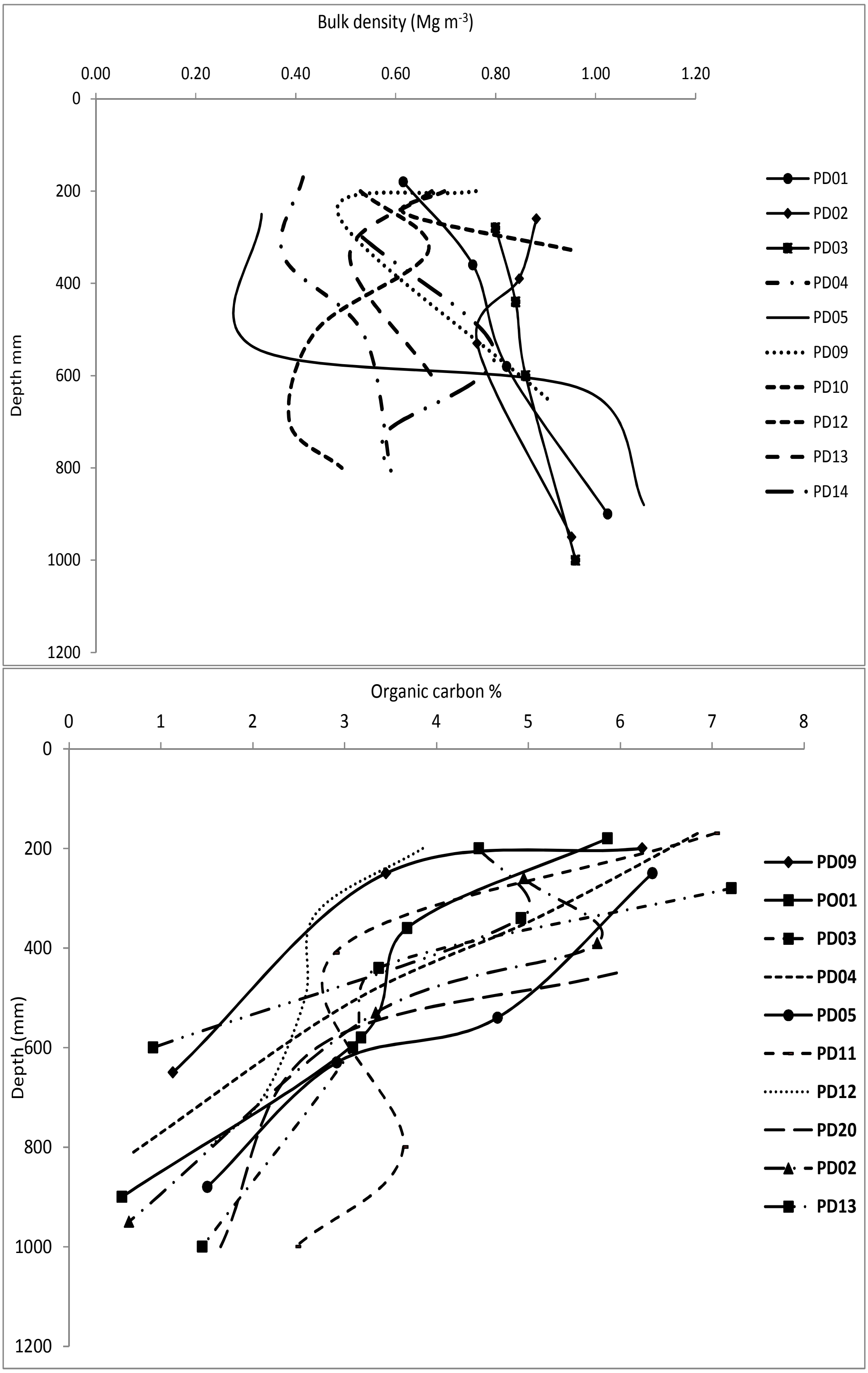


Figure 7-4 Bulk density (Mg m^{-3}) and organic carbon profiles in permanently dry (PD) soil.

7.2.3 Comparison of organic carbon levels between hydric and non-hydric soils.

There was no significant difference in the organic carbon content between permanently wet soils and permanently dry soils (Table 7-1). However, organic carbon was apparently higher in permanently wet soils with higher levels in the topsoil. The transitional horizon of the permanently dry soils showed higher organic carbon levels than the hydric soils (Table 7-1), which was attributed to profile differentiation. Most profiles of the permanently dry soils had AB or BA transitional horizons, while permanently wet soils had distinctly clear different horizon developed below the A horizon, designated as B1 horizons.

Table 7-1 Mean bulk density (Mg m^{-3}) and soil organic carbon content (%) in different horizons of permanently dry and permanently wet soils.

Profiles*	HORIZONS									
	A1		A2		AB/BA/B1		B/B2/AC		Profile	
	BD	OC	BD	OC	BD	OC	BD	OC	BD	OC
	Mg m^{-3}	%	Mg m^{-3}	%	Mg m^{-3}	%	Mg m^{-3}	%	Mg m^{-3}	%
PD01	0.62	5.86	0.75	3.68	0.82	3.18	1.02	0.58	0.80	3.33
PD02	0.88	4.95	0.85	5.75	0.76	3.34	0.95	0.65	0.86	3.67
PD03	0.80	7.21	0.84	3.37	0.86	3.09	0.96	1.45	0.87	3.78
PD04	0.41	6.84	0.38	5.09	0.54	3.06	0.59	0.70	0.48	3.92
PD05	0.33	6.35	0.32	4.67	0.97	2.92	1.10	1.51	0.68	3.86
PD09	0.76	6.24	0.48	3.45	‡‡	‡‡	0.90	1.13	0.71	3.61
PD10	0.70	3.65	0.62	2.52	‡‡	‡‡	0.96	2.06	0.76	2.74
PD11	0.57	7.03	0.65	2.89	1.01	3.64	0.72	2.47	0.74	4.01
PD12	0.53	3.85	0.67	2.69	0.44	2.57	0.44	1.82	0.52	2.73
PD13	0.67	4.46	‡‡	‡‡	0.51	4.92	0.67	0.91	0.62	3.43
PD14	0.53	4.53	0.80	1.06	0.58	1.06	0.58	0.31	0.62	1.74
PD16	0.61	7.40	0.71	3.38	‡‡	‡‡	0.70	0.18	0.67	3.65
PD20	0.72	5.96	‡‡	‡‡	0.73	2.70	0.63	1.65	0.69	3.44
PD mean	0.63^{a}	**5.72^{a}**	0.64^{a}	**3.50^{a}**	0.72^{a}	**3.05^{a}**	0.79^{a}	**1.19^{a}**	0.69^{a}	3.38^{a}
PW06	0.26	12.60	0.29	6.64	0.85	0.46	0.85	0.26	0.56	4.99
PW07	0.30	14.90	0.55	5.87	0.92	1.32	0.82	0.53	0.65	5.66
PW08	0.33	3.84	0.95	3.36	1.05	2.26	1.05	0.19	0.85	2.41
PW19	0.40	3.36	‡‡	‡‡	0.91	2.62	0.90	1.33	0.74	2.44
PW21	0.34	3.61	1.03	1.51	2.60	1.51	1.07	0.69	1.26	1.83
PW24	0.88	2.86	0.85	5.89	0.76	3.66	0.95	0.32	0.86	3.18
PW25	0.34	3.45	0.44	2.94	0.87	1.41	0.90	0.91	0.64	2.18
PW26	0.32	5.83	0.44	4.69	‡‡	‡‡	1.08	1.42	0.61	3.98
PW27	0.40	12.40	0.42	5.58	‡‡	‡‡	0.39	7.29	0.40	8.42
PW32	0.37	4.06	0.46	3.33	0.68	2.34	0.84	0.93	0.59	2.67
PW mean	0.39^{b}	**6.69^{a}**	0.60^{a}	**4.42^{a}**	1.08^{a}	**1.95^{a}**	0.86^{a}	**1.39^{a}**	0.73^{a}	3.61^{a}
t-test (P>0.05)	0.003	0.479	0.702	0.190	0.109	0.084	0.285	0.687	0.79	0.56

† The means of PD and PW under each parameter and horizon followed by the same letter are not significantly different according to t- test (P >0.05).
‡ Profiles*: PD permanently dry soils PW permanently wet soils; BD bulk density; OC – organic carbon
†† PD 12 and PW32 had three horizons in the topsoil (A1, A2 and A3) and A3 BD and OC were added to A2 to enable comparison with other profiles to be done.
‡‡ Profiles with missing data did not have the designated horizons.

The bulk density was significantly lower in the A1 horizon of permanently wet soils (Table 7-1; 0.39 Mg m^{-3}). This was attributed to the development of peat (SSSA, 1997) in the top surface layer of most permanently wet soils. Marneweck and Grundling (1999) reported the peat Von Post Humification scale of peat of Bokong wetlands between 6 and 8 in the top 600 mm of the soil surface and 4 within the 1000 mm depth. Verry *et al*. (2011) reviewed the correlations between bulk density and Von Post Humufication and observed comparable high correlations between different studies. According to Paivanen (1969) the bulk density associated with 4 to 8 Von Post Humification scale values in bogs range between 0.10 and 0.15 Mg m^{-3}. Wellock *et al*. (2011) also reported mean bulk density of 0.13 Mg m^{-3} for raised bogs peat in Ireland.

7.3 SOIL CARBON STOCK

7.3.1 Soil organic carbon stock in hydric and non-hydric soils

The bulk density and the thickness of a horizon affect the amount of organic carbon stored in a horizon (Brahim *et al*., 2010). Hence the estimation of soil organic carbon (SOC) stock requires knowledge of the vertical distribution of bulk density, OC, and horizon thickness in profiles. Total carbon percentage was multiplied by the bulk density and thickness of each soil horizon to get horizon carbon mass (C_{hor}). All horizons carbon mass in one profile were added to provide an estimate of the mass of carbon stored (kg C m^{-2}) in the entire soil profile. The profile carbon mass (C_{mass}) is a measure of the carbon stored in 1 m^2 area to the depth of the entire soil profile (Eswaran *et al.,* 2000; Brahim *et al*., 2010) given in the equation as:

$$SOC = \sum_{i=1}^{n} D_b \, iC_i \, D_i \tag{7-1}$$

Where SOC is the soil organic carbon stock (kg C m^{-2}), D_b is the bulk density (Mg m^{-3}) of a horizon i, C_i is the proportion of organic carbon (g C g^{-1}) in horizon i and D_i is the thickness of this horizon (cm). The SOC density was multiplied by area to estimate SOC storage of the study area.

The soil carbon stock estimated in this study were from the primary field data obtained from the detailed soil survey. The mean SOC density of the study area was 166±78.3 Mg C ha^{-1} (Table 7-2) or (16.6±7.83 kg C m^{-2}). The estimated soil carbon density in this study was comparable with other studies on similar soils. Lal (2004) reports the soil organic carbon density in Inceptisols were 148 Mg C $ha^{-1}$and 1170 Mg C ha^{-1}in Histisols (adapted from Eswaran *et al*., 2000). While the estimates of soil organic carbon densities from temperate grassland are between 141 and 236 Mg C ha^{-1} (adapted and recalculated from Watson *et al*., 2000; Prentice, 2001).

This was consistent with the calculations by Esteban and Jackson (2000), who estimated the global soil organic carbon content in temperate grasslands between 0 to 1000 mm depth at 11.7 kg C m^{-2} with a standard deviation of 6.6. Brahim *et al.* (2010) calculated the carbon stock of Tunisia with the highest densities observed under Luvisols with densities of 15.92 kg C m^{-2} in 0-1000 mm depth. They compared their data with Batjes (1996), who derived worldwide mean carbon stock from Regosols, Vertisols and Cambisols for 1-1000 mm depth of 9.6, 11.1 and 9.6 kg C m^{-2} respectively. The default reference soil organic carbon stock (SOC_{REF}) under native vegetation in cold temperate moist Umbrisols/Inceptisols is 95 Mg C ha^{-1} for the top 300 mm depth (Watson *et al*., 2000). The mean profile soil carbon density in permanently dry soils soils of the study area was 174.4±77 Mg C ha^{-1}, while in permanently wet soils soils was 155.1±83 Mg C ha^{-1} (Table 7-2). Soil organic carbon density vary amongst soil profiles which was to some extent attributed to the shallow soil depth in many profiles, low bulk density due to high soil aggregation and the effect of soil water content, which affects the vegetation and activity of microbes in the soils.

The estimated carbon stored was 21619 Mg C (0.022 Tg C; 1Tg = 10^{12}g) within the 1000 mm soil depth. About 384.9 Mg C is stored in the wetlands soils within the study area, which is about 1.9% of the total carbon stored within 1300 ha to the depth of 1000 mm. Wiesmeier *et al.* (2012) reported the highest amount of soil organic carbon with a median value of 11.8 kg m^{-2} in grasslands and considerably lower stocks of 9.8 and 9.0 kg m^{-2} in forest and cropland soils, respectively from southeast Germany. Wiesmeier *et al.* (2012) associated the higher soil organic carbon stocks in grassland to the accumulation of organic carbon in the B horizon which was attributable to a high proportion of carbon rich Gleysols. Rantoa (2009) also reported the soil organic carbon stocks from 27 land cover classes of the soils of South Africa to range between 9 Mg ha^{-1} in barren rock to 120.2 Mg ha^{-1} in forest plantations and the total organic carbon storage of 8.99 ± 0.10 Pg calculated to a depth of 0.30 m, which was associated with 0.59% of global soil organic carbon.

The depth distribution of soil organic carbon stocks showed that despite the lower organic carbon concentrations in the A horizons of non-hydric soils, their stocks were considerably higher compared with hydric soils (Table 7-2). This was due to a deepening of the topsoil. Wiesmeier *et al.* (2012) emphasised the importance of determination of soil organic carbon stocks by horizon for the entire soil profile to incorporate the effect of pedogenic soil organic carbon. They felt that the soil organic carbon stocks in hydric soils maybe overestimated since most studies use fixed depth increments to estimate organic carbon sequestration or emission potential from soils.

Table 7-2 Soil organic carbon density (Mg C ha^{-1}) per horizon in each profile

		Horizons				
Profiles	(0-20 cm)	A1	A2	AB/BA/B1	B/B2/AC	Total
	---------------------------------------Mg C ha^{-1}---					
PD01	72	65	50	57	19	191.2
PD02	87	113	63	36	26	238.5
PD03	115	162	45	43	56	305.0
PD04	57	48	32	28	12	120.9
PD05	42	53	43	26	41	162.6
PD09	65	95	‡‡	8	41	146.1
PD10	89	51	‡‡	8	16	74.6
PD11	25	68	45	144	36	292.1
PD12	95	41	23	35	8	107.2
PD13	51	60	35	‡‡	16	110.9
PD14	80	72	21	11	2	105.8
PD16	41	135	12	1	-	148.1
PD20	60	193	‡‡	29	42	264.1
PD Means	68	89	37	36	26	**174.4**
PW06	48	23	23	9	4	58.5
PW07	90	94	61	17	20	192.2
PW08	27	9	41	131	2	182.9
PW19	86	60	‡‡	36	30	126.2
PW21	25	27	22	34	22	105.1
PW24	50	28	190	72	8	297.9
PW25	23	18	26	31	16	90.5
PW26	37	22	68	‡‡	‡‡	90.5
PW27	99	50	94	142	15	285.5
PW32	30	13	28	16	64	121.6
PW Means	52	35	61	54	20	**155.1**
Grand means	61	65.3	48.5	43.5	23.6	**166.3**
Std dev.	28	47.9	39.7	43.4	17.4	78.3
Max	115	193	190	144	64	305
Min	23	9	12	1	2	58.5
% contributed	**33.5**	**36.1**	**26.8**	**24.0**	**13.1**	

†Profiles*: PD permanently dry soils PW permanently wet soils

‡BD bulk density; OC – organic carbon

†† PD 12 and PW32 had three horizons in the topsoil (A1, A2 and A3) and A3 BD and OC were added to A2 to enable comparison with other profiles to be done.

‡‡ Profiles with missing data did not have those horizons.

7.3.2 Soil organic carbon stock in different horizons

About 36% of soil oragnic carbon was stored in the surface horizon (A1) and about 33% was stored in the top 200 mm (Table 7-2). The results were comparable with Esteban and Jackson (2000), who reported 40% of soil oragnic carbon distribution in the top layer of 0-200 mm. This is also in agreement with Batjes (2002) who reported that 44% of the global soil organic carbon pool is held in the top 300 mm of the soil. Nevertheless, the topsoil is most prone to changes in land use and soil management (Post *et al*., 2000; Batjes, 2002; Ghimire *et al*., 2011; Bu *et al*. 2011). Land use and management impact on soil structural formation and soil organic carbon storage (Han *et al*., 2010). Occlusion of soil organic carbon within soil aggregates also preserves it in soil.

The t-test indicated that there is no significant difference in soil organic carbon storage between topsoil horizons and transitional horizons; however the A1-horizon was significantly different from B/B2/AC horizons (Table 7-3). The low soil organic carbon in the subsoil is stable compared to topsoil soil organic carbon. Rumpel and Knabner (2011) indicated that the type of soil organic carbon in the subsoil is enriched in microbial-derived C compounds and depleted in energy-rich plant material, and it is characterised by high mean residence times of up to several thousand years. Rumpel and Knabner (2011) also observed the possible stabilization mechanism of soil organic carbon in the subsoil through amorphous iron and aluminium oxides. The decomposition of subsoil C could only occur by disrupting the physical structure and adding nutrient supply to soil microorganisms (Han *et al*., 2010; Ghimire *et al*., 2011).

Table 7-3 Means comparison of soil organic carbon (SOC) density in different horizons.

Paired horizons	SOC density means		t-test $_{(\alpha = 0.05)}$
	----------Mg C ha^{-1}-----------		
A1 and A2	65.3	48.5	ns
A1 and AB/BA/B1	65.3	43.5	ns
A1 and B/B2/AC	65.3	23.6	**
A2 and AB/BA/B1	48.5	43.5	ns
A2 and B/B2/AC	48.5	23.6	ns
AB/BA/B1 and B/B2/AC	43.5	23.6	ns

** Significant at the 0.05 probability level
ns - non-significant at the 0.05 probability level

7.4 DISTRIBUTION OF SOIL ORGANIC CARBON IN DIFFERENT WETLAND TYPES.

Soil organic carbon levels, total N and C mass were significantly different between wetland types with the significantly higher accumulations in the bogs (Table 7-4). The Bogs stored the highest carbon in the soil (179 Mg C ha^{-1}) of which at least 44% was stored in the A1 horizon (Figure 7-5). This was expected since the higher organic carbon content of bogs differentiates them from fens since the fens represent an earlier successional stage of peat accumulation. Wellock *et al*. (2011) reported 1160 ± 520 Mg C ha^{-1} for raised bog peat in Ireland with the mean bulk density of 0.13 Mg m^{-3} and mean organic carbon levels of 46%.

The hillslope seeps and the valley head fens stored the same amount of carbon (Table 7-4). This indicates that the formation of hillslope seeps and resulting characteristics are comparable with the fens. Marneweck and Grundling (1999) indicated that hillslope seeps are formed due to presence of an impermeable layer causing lateral flow that either seeps out the sloping land surface or accumulate in concave slopes forming a perched aquifer (Marneweck & Grundling, 1999). The size of hillslope seeps depends on the quantity of groundwater discharge and the slope of land surface down the seepage area. Large hillslope seeps develop into valley head fens. The valley head fens are the dominant type of wetland in Bokong.

The C/N ratio was not significantly different between the wetland types (Table 7-4). This suggested that wetlands receive a similar quality of decomposable material (Webster & McLaughlin, 2010). Schwabe (1995) observed that both bogs and fens of the Maloti Mountains have the same type of vegetation species. However, the C/N ratio was significantly different between horizons. The significant decrease in soil organic carbon levels between horizons could explain the observed significant differences in C/N ratio. The decline in C/N ratio means a decrease in dissolved organic carbon flux from watersheds, hence C/N ratio is used as a site quality indicator or NO_3^- is preferentially leached (Aitkenhead & McDowell, 2000).

C/N ratio also showed highest CV (Table 7-4). The highest variation in C/N ratio (CV = 61%) suggested that the C/N ratio can readily change with change in land use or management. Studies use C/N ratio as an indicators which can change over a short period such as one year of land use change (Aitkenhead & McDowell, 2000; Vranová, 2007). Vranová (2000) suggested that short term management do not have sufficient time to effect the change in organic carbon in the soil but C/N can indicate such a change.

Table 7-4 Soil organic carbon pools in different wetland types in Bokong

Wetland type	n	SOC	Total N	C/N ratio	C-mass
		---------------%-------------			(kg C m^{-2})
Bogs	11	6.17a	0.89a	6.3a	179a
Valley head fens	19	3.02b	0.52b	6.6a	141b
Hillslope seeps	13	2.85b	0.40b	6.6a	154b
		Analysis of Variance			
Sources of variation	df				
Wetland type	2	*	*	ns	*
Depth	3	*	ns	*	*
CV%		41	25	61	31

*Significant at the 0.05 probability level

ns, non-significant at the 0.05 probability level

† Within columns, means followed by the same letter are not significantly different according to Duncan multiple range test (0.05).

‡ n = number of samples, SOC = soil organic carbon, C/N ratio = Carbon/Nitrogen ratio, C-mass = amount of carbon stored, df = degrees of freedom, CV% = coefficient of variation.

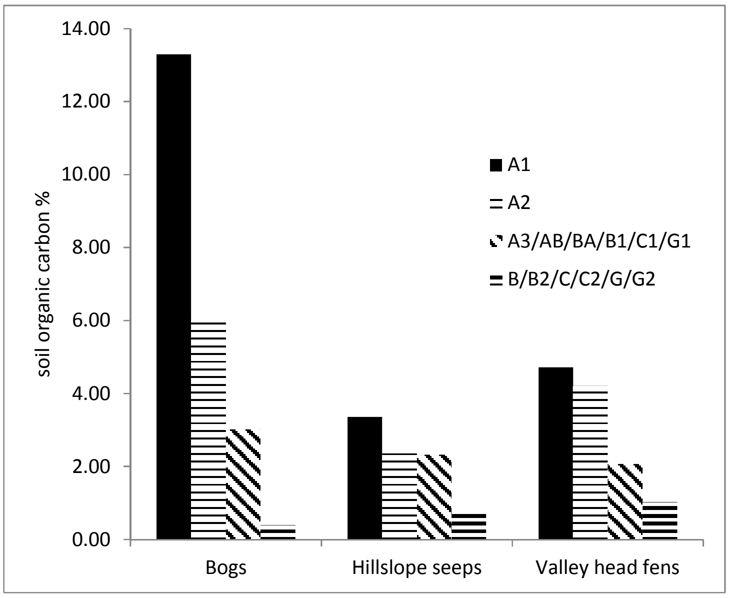


Figure 7-5 Soil organic carbon profiles in different wetland types of Bokong

7.5 CONCLUSIONS

Soil water saturation affected the patterns of organic carbon in the soil. Higher organic carbon contents were observed in hydric soils (3.61%) than in that of non-hydric soils (3.38%). However, the influence of soil water saturation in the sequestration of organic carbon was not evident since non-hydric soils had apparently higher amounts of carbon stored than hydric soils. The high organic carbon stock observed in the non-hydric soil was attributed to the deeper topsoil and higher bulk densities, hence deeper distribution of organic carbon. Furthermore, the stock of organic carbon present in natural soils represents a dynamic balance between the input of dead plant material and loss from decomposition and the lower organic carbon storage in hydric could be due to low inputs of the plant material because of generally low productivity of wetlands soils.

Furthermore, research highlighted the role of soil water saturation in regulating the decomposition of organic matter in different wetland types. Bogs stored more soil carbon than other wetland types and 44% was distributed in the topsoil, while the valley head fens and hillslope seeps stored same amount of soil organic carbon. This indicated the importance of hillslope seeps which may be regarded as minor wetlands yet their ecological role is still comparably significant as valley head fens.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

Wetlands are areas with high water table at or near the soil surface long enough to develop anaerobic conditions. The duration and frequency at which the water table resides near the soil surface is called wetland hydrology. The presence of the water table must be accompanied by anaerobic conditions for the area to have functions of a wetland. The area that has a wetland hydrology is supposed to have hydric soils and supports wetland vegetation. Therefore, hydric soil may be used to infer the existence of a wetland. Hydric soils are identified in the field using hydric soil indicators, which are morphological features of specific thickness and abundance that reflect different soil water regimes. The differences in soil properties and climate in different landscapes affect the direct use morphological features to interpret soil water regime. Therefore, the established relationship between soil saturation and development of redoximorphic features is required if soil survey interpretations are to be used in hydric soil and wetland hydrology determinations. The aims of this study were to determine the variation in soil properties and hydric soil indicators along the toposequence, and determine the relationships between soil redoximorphic features, soil properties redistribution and organic carbon accumulation with hydrology.

The main factors of variability in soil properties in small catchments with uniform geology are the microclimate and the topography, hence variability was determined between topographic units along a toposequence named slope positions. Soil pH, soil texture, bulk density and CEC were relatively stable properties. Summits had coarser texture and higher bulk density. The valleys had relatively lower pH and CEC and significantly low bulk density. The lower pH in the valleys could be due to ferrolysis that releases H^+ and lowers pH and reduces CEC. The principal component analysis (PCA) showed that dynamic soil properties especially those related to organic matter inputs and inherent fertility, acidity and textural variation are important for management of the site. The four factors can be used to group soils into homogenous units that could be subjected to the same use or management.

Two systems that tried to develop the relationship between hydric soils and wetland hydrology were reviewed. Kotze *et al*. (1996) summarised hydric soil indicators observed in the three soil water regime classes for wetlands soils of South Africa. USDA-NRCS (2010) has developed more site specific hydric soil indicators for United States. The indicators of the two systems were used as reference to develop relevant indicators for the wetlands of

Lesotho. Seven hydric indicators were identified and described. The depletions and loamy gley matrix (A12 and F7) occurred in the valleys, while the midslopes and footslopes were dominated by umbric surfaces (A13). Indicators that were related to the peat formation were frequently observed. Therefore, further characterisation of peat to develop more hydric indicators is important.

Galusky *et al* (1998) developed redoximorphic indices and many other indices mostly developed for waste water treatment were used to determine the relationship between hydric soil indicators and the current soil water regimes. Strong correlations were observed between the depth to the gleyed matrix (*d_gley*) and depth to chroma 3 and 4 (*d_34*) and cumulative saturation. The profile darkening index (PDI) correlated with both water table characteristics. Therefore, field indicators such as histisols, histic epipedon, umbric surfaces represented by PDI, and thick dark surfaces and loamy gleyed matrix represented by *d_34* and *d_gley* were verified to be representing the current wetland hydrology and can be used to delineate wetlands.

The statistical difference between dithionite citrate bicarbonate extractable Fe, Mn and Al and selected soil properties for hydric and non-hydric soils were determined using t-test. Significantly higher Fe_d, Mg^{2+}, Na^+ contents were observed in hydric soils and lower soil pH and Al_d and apparently lower Mn_d. The solubility of Fe under anaerobic conditions resulted into mobility of Fe^{2+} and accumulation within the profile due to alternating redox conditions. The Fe^{2+} was not lost from profile such as with Mn^{2+}. The ecological implication of this is that Fe oxide is effective in adsorbing anions such as phosphate and this may result in lower release of available P into the water bodies. Iron and Mn oxide distribution did not follow genetic horizon development patterns and their movement was more controlled by fluctuating water regimes since more of the oxides were observed where redox concentrations were in abundance in the profile.

Higher organic carbon levels and lower organic carbon stock observed in the hydric soil compared with non-hydric soils may be due to lower the organic carbon input in hydric soil. Hence, the hydric soil may be subjected to a different use or management from non-hydric soil. Among wetland types, bogs stored more soil carbon than the valley head fens and hillslope seeps as was expected. The hillslopes seeps were also comparably providing significant ecological function as valley head fens in terms of storing carbon.

8.2 RECOMMENDATIONS

The following recommendations were made:

- Wetlands and their delineation for management purposes is a topic of considerable importance worldwide as land for building, agriculture and other conflicting uses become scarce. This study added to the body of knowledge by exploring methods in which morphological properties can be verified for use in delineating wetlands. Through such methodologies, wetland hydrology criteria for different uses can be developed.
- The two international systems (FAO, 2006 and Soil Survey Staff, 2010) satisfactorily classified hydric soils of Bokong, suggesting the two systems can be used in conjunction with hydric soils delineation tools to reduce time of onsite investigations.
- Future research focus should be on verifying and adding more soil indicators within the mountain ecosystems to develop hydrologic criteria that will be used to delineate the mountain wetlands.
- Further characterisation of peat to develop more hydric indicators is important.
- The study encountered much challenges to generate continuous hydrologic measurements using data loggers, such that discontinuous data was obtained. More robust methods should be explored for longer term monitoring. Such methods may improve the relationships observed between redoximorphic features and soil water characteristics.

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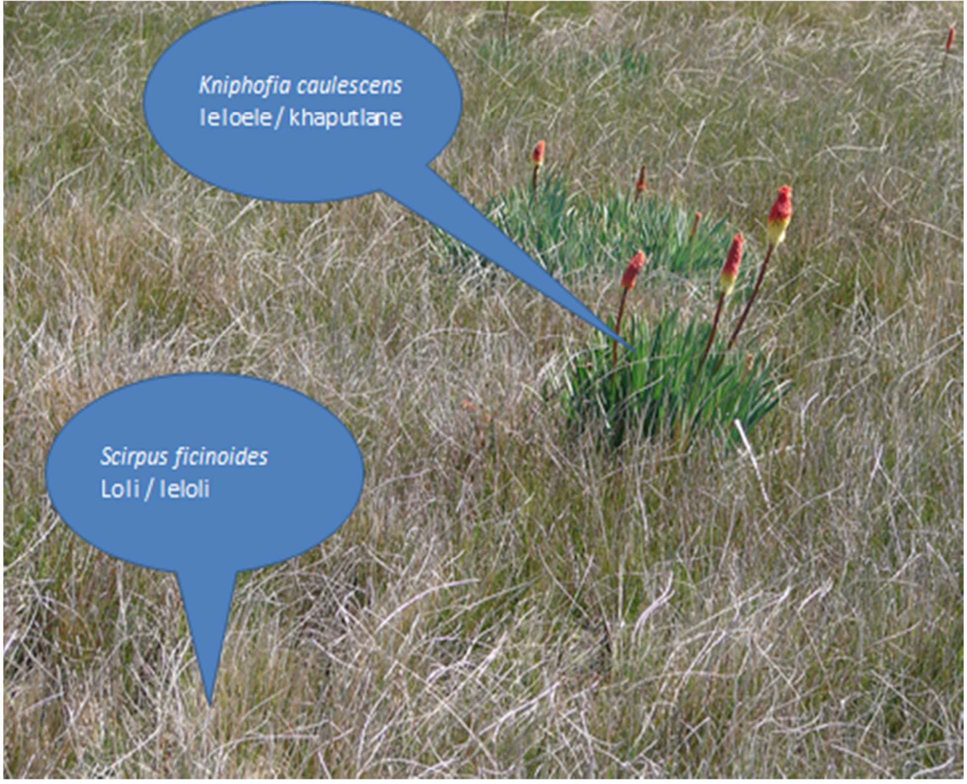
APPENDICES

APPENDIX 1: WETLAND SPECIES OF BOKONG

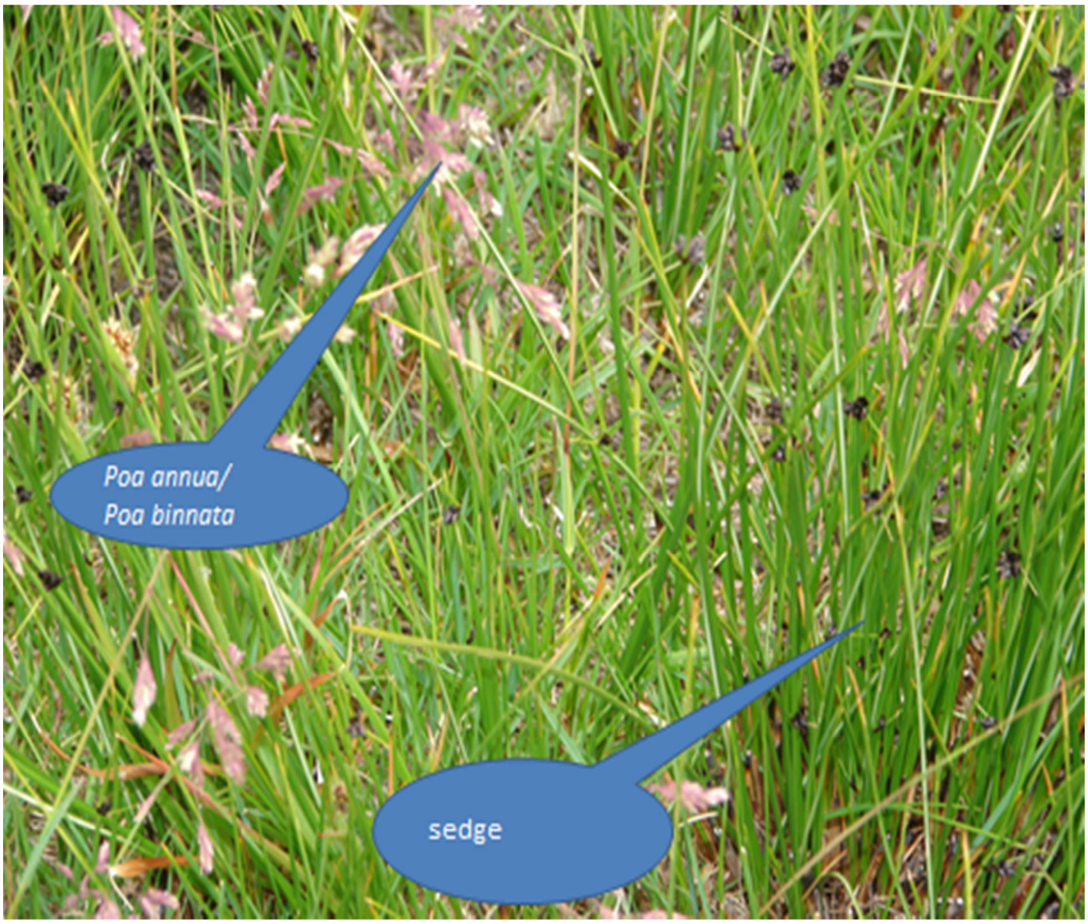



Poa annua/
Poa binnata


Carex cognata
lesuoane


Eumorphia sericea


Merxmuellera macowanii


Poa annua/
Poa binnata
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APPENDIX 2A: SOIL PROFILES DESCRIPTIONS

SOIL PROFILE: PD01

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 5' 14.58" S/ 28° 25' 36.42"E	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2903 m	**Wind erosion:**	None
Terrain Unit:	Footslopes	**Water Erosion:**	Rill moderate, partially stabilized
Slope:	18%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Straight/Concave	**Water table:**	None
Aspect:	North-west	**Described by:**	B.E. Mapeshoane
Micro-relief:	Dongas 1.0 m deep, 20% coverage, profile between features	**Date described:**	06/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 180	Moist state; dry colour: very dark grey 10YR3/1; moist colour: black 10YR2/1; structure: strong coarse granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, few medium & coarse normal pores; very few mixed gravel 2-6mm; many roots;	Melanic A
A2	180 - 360	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: black 10YR2/1. Structure: strong coarse granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, few medium & coarse normal pores; many mixed-shape gravel 2-6mm; many roots; gradual smooth transition.	Melanic A
AB	360 - 580	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: dark brown 10YR3/3. Structure: strong coarse granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, few medium & coarse normal pores; many mixed-shape gravel 2-6mm; common rounded stones 25-75mm; common roots; clear	Non-diagnostic yellow-brown apedal B
B	580 - 900	Moist state; dry colour: yellowish brown 10YR5/4; moist colour: strong brown 7.5YR4/6. Structure: moderate medium sub-angular blocky; consistence: friable, non-sticky, non- plastic; many fine normal pores, few medium & coarse normal pores; many mixed-shape gravel 2-6mm; common rounded coarse gravel 6-25mm; few roots; parent rock.	Non-diagnostic yellow-brown apedal B

SOIL PROFILE: PD02

Map/photo:	2928AB
Latitude + Longitude:	29° 5' 12.48''S / 28° 25' 46.14''E
Surface stoniness:	None
Altitude:	2976 m
Terrain Unit:	Midslopes
Slope:	41%
Slope Shape:	Convex
Aspect:	South-west
Micro-relief:	None
Parent Material Solum:	Origin single, solid rock
Underlying Material:	Basalt

Soil form:	Inhoek
Surface rockiness:	2-10% exposed surface
Occurrence of flooding:	None
Wind erosion:	None
Water Erosion:	Rill slight, stabilized
Vegetation / Land use:	Grassveld, open
Water table:	650 mm
Described by:	B.E. Mapeshoane
Date described:	06/2009
Weathering of underlying material:	Advanced physical, strong chemical
Alteration of underlying material:	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 260	Moist state; dry colour very dark grey 10YR3/1; moist colour: black 10YR2/1; structure: strong coarse granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, few medium & coarse normal pores; very few rounded gravel 2-6mm; many roots;	Melanic A
A2	260 - 390	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: very dark brown 10YR2/2; structure: strong medium granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, few medium & coarse normal pores; common rounded gravel 2-6mm; many roots; clear smooth transition	Melanic A
AB	390 - 530	Wet state; dry colour: dark greyish brown 10YR4/2; moist colour: dark brown 10YR3/3; structure: moderate coarse granular; consistence: friable, non-sticky, non-plastic; many fine rusty streaked pores, common medium & coarse rusty streaked pores; common rounded gravel 2-6mm; common angular coarse stones 75-250mm; stoneline multiple occurrence, throughout horizon; many roots; clear smooth transition.	Non-diagnostic yellow-brown apedal B
B	530 - 950	Wet state; dry colour: yellowish brown 10YR5/4; moist colour: dark yellowish brown 10YR4/6; structure: apedal massive; consistence: friable, non-sticky, non-plastic; few fine normal pores, few medium & coarse normal pores; few rounded gravel 2-6mm; few rounded stones 25-75mm; weathered remnants of stones multiple occurrence, throughout horizon; parent rock	Non-diagnostic yellow-brown apedal B

SOIL PROFILE: PD03

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 5' 26.76"S / 28° 25' 49.92"E	**Surface rockiness:**	None
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2961 m	**Wind erosion:**	None
Terrain Unit:	Summits	**Water Erosion:**	Rill slight, stabilized
Slope:	11%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Straight	**Water table:**	610 mm
Aspect:	North-west	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	7/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0- 280	Moist state; dry colour very dark grey 10YR3/1; moist colour: black 10YR2/1; structure: strong coarse granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, few medium & coarse normal pores; many roots; diffuse smooth transition	Orthic/Melanic A
A2	280 - 440	Moist state; dry colour very dark grey 10YR3/1; moist colour: very dark greyish brown 10YR3/2; structure: moderate; many fine normal pores, few medium &coarse normal pores; common rounded gravel 2-6mm; many roots; abrupt smooth transition.	Melanic A
AB	400 - 600	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: dark brown 10YR3/3; structure: moderate coarse granular; consistence: friable, non-sticky, non-plastic; many fine rusty streaked pores, common medium & coarse rusty streaked pores; common rounded gravel 2-6mm; common angular coarse stones 75-250mm; stoneline multiple occurrence, throughout horizon; many roots; clear smooth transition	Non-diagnostic yellow-brown apedal B
BC	600 - 1000	Wet state dry colour: yellowish brown 10YR5/6; moist colour: dark yellowish brown 10YR4/6; many fine normal pores, few medium & coarse normal pores; common rounded gravel 2-6mm; common angular boulders >250mm; stoneline single occurrence, throughout horizon; common roots, transition not observed.	Non-diagnostic yellow-brown apedal B

SOIL PROFILE: PD04

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 5' 30.18"S / 28° 25' 51.66"E	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	Occasional
Altitude:	2977 m	**Wind erosion:**	None
Terrain Unit:	Midslopes	**Water Erosion:**	Rill slight, stabilized
Slope:	21%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	600 mm
Aspect:	North	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	7/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 170	Wet state; dry colour very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; structure: strong coarse granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, common medium & coarse normal pores; many roots; diffuse smooth transition.	Melanic A
A2	170 - 340	Wet state; dry colour very dark greyish brown 10YR3/2; moist colour: very dark brown 10YR2/2; structure: strong coarse granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, common medium & coarse normal pores; very few rounded gravel 2-6mm; many roots; diffuse smooth transition	Orthic/Melanic A
A3	340 - 510	Wet state; dry colour very dark grey 10YR3/1; moist colour: very dark greyish brown 10YR3/2; structure: moderate coarse granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, common medium & coarse normal pores; common rounded gravel 2-6mm; few rounded stones 25-75mm; stoneline single occurrence, middle part of horizon; many roots; clear smooth transition.	Melanic A
B	510 - 810	Wet state; dry colour: brown to dark brown 10YR4/3; moist colour: dark yellowish brown 10YR3/4; structure: apedal massive; consistence: slightly firm, non-sticky, non-plastic; common fine normal pores, few medium & coarse normal pores; few rounded gravel 2-6mm; few roots; parent rock.	Non-diagnostic yellow-brown apedal B

SOIL PROFILE: PD05

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 5' 10.44"S / 28° 25' 28.38"E	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2860 m	**Wind erosion:**	None
Terrain Unit:	Footslopes	**Water Erosion:**	Rill slight, stabilized
Slope:	22%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	620 mm
Aspect:	West	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	7/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 250	Moist state; dry colour very dark grey 10YR3/1; moist colour: black 10YR2/1; structure: strong coarse granular; consistence; friable, non-sticky, non-plastic; many fine normal pores, common medium & coarse normal pores; very few rounded gravel 2-6mm; many roots; diffuse smooth transition.	Melanic A
A2	250 - 540	Moist state; dry colour very dark grey 10YR3/1; moist colour: black 10YR2/1; structure: strong coarse granular; consistence; loose, non-sticky, non-plastic; many fine normal pores, common medium & coarse normal pores; few rounded gravel 2-6mm; common angular coarse stones 75-250mm; stoneline 120mm, single occurrence, middle part of horizon; many roots; diffuse smooth transition.	Melanic A
B1	540 - 630	Moist state; dry colour dark brown 10YR3/3; moist colour: dark yellowish brown 10YR3/4; structure: strong medium sub-angular blocky; consistence; slightly firm, slightly sticky, slightly plastic; many fine normal pores, few medium & coarse normal pores; few rounded gravel 2-6mm; common roots; clear smooth transition	Non-diagnostic Yellow-brown apedal
B2	630 - 880	Wet state; dry colour: brown to dark brown 10YR4/3; moist colour: dark yellowish brown 10YR3/6; structure: strong medium sub-angular blocky; consistence; slightly firm, slightly sticky, slightly plastic; many fine normal pores, few medium & coarse normal pores; many rounded gravel 2-6mm; few roots; parent rock.	Non-diagnostic yellow-brown apedal B

SOIL PROFILE: PW06

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 6' 9.9" S/ 28° 25' 14.34"E	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	Frequent
Altitude:	2861 m	**Wind erosion:**	None
Terrain Unit:	Midslopes	**Water Erosion:**	Rill slight, stabilized
Slope:	30%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	10 mm
Aspect:	North	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	7/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 70	Wet state; dry colour very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; structure: moderate medium granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, many medium & coarse normal pores; many roots; diffuse wavy transition.	Melanic A
A2	70 - 190	Wet state; dry colour very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; structure: moderate medium granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, many medium & coarse normal pores; many roots; clear wavy transition.	Melanic A
B1	190 - 410	Wet state; dry colour: yellowish brown 10YR5/4; moist colour: reddish brown 5YR4/4; common fine distinct red oxidized iron oxide mottles; structure: strong coarse sub-angular blocky; consistence: friable, non-sticky, non-plastic; many fine bleached pores, few medium & coarse bleached pores; many rounded gravel 2-6mm; common fine <2-6mm sesquioxide concretions; few roots; diffuse wavy transition.	Non-diagnostic Yellow-brown apedal
B2	410 - 590	Wet state; dry colour: brownish yellow 10YR6/8; moist colour: yellowish red 5YR4/6; common fine distinct red oxidized iron oxide mottles; structure: strong fine sub-angular blocky; consistence; friable, non-sticky, non-plastic; many fine rusty streaked pores, few medium & coarse rusty streaked pores; many rounded gravel 2-6mm; common medium 6-25mm sesquioxide concretions; parent rock.	Non-diagnostic yellow-brown apedal B

SOIL PROFILE: PW07

Map/photo:	2928AB	**Soil form:**	Champagne
Latitude + Longitude:	29° 6' 2.88"S / 28° 25' 10.74"E	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	Frequent
Altitude:	2828 m	**Wind erosion:**	None
Terrain Unit:	Footslopes	**Water Erosion:**	Rill slight, stabilized
Slope:	11%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	10 mm
Aspect:	North-west	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	7/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
O	0 - 210	Wet state; dry colour: black N2.5/0; moist colour: black 10YR2/1; structure: moderate coarse granular; consistence: friable, non-sticky, non-, plastic; many fine normal pores, few medium & coarse pores; many roots; diffuse smooth transition.	Organic O
A2	210 - 400	Wet state; dry colour: dark yellowish brown 10YR4/4; moist colour: very dark brown 10YR2/2; few fine distinct orange oxidized iron oxide mottles; structure: moderate coarse granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, common medium & coarse pores; many roots; clear smooth transition.	Orthic A
B2	400 - 540	Wet state; dry colour: strong brown 7.5YR5/6; moist colour: brown to dark brown 7.5YR4/4; common fine distinct orange oxidized iron oxide mottles; common fine distinct blue and green reduced iron oxide mottles; structure: apedal massive; consistence: slightly firm, sticky, plastic; common fine rusty streaked pores; common rounded gravel 2-6mm; few rounded stones 25-75mm; few roots; diffuse smooth transition	Non-diagnostic yellow-brown apedal B
B2	540 - 1000	Wet state; dry colour: brownish yellow 10YR6/6; moist colour: yellowish brown 10YR5/6; common fine distinct blue and green reduced iron oxide mottles; structure: apedal massive; consistence: slightly firm, sticky, plastic; common fine rusty streaked pores; few rounded gravel 2-6mm; no observed transition.	Non-diagnostic yellow-brown apedal B

SOIL PROFILE: PW08

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 6' 1.86"S / 28° 25' 16.98"E	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	Frequent
Altitude:	2844 m	**Wind erosion:**	None
Terrain Unit:	Footslopes	**Water Erosion:**	Rill slight, stabilized
Slope:	13%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	10 mm
Aspect:	West	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	7/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A1	0 - 70	Wet state; dry colour: very dark greyish brown 10YR3/2 moist colour: black 10YR2/1; structure: moderate coarse granular; consistence: friable, non-sticky, non-plastic; many fine normal pores, many medium & coarse normal pores; many roots; diffuse wavy transition	Melanic A
A2	70 - 200	Wet state; dry colour: very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; few fine distinct red oxidized iron oxide mottles structure: moderate coarse granular; consistence: friable, non-sticky, non-plastic; few fine normal pores, many medium & coarse normal pores; few rounded gravel 2-6mm; many roots; diffuse wavy transition.	Melanic A
C1	200 - 750	Wet state; dry colour: reddish brown 5YR5/4; moist colour: very dark brown 10YR2/2; few fine distinct red oxidized iron oxide mottles; structure: moderate coarse granular; consistence: friable, non-sticky, non-plastic; few fine normal pores, many medium & coarse normal pores; many rounded gravel 2-6mm; stoneline 450mm, multiple occurrence, throughout horizon; common roots; clear broken transition.	Unspecified
C2	750 - 850	Wet state; dry colour: light reddish brown 2.5YR6/4; moist colour: red 2.5YR5/6; many coarse prominent yellow oxidized iron oxide mottles; many coarse prominent grey reduced iron oxide mottles; structure: apedal massive; consistence: friable, non-sticky, non-plastic; many fine bleached pores, few medium & coarse bleached pores; few skeletan cutans; common flat gravel 2-6mm; few angular boulders >250mm; very few fine <2-6mm sesquioxide concretions; lamella 150mm, single occurrence, throughout horizon; parent rock.	Unspecified

SOIL PROFILE: PD09

Map/photo:	2928AB	**Soil form:**	Mayo
Latitude + Longitude:	29° 5' 58.98"S / 28° 25' 37.74"E	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2963 m	**Wind erosion:**	None
Terrain Unit:	Summit	**Water Erosion:**	Rill slight, stabilized
Slope:	8%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	None
Aspect:	East	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	7/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A1	0 - 200	Dry state; dry colour: very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; structure: strong coarse granular; consistence: loose, friable, non-sticky,	Melanic A
A2	200 - 250	Moist state; dry colour: brown to dark brown 7.5YR4/4; moist colour: very dark brown 10YR2/2; structure: moderate coarse granular; consistence: soft, friable, non-sticky, non-plastic; few fine bleached pores, many medium & coarse normal pores; common mixed-shape coarse stones 75-250mm; stoneline multiple occurrence, throughout horizon; colluvial ; common roots; diffuse wavy transition.	Orthic A
B	250 - 650	Moist state; dry colour: yellowish brown 10YR5/4; moist colour: dark brown 10YR3/3; common fine distinct red and yellow oxidized iron oxide mottles; structure: apedal massive; consistence: slightly hard, slightly firm, slightly sticky, non-plastic; many fine rusty streaked pores, few medium & coarse rusty streaked pores; very many mixed-shape coarse stones 75-250mm; weathered remnants of stones multiple occurrence, throughout horizon; hard rock transition.	Lithocutanic B

SOIL PROFILE: PD10

Map/photo:	2928AB	**Soil form:**	Mayo
Latitude + Longitude:	29° 5' 26.34" S/ 28° 25' 39.36"E	**Surface rockiness:**	2-25% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2959 m	**Wind erosion:**	None
Terrain Unit:	Summit	**Water Erosion:**	Rill slight, stabilized
Slope:	13%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Straight	**Water table:**	None
Aspect:	North-west	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	8/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A1	0 - 200	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; structure: strong coarse granular; consistence: loose, friable, non-sticky, non-plastic; few fine normal pores, many medium & coarse normal pores; very few rounded gravel 2-6mm; many roots; diffuse wavy transition	Melanic A
A2	200 - 250	Moist state; very dark greyish brown 10YR3/2; moist colour: very dark brown 10YR2/2; structure: moderate medium granular; consistence: friable, non-sticky, non-plastic; few fine normal pores, many medium & coarse normal pores; common mixed-shape gravel 2-6mm; common rounded coarse gravel 6-25mm; colluvial; stoneline multiple occurrence, throughout horizon; common roots; gradual transition	Melanic A
B	250 - 330	Moist state; dry colour: strong brown 7.5YR4/6; moist colour: dark yellowish brown 10YR3/4; structure: moderate fine angular blocky; consistence: slightly firm, non-sticky, non-plastic; common fine normal pores, few medium & coarse normal pores; common mixed-shape stones 25-75mm; stoneline multiple occurrence, throughout horizon; few roots; parent rock.	Lithocutanic B

SOIL PROFILE: PD11

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 4' 42.72"S/ 28° 25' 39.3"E	**Surface rockiness:**	10-25% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2897 m	**Wind erosion:**	None
Terrain Unit:	Footslopes	**Water Erosion:**	Rill slight, stabilized
Slope:	15%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	None
Aspect:	West	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	8/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 170	Moist state; dry colour: very dark grey 10YR3/1; moist colour: black 10YR2/1; structure: strong coarse granular; consistence: friable, non-sticky, non-plastic; few fine normal pores, many medium & coarse normal pores; common rounded gravel 2-6mm; many roots; diffuse wavy transition.	Melanic A
A2	170 - 410	Moist state; very dark greyish brown 10YR3/2; moist colour: very dark brown 10YR2/2; structure: moderate medium granular; consistence: friable, non-sticky, non-plastic; few fine normal pores, common medium & coarse normal pores; common rounded gravel 2-6mm; few roots; gradual tonguing	Melanic A
C1	410 - 800	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: very dark brown 10YR2/2; structure: moderate fine subangular blocky; consistence: friable, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; few rounded gravel 2-6mm; common mixed-shape coarse stones 75-250mm; stoneline 20mm, multiple occurrence, lower part of horizon; colluvial ; few roots; diffuse wavy transition.	Unspecified
C2	800 - 1000	Moist state; dry colour: dark yellowish brown 10YR3/4; moist colour: dark brown 7.5YR3/4; structure: apedal massive; consistence: slightly firm, non-sticky, non-plastic; many fine normal pores, few medium & coarse normal pores; common rounded gravel 2-6mm; transition not observed.	Unspecified

SOIL PROFILE: PD12

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 4' 20.52" S/ 28° 25' 39.12" E	**Surface rockiness:**	10-25% exposed surface
Surface stoniness:	25-60% exposed surface	**Occurrence of flooding:**	None
Altitude:	2888 m	**Wind erosion:**	None
Terrain Unit:	Valley	**Water Erosion:**	Rill slight, stabilized
Slope:	5%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	None
Aspect:	South-east	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	8/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A1	0 - 200	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; structure: strong coarse granular; consistence: friable, non-sticky, non-plastic; few fine normal pores, many medium & coarse normal pores; many rounded gravel 2-6mm; many roots; abrupt smooth transition.	Melanic A
A2	200 - 330	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; structure: strong coarse granular; consistence: friable, non-sticky, non-plastic; few fine normal pores, many medium & coarse normal pores; very many rounded gravel 2-6mm; stoneline single occurrence, throughout horizon; colluvial; many roots; abrupt smooth transition.	Melanic A
A3	330 - 500	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: very dark brown 10YR2/2; structure: strong coarse granular; consistence: friable, non-sticky, non-plastic; few fine normal pores, common medium & coarse normal pores; common rounded gravel 2-6mm; common roots; abrupt smooth transition.	Melanic A
C1	500 - 700	Moist state; dry colour: dark greyish brown 10YR4/2; moist colour: very dark greyish brown 10YR3/2; structure: weak fine subangular blocky; consistence: slightly firm, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; very few rounded gravel 2-6mm; few roots; diffuse wavy	Unspecified
C2	700 - 800	Moist state; dry colour: brown to dark brown 10YR4/3; moist colour: dark brown 10YR3/3; structure: weak fine subangular blocky; consistence: slightly firm, non-sticky, non-plastic; many & coarse rusty streaked pores; few rounded gravel 2-6mm; parent rock.	Unspecified

SOIL PROFILE: PD13

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 4' 52.26"S / 28° 25' 4.98"E	**Surface rockiness:**	25-60% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2913 m	**Wind erosion:**	None
Terrain Unit:	Midslopes	**Water Erosion:**	Rill slight, partially stabilized
Slope:	21%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Straight	**Water table:**	None
Aspect:	North-east	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	8/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A1	0 - 200	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; structure: strong medium granular; consistence: loose, friable, non-sticky, non-plastic; few fine pores, many medium & coarse normal pores; many rounded gravel 2-6mm; colluvial ; many roots; diffuse wavy transition.	Melanic A
A2	200 - 340	Moist state; dry colour: dark brown 10YR3/3; moist colour: dark brown 10YR3/3; structure: strong medium granular; consistence: loose, friable, non-sticky, non-plastic; few fine pores, common medium & coarse normal pores; few rounded gravel 2-6mm; many roots; abrupt wavy transition.	Orthic A
B	340 - 600	Moist state; dry colour: brown to dark brown 10YR4/3; moist colour: dark yellowish brown 10YR3/4; structure: apedal; consistence: slightly hard, slightly firm, non-sticky, non-plastic; common fine normal pores, few medium & coarse normal pores; very few rounded gravel 2-6mm; common mixed-shape coarse gravel 6-25mm; few roots; parent rock	Non-diagnostic yellow-brown apedal B

SOIL PROFILE: 14

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 4' 55.74"S / 28° 25' 16.86"E	**Surface rockiness:**	25-60% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2897 m	**Wind erosion:**	None
Terrain Unit:	Footslopes	**Water Erosion:**	Rill slight, partially stabilized
Slope:	18%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Convex	**Water table:**	None
Aspect:	North-east	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	11/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 -300	Moist state; dry colour: very dark grey 10YR3/1; moist colour: black 10YR2/1; structure: strong medium granular; consistence: loose, friable, non-sticky, non-plastic;common fine normal pores, many medium & coarse normal pores; very few rounded gravel 2-6mm; many roots; gradual wavy transition.	Melanic A
A2	300 - 550	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: very dark brown 10YR2/2; structure: strong medium granular; consistence: loose, friable, non-sticky, non-plastic;common fine normal pores, common medium & coarse normal pores; common rounded gravel 2-6mm; many roots; clear wavy transition.	Melanic A
B1	550 - 720	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: dark yellowish brown 10YR3/4; structure: apedal; consistence: slightly hard, slightly firm, non-sticky, non-plastic; few fine normal pores, few medium & coarse normal pores; many rounded gravel 2-6mm; few roots; diffuse wavy transition.	Non-diagnostic yellow-brown apedal B
B2	720 - 810	Moist state; dry colour: dark yellowish brown 10YR4/4; moist colour: dark yellowish brown 10YR4/4; structure: apedal; consistence: hard, firm, non-sticky, non-plastic; few medium and coarse normal pores; very many mixed-shape coarse gravel 6-25mm; parent rock.	Non-diagnostic yellow-brown apedal B

SOIL PROFILE: 15

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 4' 48.96"S / 28° 25' 16.38"E	**Surface rockiness:**	<2% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2898 m	**Wind erosion:**	None
Terrain Unit:	Footslopes	**Water Erosion:**	Rill slight, stabilized
Slope:	16%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Convex	**Water table:**	None
Aspect:	South-east	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	11/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 100	Moist state; dry colour: very dark grey 10YR3/1; moist colour: black 10YR2/1; structure: moderate medium granular, secondary structure: moderate fine granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; common rounded gravel 2-6mm; many roots; diffuse tonguing transition.	Melanic A
A2	100 - 300	Moist state; dry colour: very dark grey 10YR3/1; moist colour: very dark brown 10YR2/2; structure: strong coarse granular, secondary structure: moderate fine granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; common rounded gravel 2-6mm; many roots; diffuse tonguing transition.	Melanic A
C1	300 - 600	Moist state; moist colour: very dark grey brown 10YR3/2; structure: moderate medium granular, secondary structure: moderate fine granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; common mixed-shape coarse gravel 6-25mm; common roots; diffuse transition.	Unspecified
C2	600 - 800	Wet state; moist colour: dark yellowish brown 10YR3/6; structure: moderate medium subangular blocky, secondary structure: moderate fine subangular blocky; consistence: slightly hard, slightly firm, slightly sticky, non-plastic; common fine normal pores, few medium & coarse normal pores; very many mixed-shape coarse gravel 6-25mm; few roots; parent rock.	Unspecified

SOIL PROFILE: PD16

Map/photo:	2928AB	**Soil form:**	Mayo
Latitude + Longitude:	29° 4' 58.02"S / 28° 25' 53.4"E	**Surface rockiness:**	25-60% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2976 m	**Wind erosion:**	None
Terrain Unit:	Summits	**Water Erosion:**	Rill slight, stabilized
Slope:	8%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Convex	**Water table:**	None
Aspect:	North	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	11/2009
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A1	0 - 300	Moist state; dry colour: very dark grey 10YR3/1; moist colour: black 10YR2/1; structure: strong coarse granular, secondary structure: strong medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, many medium & coarse normal pores; common angular gravel 2-6mm; many roots; abrupt smooth transition	Melanic A
A2	300 - 350	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; structure: strong coarse granular, secondary structure: strong medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, many medium & coarse normal pores; many angular gravel 2-6mm; colluvial ; many roots; abrupt smooth transition	Melanic A
B	350 - 420	Moist state; dry colour: dark greyish brown 10YR4/2; moist colour: brown to dark brown 10YR4/3; structure: apedal, secondary structure: apedal; consistence: slightly hard, slightly firm, non-sticky, non-plastic; many fine normal pores, common medium & coarse normal pores; very many mixed-shape gravel 2-6mm; very many angular coarse gravel 6-25mm; few roots; parent rock	Lithocutanic B

SOIL PROFILE: PD17

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 4' 36.6"S / 28° 25' 40.98"E	**Surface rockiness:**	10-25% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2901 m	**Wind erosion:**	None
Terrain Unit:	Footslopes	**Water Erosion:**	Rill slight, stabilized
Slope:	19%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	None
Aspect:	West	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	1/2010
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 300	Moist state; moist colour: very dark brown 10YR2/2; texture: sandy loam; structure: strong medium granular, secondary structure: moderate medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; common mixed-shape gravel 2-6mm; very few angular stones 25-75mm; many roots; clear smooth transition.	Melanic A
A2	300 - 500	Moist state; moist colour: black 10YR2/1;structure: strong medium granular, secondary structure: moderate medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; common mixed-shape gravel 2-6mm; many roots; diffuse wavy transition.	Melanic A
A3	500 - 800	Moist state; moist colour: black 10YR2/1; structure: strong medium granular, secondary structure: moderate medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; common mixed-shape gravel 2-6mm; many roots; diffuse wavy transition.	Melanic A
B	800 - 1100	Moist state; moist colour: yellowish brown 10YR5/8; few mottles; structure: apedal, secondary structure: apedal; consistence: slightly hard, slightly firm, non-sticky, non-plastic; many fine rusty streaked pores, few medium & coarse rusty streaked pores; many mixed-shape coarse gravel 6-25mm; few roots; no observed transition.	Non-diagnostic yellow-brown apedal B

SOIL PROFILE: PW18

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 4' 26.46'S' / 28° 25' 57"E.	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	3062 m	**Wind erosion:**	None
Terrain Unit:	Summit	**Water Erosion:**	Rill slight, stabilized
Slope:	8%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	400 mm
Aspect:	South-east	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	1/2010
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 400	Moist state; moist colour: black 10YR2/1; texture: clay loam; structure: strong medium granular, secondary structure: moderate medium granular; consistence: loose, friable, non-sticky, non-plastic; many fine normal pores, many medium & coarse normal pores; many roots; clear wavy transition	Melanic A
B	400 - 800	Moist state; moist colour: dark yellowish brown 10YR3/4; texture: clay loam; many medium prominent yellow reduced iron oxide mottles; structure: apedal, secondary structure: weak fine sub-angular blocky; consistence: loose, slightly firm, non-sticky, non-plastic; common fine rusty streaked pores, common medium & coarse rusty streaked pores; common rounded gravel 2-6mm; common mixed-shape coarse gravel 6-25mm; few roots; parent rock.	Non-diagnostic yellow-brown apedal B

SOIL PROFILE: PW19

Map/photo:	2928AB
Latitude + Longitude:	29° 4' 44.58"S / 28° 25' 39.9"E
Surface stoniness:	None
Altitude:	2887 m
Terrain Unit:	Footslopes
Slope:	13%
Slope Shape:	Concave
Aspect:	West
Micro-relief:	Dongas 1.0 m deep, 20% coverage, profile between features
Parent Material Solum:	Origin single, solid rock
Underlying Material:	Basalt

Soil form:	Willowbrook
Surface rockiness:	2-10% exposed surface
Occurrence of flooding:	Occasional
Wind erosion:	None
Water Erosion:	Rill slight, partially stabilized
Vegetation / Land use:	Grassveld, open
Water table:	400 mm
Described by:	B.E. Mapeshoane
Date described:	1/2010
Weathering of underlying material:	Advanced physical, strong chemical
Alteration of underlying material:	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 450	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; structure: strong medium granular, secondary structure: moderate medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; few rounded gravel 2-6mm; many roots; diffuse wavy transition.	Melanic A
AG	450 - 600	Moist state; dry colour: very dark greyish brown 10YR3/2; moist colour: dark yellowish brown 10YR3/4; structure: weak fine subangular blocky, secondary structure: weak fine subangular blocky; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, few medium & coarse normal pores; few rounded gravel 2-6mm; common roots; gradual wavy transition	Melanic/G horizon
G	600 - 850	Wet state; dry colour: grey 10YR6/1; moist colour: grey 10YR5/1(G1.5/N); structure: apedal; consistence: soft, slightly firm, slightly sticky, slightly plastic; few fine bleached pores, few medium & coarse bleached pores; few rounded gravel 2-6mm; few roots; parent rock.	G-horizon

SOIL PROFILE: PD20

Map/photo: 2928AB
Latitude + Longitude: 29° 4' 55.08"S / 28° 25' 35.28"E
Surface stoniness: None
Altitude: 2909 m
Terrain Unit: Footslopes
Slope: 18%
Slope Shape: Straight
Aspect: West
Micro-relief: None
Parent Material Solum: Origin single, solid rock
Underlying Material: Basalt

Soil form: Inhoek
Surface rockiness: 2-10% exposed surface
Occurrence of flooding: None
Wind erosion: None
Water Erosion: Rill slight, partially stabilized
Vegetation / Land use: Grassveld, open
Water table: None
Described by: B.E. Mapeshoane
Date described: 1/2010
Weathering of underlying material: Advanced physical, strong chemical
Alteration of underlying material: Kaolinised

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 450	Moist state; moist colour: black 10YR2/1; structure: strong coarse granular, secondary structure: strong medium granular; consistence: loose, friable, non-sticky, non-plastic; many fine normal pores, many medium & coarse normal pores; very few mixed-shape gravel 2-6mm; many mixed-shape stones 25-75mm; many roots; gradual tonguing transition.	Melanic A
BA	450 - 600	Moist state; moist colour: dark brown 10YR3/3; structure: moderate fine granular, secondary structure: apedal; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; few mixed-shape gravel 2-6mm; many mixed-shape stones 25-75mm; common roots; diffuse wavy transition.	Non-diagnostic yellow-brown apedal B
B	600 -1000	Moist state; moist colour: dark yellowish brown 10YR4/4; structure: apedal, secondary structure: apedal; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; few mixed-shape gravel 2-6mm; few mixed-shape stones few roots; no observed transition	Non-diagnostic yellow-brown apedal B

SOIL PROFILE: PW21

Map/photo:	2928AB	**Soil form:**	Pinedene
Latitude + Longitude:	29° 4' 51.72"S / 28° 25' 28.92"E	**Surface rockiness:**	<2% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	Occasional
Altitude:	2862 m	**Wind erosion:**	None
Terrain Unit:	Valley bottom	**Water Erosion:**	Rill slight, partially stabilized
Slope:	4%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	400 mm
Aspect:	West	**Described by:**	B.E. Mapeshoane
Micro-relief:	Dongas 1.0 m deep, 20% coverage, profile between features	**Date described:**	1/2010
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 220	Wet state; dry colour: dark greyish brown 10YR4/2; moist colour: dark bluish grey 5B4/1; structure: apedal; consistence: loose, non-sticky, non-plastic; few fine normal pores, many medium & coarse normal pores; many roots; clear smooth transition.	Orthic A
A2	220 - 480	Wet state; dry colour: brown to dark brown 7.5YR4/2; moist colour: brown to dark brown 7.5YR4/2; common fine distinct orange oxidized iron oxide mottles; structure: strong medium granular; consistence: friable, non-sticky, non-plastic; common fine rusty streaked pores, many medium & coarse rusty streaked pores; many roots; gradual wavy transition.	Orthic A
BA	480 - 700	Wet state; moist colour: light brown 7.5YR6/4; moist colour: brown to dark brown 7.5YR4/4; few fine distinct orange oxidized iron oxide mottles; structure: moderate coarse granular; consistence: friable, non-sticky, non-plastic; few fine rusty streaked pores, common medium & coarse rusty streaked pores; very few gravel 2-6mm; few roots; gradual wavy transition.	Non-diagnostic yellow-brown apedal B
C	700 - 1000	Wet state; moist colour: light yellow brown 10YR6/4; moist colour: dark yellowish brown 10YR4/4; many coarse distinct orange oxidized iron oxide mottles; few medium faint yellow reduced iron oxide mottles; structure: apedal; consistence: friable, non-sticky, non-plastic; few fine rusty streaked pores, many medium & coarse rusty streaked pores; many gravel 2-6mm; weathered remnants of stones single occurrence, throughout horizon; no observed transition.	Unspecified material with signs of wetness

SOIL PROFILE: PD23

Map/photo: 2928AB
Latitude + Longitude: 29° 5' 7.8"S / 28° 25' 13.74"E
Surface stoniness: None
Altitude: 2907 m
Terrain Unit: Midslopes
Slope: 39%
Slope Shape: Straight
Aspect: South-east
Micro-relief: None
Parent Material Solum: Origin single, solid rock
Underlying Material: Basalt

Soil form: Inhoek
Surface rockiness: 10-25% exposed surface
Occurrence of flooding: None
Wind erosion: None
Water Erosion: Rill slight, stabilized
Vegetation / Land use: Grassveld, open
Water table: None
Described by: B.E. Mapeshoane
Date described: 1/2010
Weathering of underlying material: Advanced physical, strong chemical
Alteration of underlying material: Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 90	Moist state; moist colour: black 10YR2/1; structure: strong coarse granular, secondary structure: moderate fine granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, many medium & coarse normal pores; few gravel 2-6mm; many roots; abrupt smooth transition	Melanic A
C1	90 - 115	Moist state; moist colour: very dark brown 10YR2/2; structure: moderate medium subangular blocky, secondary structure: moderate medium subangular blocky; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; few gravel 2-6mm; many roots; abrupt smooth transition.	Unspecified
C2	115 - 150	Moist state; moist colour: dark yellowish brown 10YR3/4; structure: apedal; consistence: non-sticky, non-plastic; many fine normal pores, few medium & coarse normal pores; common gravel 2-6mm; common rounded stones 25-75mm; few roots; parent rock.	Unspecified

SOIL PROFILE PW24

Map/photo:	2928AB	**Soil form:**	Katspruit
Latitude + Longitude:	29° 5' 9.6" S/ 28° 25' 25.08"E	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	Occasional
Altitude:	2850 m	**Wind erosion:**	None
Terrain Unit:	Footslopes	**Water Erosion:**	Rill slight, stabilized
Slope:	14%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	400 mm
Aspect:	South-west	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	1/2010
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 110	Moist state; dry colour: brown to dark brown 10YR4/3; moist colour: dark brown 10YR3/3; structure: moderate medium granular; consistence: loose, friable, non-sticky, non-	Orthic A
A2	110 - 490	Moist state; dry colour: dark grey 10YR4/1; moist colour: black 10YR2/1; common medium faint orange mottles; structure: moderate medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine bleached pores, common mixed-shape coarse gravel 6-25mm; few roots; gradual wavy transition.	Orthic A
G1	490 - 750	Wet state; dry colour: dark grey 5Y4/1; moist colour: dark grey 5Y4/1; many coarse faint orange mottles; structure: apedal massive; consistence: slightly hard, slightly firm, non-sticky, non-plastic; many medium & coarse bleached pores; many mixed-shape coarse gravel 6-25mm; gradual transition.	G horizon
G2	750 - 1000	Wet state; dry colour: dark grey 5Y4/1; moist colour: grey 5Y5/1; structure: apedal massive; consistence: slightly hard, slightly firm, non-sticky, non-plastic; many medium & coarse bleached pores; very many mixed-shape coarse gravel 6-25mm; parent rock.	G horizon

SOIL PROFILE: PW25

Map/photo:	2928AB	**Soil form:**	Willowbrook
Latitude + Longitude:	29° 4' 35.58"S / 28° 25' 37.44"E	**Surface rockiness:**	10-25% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	Frequent
Altitude:	2883 m	**Wind erosion:**	None
Terrain Unit:	Valley bottom	**Water Erosion:**	Rill slight, partially stabilized
Slope:	6%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	70 mm
Aspect:	South-east	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	1/2010
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 150	Wet state; dry colour: very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; common fine distinct orange oxidized iron oxide mottles; structure: strong medium granular; consistence: friable, non-sticky, non-plastic; common fine rusty streaked pores, many medium & coarse normal pores; many roots; gradual transition.	Melanic A
A2	150 - 350	Wet state; dry colour: very dark grey 10YR3/1; moist colour: black 10YR2/1; common fine distinct orange oxidized iron oxide mottles; structure: strong medium granular; consistence: friable, non-sticky, non-plastic; common fine rusty streaked pores, many medium & coarse normal pores; very few rounded gravel 2-6mm; common roots; clear smooth transition	Melanic A
G1	350 - 600	Wet state; dry colour: dark greyish brown 10YR4/2; moist colour: dark grey 5Y4/1(G2/N); many medium prominent orange oxidized iron oxide mottles; common medium distinct blue and green reduced iron oxide mottles; structure: apedal; consistence: loose, non-sticky, non-plastic; common fine bleached pores, few medium & coarse rusty streaked pores; common rounded gravel 2-6mm; few roots; gradual wavy transition.	G horizon
G2	600 - 800	Wet state; dry colour: dark greyish brown 10YR4/2; moist colour: grey 5Y5/1(G1.5/N); many medium prominent orange oxidized iron oxide mottles; common medium distinct blue and green reduced iron oxide mottles; structure: apedal; consistence: loose, non-sticky, non-plastic; common fine bleached pores, few medium & coarse rusty streaked pores; continuous moderate rock structured cementation of unknown agent; very many mixed-shape coarse gravel 6-25mm; stoneline single occurrence, throughout horizon; parent rock.	G horizon

SOIL PROFILE: PW26

Map/photo:	2928AB	**Soil form:**	Pinedene
Latitude + Longitude:	29° 4' 43.8"S / 28° 25' 37.02"E	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	Occasional
Altitude:	2882 m	**Wind erosion:**	None
Terrain Unit:	Valley bottom	**Water Erosion:**	Rill slight, partially stabilized
Slope:	10%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Straight	**Water table:**	400 mm
Aspect:	West	**Described by:**	B.E. Mapeshoane
Micro-relief:	Dongas 1.0m deep, 2% coverage, profile between features	**Date described:**	1/2010
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 120	Wet state; dry colour: very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; structure: moderate medium granular, secondary structure: weak fine crumb; consistence: loose, friable, non-sticky, non-plastic; many fine normal pores, few medium & coarse normal pores; few rounded gravel 2-6mm; many roots; diffuse transition.	Melanic A
BA	120 - 450	Wet state; dry colour: very dark greyish brown 10YR3/2; moist colour: very dark grey 10YR3/1; structure: moderate medium granular, secondary structure: weak fine crumb; consistence: loose, friable, non-sticky, non-plastic; common medium bleached pores; common rounded gravel 2-6mm; common roots; abrupt tonguing transition.	Non-diagnostic yellow-brown apedal B
C	450 - 767	Wet state; dry colour: yellowish brown 10YR5/4; moist colour: grey 10YR5/1; structure: apedal, secondary structure: apedal; consistence: hard, friable, non-sticky, non-plastic; many coarse bleached pores; many mixed-shape gravel 2-6mm; common mixed-shape stones 25-75mm; few roots; parent rock.	Unspecified material with signs of wetness

SOIL PROFILE: PW27

Map/photo:	2928AB	**Soil form:**	Champagne
Latitude + Longitude:	29° 4' 43.62"S / 28° 25' 36.12"E	**Surface rockiness:**	10-25% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	Frequent
Altitude:	2872 m	**Wind erosion:**	None
Terrain Unit:	Valley bottom	**Water Erosion:**	Rill slight, Gully slight partially stabilized
Slope:	7%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Straight	**Water table:**	60 mm
Aspect:	West	**Described by:**	B.E. Mapeshoane
Micro-relief:	Dongas 1.0m deep, 2% coverage, profile between features	**Date described:**	1/2010
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
O1	0 - 100	Wet state; dry colour: black 2.5Y2/0; moist colour: black 2.5Y2.5/0; peat; consistence: soft, loose, slightly sticky, non-plastic; common fine normal pores,few medium & coarse normal pores; many roots; gradual broken transition.	Organic O
O2	100 - 500	Wet state; dry colour: black 2.5Y2/0; moist colour: black 2.5Y2.5/0; peat; consistence: soft, loose, slightly sticky, non-plastic; common fine normal pores,few medium & coarse normal pores; common roots; gradual broken transition.	Unspecified
O3	500 - 1000	Wet state; dry colour: black 2.5Y2/0; moist colour: black 2.5Y2.5/0;peat; consistence: soft, loose, slightly sticky, non-plastic; common fine normal pores,few medium & coarse bleached pores; common mixed-shape stones 25-75mm; common roots; no observed transition.	Unspecified

SOIL PROFILE: PW28

Map/photo:	2928AB	**Soil form:**	Pinedene
Latitude + Longitude:	29° 4' 34.46" S/ 28° 25' 13.86"E	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	3034 m	**Wind erosion:**	None
Terrain Unit:	Midslopes	**Water Erosion:**	Rill slight, stabilized
Slope:	20%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	600 mm
Aspect:	East	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	1/2010
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 150	Moist state; dry colour: brown to dark brown 10YR4/3; moist colour: very dark brown 10YR2/2; structure: moderate medium granular, secondary structure: weak fine crumb; consistence: loose, loose, non-sticky, non-plastic; common fine normal pores, many medium & coarse normal pores; few rounded gravel 2-6mm; many roots; diffuse wavy transition.	Orthic A
A2	150 - 450	Moist state; dry colour: brown to dark brown 10YR4/3; moist colour: black 10YR2/1; structure: strong medium granular, secondary structure: weak medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, many medium & coarse normal pores; few rounded gravel 2-6mm; many roots; diffuse transition.	Orthic A
AB	450 - 600	Moist state; dry colour: yellowish brown 10YR5/4; moist colour: dark brown 10YR3/3; structure: moderate medium granular, secondary structure: weak medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, many medium & coarse normal pores; common rounded gravel 2-6mm; common roots; clear tonguing transition	Non-diagnostic yellow-brown apedal B
C	600 - 1000	Wet state; dry colour: yellowish brown 10YR5/4; moist colour: dark brown 10YR3/3; few fine faint yellow reduced iron oxide mottles; structure: moderate medium subangular blocky, secondary structure: moderate fine subangular blocky; consistence: slightly hard, slightly firm, non-sticky, non-plastic; many fine rusty streaked pores, few medium & coarse normal pores; many mixed-shape gravel 2-6mm; common mixed-shape stones 25-75mm; few roots; parent rock.	Unspecified material with signs of wetness I

SOIL PROFILE: PD29

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 4' 42.96"S / 28° 25' 17.4"E	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2926 m	**Wind erosion:**	None
Terrain Unit:	Midslopes	**Water Erosion:**	Rill slight, stabilized
Slope:	23%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Concave	**Water table:**	None
Aspect:	South	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	1/2010
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 330	Moist state; moist colour: black 10YR2/1; structure: strong coarse granular, secondary structure: moderate medium granular; consistence: loose, friable, non-sticky, non-plastic; many fine normal pores, many medium & coarse normal pores; many roots; diffuse smooth transition.	Melanic A
A2	330 - 650	Moist state; moist colour: black 10YR2/1; structure: strong medium granular, secondary structure: weak medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, many medium & coarse normal pores; common angular boulders >250mm; stoneline single occurrence, throughout horizon; many roots; diffuse smooth transition	Melanic A
C	650 - 750	Moist state; moist colour: very dark brown 10YR2/2; structure: moderate medium subangular blocky, secondary structure: weak medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, common medium & coarse normal pores; common roots; diffuse tonguing transition.	Unspecified
C	750 - 1000	Moist state; moist colour: dark brown 10YR3/3; structure: apedal; consistence: slightly hard, slightly firm, non-sticky, non-plastic; few fine normal pores, few medium & coarse normal pores; parent rock	Unspecified

SOIL PROFILE: PD30

Map/photo:	2928AB	**Soil form:**	Inhoek
Latitude + Longitude:	29° 4' 50.58"S / 28° 25' 19.2"E	**Surface rockiness:**	<2% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2873 m	**Wind erosion:**	None
Terrain Unit:	Footslopes	**Water Erosion:**	Rill slight, stabilized
Slope:	12%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Straight	**Water table:**	None
Aspect:	South-east	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	1/2010
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 100	Moist state; moist colour: black 10YR2/1; structure: strong coarse granular; consistence: loose, friable, non-sticky, non-plastic; many fine normal pores, many medium & coarse normal pores; common rounded gravel 2-6mm; many roots; abrupt tonguing transition.	Melanic A
A2	100 - 340	Moist state; moist colour: black 10YR2/1; structure: strong coarse granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, many medium & coarse normal pores; common rounded gravel 2-6mm; many roots; abrupt wavy transition.	Melanic A
C1	340 - 830	Moist state; moist colour: very dark brown 10YR2/2; common fine faint yellow reduced iron oxide mottles; few fine faint orange reduced iron oxide mottles; structure: moderate medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine rusty streaked pores, many medium & coarse rusty streaked pores; common rounded gravel 2-6mm; common roots; gradual tonguing transition	Unspecified
C2	830 - 880	Moist state; moist colour: dark yellowish brown 10YR3/4; few fine faint yellow reduced iron oxide mottles; few fine faint orange reduced iron oxide mottles; structure: moderate medium sub-angular blocky; consistence: slightly hard, friable, non-sticky, non-plastic; common fine rusty streaked pores, common medium & coarse rusty streaked pores; common rounded gravel 2-6mm; common rounded coarse gravel 6-25mm; few roots; parent rock.	Unspecified

SOIL PROFILE: PD31

Map/photo:	2928AB	**Soil form:**	Mayo
Latitude + Longitude:	29° 4' 56.82"S / 28° 25' 22.14'E'	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	None
Altitude:	2865 m	**Wind erosion:**	None
Terrain Unit:	Footslopes	**Water Erosion:**	None
Slope:	14%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Straight	**Water table:**	None
Aspect:	East	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	1/2010
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 200	Moist state; moist colour: black 10YR2/1; structure: strong coarse granular, secondary structure: moderate medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, many medium & coarse normal pores; many roots; gradual smooth transition.	Melanic A
A2	200 - 470	Moist state; moist colour: very dark brown 10YR2/2; structure: strong coarse granular, secondary structure: moderate medium granular; consistence: loose, friable, non-sticky, non-plastic; common fine normal pores, many medium & coarse normal pores; very few mixed-shape gravel 2-6mm; common roots; abrupt tonguing transition.	Melanic A
B	470 - 760	Moist state; moist colour: dark brown 10YR3/3; structure: apedal; consistence: loose, slightly firm, non-sticky, non-plastic; few fine normal pores, few medium & coarse normal pores; common mixed-shape gravel 2-6mm; many mixed-shape stones 25-75mm; parent rock	Lithocutanic B

SOIL PROFILE: PW32

Map/photo:	2928AB	**Soil form:**	Katspruit
Latitude + Longitude:	29° 4' 52.14"S / 28° 25' 22.86"E	**Surface rockiness:**	2-10% exposed surface
Surface stoniness:	None	**Occurrence of flooding:**	Frequent
Altitude:	2868 m	**Wind erosion:**	None
Terrain Unit:	Valley bottom	**Water Erosion:**	Rill slight, stabilized
Slope:	3%	**Vegetation / Land use:**	Grassveld, open
Slope Shape:	Straight	**Water table:**	10 mm
Aspect:	West	**Described by:**	B.E. Mapeshoane
Micro-relief:	None	**Date described:**	1/2010
Parent Material Solum:	Origin single, solid rock	**Weathering of underlying material:**	Advanced physical, strong chemical
Underlying Material:	Basalt	**Alteration of underlying material:**	Kaolinised

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	0 - 100	Wet state; dry colour: very dark greyish brown 10YR3/2; moist colour: very dark brown 10YR2/2; structure: moderate fine granular; consistence: loose, non-sticky, non-plastic; many fine normal pores, many medium & coarse normal pores; many roots; clear smooth transition	Orthic A
A2	100 - 280	Wet state; dry colour: dark greyish brown 10YR4/2; moist colour: very dark grey 10YR3/1; few fine faint orange oxidized iron oxide mottles; structure: strong medium granular; consistence: friable, non-sticky, non-plastic; common fine rusty streaked pores, many medium & coarse normal pores; many roots; gradual wavy transition	Orthic A
A3	280 - 370	Wet state; dry colour: very dark greyish brown 10YR3/2; moist colour: very dark grey 10YR3/1; common medium distinct orange oxidized iron oxide mottles; few medium faint blue and green reduced iron oxide mottles; structure: strong medium granular; consistence: friable, non-sticky, non-plastic; common fine rusty streaked pores, many medium & coarse rusty streaked pores; very few rounded gravel 2-6mm; common roots; gradual wavy transition.	Orthic A
G1	370 - 550	Wet state; dry colour: pale red 2.5YR7/2; moist colour: dark greyish brown 10YR4/2; common medium distinct orange oxidized iron oxide mottles; few medium faint blue and green reduced iron oxide mottles; structure: moderate coarse subangular blocky; consistence: friable, slightly sticky, non-plastic; common fine rusty streaked pores, common medium & coarse bleached pores; common rounded gravel 2-6mm; few roots; clear tonguing transition.	G horizon
G2	550 - 940	Wet state; dry colour: grey 10YR5/1; moist colour: grey 10YR5/1; many coarse prominent orange oxidized iron oxide mottles; common coarse distinct blue and green reduced iron oxide mottles; structure: apedal; consistence: friable, slightly sticky, non-plastic; few fine bleached pores, common medium &coarse bleached pores; continuous strong massive cementation of iron oxides; few skeletan cutans; many rounded gravel 2-6mm; common mixed-shape coarse gravel 6-25mm; weathered remnants of stones single occurrence, throughout horizon; few roots; parent rock.	G horizon

APPENDIX 2B: PHYSICAL AND CHEMICAL SOIL PROPERTIES DESCRIBED PROFILES

Profile	Hor	LD	Sand	Silt	Clay	BD	OC	N	pH	pH	Ca	K	Mg	Na	ExchC	CEC	EC*	BS	P	Fed	Mnd	Ald
		mm	-----------%-----------------			g cm^{-3}	-----------%--------		w	KCl	---------------mg kg^{-1}------------				------molc kg^{-1}------			%	mg kg^{-1}	-----g kg^{-1}-----------		
PD01	A1	180	25	46	29	0.62	5.86	0.78	5.0	4.4	1922	274	234	52	12.49	27.0	42.7	46.3	0.911	64	2.25	40
	A2	360	32	42	27	0.75	3.68	0.50	5.4	4.6	1628	142	164	48	10.08	30.1	37.4	33.5	0.554	82	4.55	75
	AB	580	31	38	31	0.82	3.18	0.46	5.7	4.8	1326	124	154	36	8.39	33.7	26.7	24.9	0.364	140	3.38	73
	B	900	31	41	27	1.02	0.58	0.12	5.7	4.9	834	172	66	50	5.38	21.8	20.1	24.6	0.579	77	2.50	35
PDO2	A1	260	24	47	30	0.88	4.95	0.72	5.3	5.1	1932	244	210	48	12.24	17.7	41.1	69.1	0.596	83	3.65	56
	A2	390	28	44	29	0.85	5.75	0.69	5.5	4.6	1630	174	178	46	10.28	38.0	36.0	27.0	0.506	64	2.75	48
	AB	530	31	39	26	0.76	3.34	0.52	5.6	4.6	1516	188	178	60	9.81	40.2	38.2	24.4	0.218	62	2.28	43
	B	950	44	30	23	0.95	0.65	0.13	5.8	4.9	984	186	64	80	6.28	20.7	26.9	30.4	0.431	37	1.68	23
PD03	A1	280	20	45	36	0.80	7.21	0.96	4.9	4.3	960	254	138	36	6.76	40.2	18.6	16.8	1.619	47	2.48	44
	A2	440	28	37	36	0.84	3.37	0.49	5.3	4.5	1222	212	130	52	7.96	22.6	22.0	35.2	0.588	43	2.48	55
	A3	600	37	33	30	0.86	3.09	0.45	5.5	4.6	992	150	94	48	6.34	28.4	21.3	22.3	0.425	71	2.03	46
	B	1000	42	31	26	0.96	1.45	0.27	5.6	4.8	1186	156	90	66	7.37	24.5	28.5	30.1	0.509	78	1.33	37
PD04	A1	170	21	45	36	0.41	6.84	0.94	5.2	4.5	1418	246	150	56	9.21	34.8	25.7	26.5	0.724	53	1.10	44
	A2	340	35	30	37	0.38	5.09	0.69	5.3	4.5	1030	166	98	38	6.56	24.3	17.6	26.9	0.548	46	0.88	39
	A3	510	38	31	31	0.54	3.06	0.42	5.5	4.6	846	136	72	50	5.40	19.7	17.2	27.4	0.385	25	1.18	22
	B	810	46	24	29	0.59	0.70	0.12	5.8	5.0	838	178	46	84	5.39	16.5	18.4	32.7	0.330	42	1.63	41
PD05	A1	250	30	38	35	0.33	6.35	0.78	5.3	4.5	2762	252	296	40	17.10	27.7	49.2	61.7	0.495	61	2.28	37
	A2	540	35	31	35	0.32	4.67	0.56	5.6	4.6	2194	158	276	40	13.85	26.8	39.6	51.6	0.313	128	3.63	64
	AB	630	52	23	23	0.97	2.92	0.39	5.7	4.7	2096	178	270	42	13.37	17.5	57.6	76.4	0.361	159	2.75	59
	B	880	46	30	21	1.10	1.51	0.21	5.9	5.0	708	116	68	36	4.56	22.9	21.7	19.9	0.728	105	2.58	74
PW06	A1	70	41	23	38	0.26	12.60	1.62	5.9	5.3	1276	126	164	88	8.45	35.9	22.4	23.6	0.645	145	14.73	39
	A2	190	38	31	32	0.29	6.64	0.94	5.1	4.6	4780	1380	560	210	33.02	44.6	104.0	74.1	0.764	100	1.65	44
	G1	410	41	30	27	0.85	0.46	0.14	5.6	5.0	2368	132	278	142	15.11	17.9	55.4	84.3	0.549	143	0.78	37
	G2	590	43	29	26	0.85	0.26	0.07	5.8	5.2	2724	118	400	90	17.65	25.7	68.7	68.8	0.579	‡‡	2.28	40
PW07	A1	210	41	26	33	0.30	14.90	1.72	5.2	4.9	3100	506	420	100	20.73	42.4	62.1	48.9	0.739	71	2.65	13
	A2	400	23	35	39	0.55	5.87	0.77	4.6	4.0	1130	112	150	54	7.42	44.6	19.0	16.7	0.381	‡‡	1.03	21
	G1	540	30	36	35	0.92	1.32	0.17	4.5	3.8	1410	102	270	106	10.02	20.4	28.6	49.0	0.346	99	0.18	11
	G2	1000	43	28	28	0.82	0.53	0.09	4.6	3.9	1910	138	380	108	13.54	17.6	49.2	76.9	0.343	95	0.30	12
PW08	A1	70	33	39	27	0.33	3.84	0.44	5.0	4.8	1106	120	180	38	7.50	40.2	28.0	18.7	0.339	112	3.03	61
	A2	200	48	26	25	0.95	3.36	0.46	5.2	4.6	1660	112	200	98	10.68	23.0	42.7	46.3	0.488	84	2.43	30
	B1	750	40	31	30	1.05	2.26	0.31	5.1	4.6	1482	106	168	92	9.48	31.5	31.4	30.1	0.454	51	0.53	24
	B2	850	35	32	34	1.05	0.19	0.05	5.4	4.6	3340	230	380	138	21.06	28.2	61.8	74.8	0.226	170	4.40	11
PD09	A1	200	46	25	27	0.76	6.24	0.84	5.6	5.1	948	516	152	24	7.43	40.2	27.5	18.5	0.723	86	3.03	57
	BC	250	50	21	32	0.48	3.45	0.48	5.1	4.5	1306	460	156	24	9.11	32.6	28.5	27.9	0.575	63	1.90	36
	C	650	58	22	24	0.90	1.13	0.17	5.7	4.5	2430	368	272	36	15.52	28.4	63.3	54.7	0.599	109	3.30	61
PD10	A1	200	43	29	28	0.70	3.65	0.48	5.8	4.6	1086	108	108	22	6.70	22.8	23.8	29.4	0.524	120	5.33	34
	AB	250	46	25	30	0.62	2.52	0.35	5.7	5.0	988	112	106	32	6.25	26.7	21.2	23.4	0.703	92	3.15	27
	B	330	55	18	23	0.96	2.06	0.32	5.0	4.6	1260	122	140	38	7.94	26.4	33.9	30.1	0.659	107	3.33	55
PD11	A1	170	45	25	28	0.57	7.03	0.78	4.8	4.3	1598	310	218	108	11.07	38.0	39.0	29.1	1.986	80	1.40	49
	A2	410	23	45	33	0.65	2.89	0.31	5.3	4.7	1594	142	258	44	10.68	40.2	32.0	26.5	0.470	106	2.43	52
	AB	800	53	22	23	1.01	3.64	0.41	6.1	4.8	1778	120	238	42	11.36	33.7	50.4	33.7	0.573	115	3.68	51
	B	1000	32	40	28	0.72	2.47	0.32	6.1	4.9	1400	132	148	54	8.81	30.4	31.7	28.9	0.779	112	3.28	57
PD12	A1	200	29	40	32	0.53	3.85	0.43	5.8	4.8	2036	214	222	42	12.76	26.3	40.4	48.5	0.675	97	3.15	50
	A2	330	39	32	27	0.67	2.69	0.31	5.8	4.6	1916	220	264	42	12.53	28.3	47.1	44.3	0.475	112	2.78	55
	A3	500	20	46	35	0.44	2.57	0.31	5.9	4.6	2238	212	340	30	14.70	24.9	42.3	59.0	0.318	108	1.83	42
	AB	700	20	45	37	0.39	2.11	0.27	6.0	4.6	2140	228	322	34	14.12	30.3	38.4	46.5	0.521	107	1.23	41
	B	800	29	40	33	0.49	1.53	0.24	6.0	4.8	1750	224	256	40	11.63	19.6	35.3	59.5	0.585	101	1.38	39
PD13	A1	200	39	31	29	0.67	4.46	0.52	5.4	4.7	1068	162	86	50	6.69	30.8	23.4	21.7	0.804	69	1.45	57
	A2	340	31	38	32	0.51	4.92	0.58	5.4	4.5	1498	118	124	38	8.99	42.4	28.5	21.2	0.544	104	2.75	67
	B	600	44	27	29	0.67	0.91	0.11	5.7	5.0	740	114	34	60	4.54	19.1	15.8	23.7	0.758	60	2.10	43

Profile	Hor	LD	Sand	Silt	Clay	BD	OC	N	pH	pH	Ca	K	Mg	Na	ExchC	CEC	EC*	BS	P	Fed	Mnd	Ald
		mm	-----------%	----------------		g cm^{-3}	-----------%	--------	w	KCl	---------------	mg kg^{-1}	------------		------molc kg^{-1}	------		%	mg kg^{-1}	-----g kg^{-1}	-----------	
PD14	A1	300	31	37	31	0.53	4.53	1.65	5.2	4.2	860	208	122	70	6.15	32.6	19.8	18.9	0.779	99	1.93	64
	A2	550	47	24	26	0.80	1.06	0.38	5.7	4.8	1526	282	252	32	10.59	33.7	40.1	31.4	0.821	78	3.50	68
	AB	720	36	34	30	0.58	1.06	0.38	5.6	4.6	790	108	154	38	5.68	30.1	18.8	18.8	0.464	146	4.18	56
	B	810	40	31	30	0.57	0.31	0.11	5.7	4.9	724	126	86	52	4.89	27.7	16.0	17.6	0.660	48	3.75	61
PD16	A	300	37	32	30	0.61	7.40	0.89	5.6	4.7	1304	166	148	22	8.27	29.7	27.8	27.9	1.049	81	3.63	49
	B	350	33	28	28	0.71	3.38	0.44	5.9	4.8	992	178	118	54	6.63	26.2	23.7	25.3	0.985	0	0.00	0
	C	420	28	43	28	0.70	0.18	0.04	5.7	4.8	528	136	42	76	3.67	19.5	13.0	18.9	2.046	34	1.60	18
PW19	A	450	47	20	34	0.4	3.36	0.44	5.7	5.5	992	178	144	80	6.96	18.4	20.7	37.9	1.129	67	2.10	31
	B	600	37	29	37	0.91	2.62	0.35	5.8	4.7	886	130	112	74	6.02	14.9	16.1	40.4	0.639	93	0.45	35
	G	850	45	30	27	0.9	1.33	0.19	5.8	4.9	726	170	84	68	5.06	16.3	18.6	31.0	0.865	31	0.28	33
PD20	A	450	37	34	27	0.72	5.96	0.67	5.5	4.5	1076	140	170	42	7.34	35.9	27.1	20.5	1.314	88	3.08	38
	B1	600	44	27	27	0.73	2.70	0.38	5.8	4.7	882	192	172	36	6.49	20.0	24.2	32.5	0.669	99	0.88	47
	B2	1000	22	42	37	0.63	1.65	0.28	5.9	4.9	1056	224	228	44	7.95	18.8	21.7	42.3	0.639	48	0.58	42
PW21	A1	220	19	44	42	0.34	3.61	0.52	5.2	4.2	900	192	266	38	7.37	27.4	17.7	26.9	0.695	90	1.33	63
	A2	480	29	30	32	0.55	1.51	0.22	5.2	4.2	2692	156	480	70	18.16	22.8	56.8	79.6	0.504	168	4.08	64
	G1	700	31	30	27	1.07	0.69	0.12	5.9	4.4	2168	134	580	64	16.30	29.6	59.4	55.1	0.566	111	3.73	84
PD24	A1	110	28	34	41	0.88	2.86	0.37	5.6	4.7	1456	136	228	58	9.78	28.3	24.1	34.6	0.965	163	4.80	61
	A2	490	38	33	32	0.85	5.89	0.72	5.3	4.2	982	122	120	56	6.47	29.0	20.3	22.3	0.736	126	2.18	38
	G1	750	42	32	22	0.76	3.66	0.44	5.4	4.4	1126	138	156	48	7.49	17.6	33.6	42.6	0.914	129	1.60	27
	G2	1000	51	25	23	0.95	0.32	0.07	5.6	4.4	478	142	74	46	3.57	12.0	15.8	29.9	0.735	181	1.23	25
PW25	A1	150	37	35	28	0.34	3.45	0.43	5.4	4.5	862	124	150	60	6.14	9.8	22.3	62.8	0.746	100	1.23	45
	A2	350	44	24	30	0.44	2.94	0.35	5.3	4.3	568	86	94	72	4.16	17.7	13.7	23.5	0.784	30	0.18	34
	G1	600	63	16	26	0.87	1.41	0.21	5.5	4.4	448	98	80	58	3.41	9.3	13.4	36.5	0.913	37	0.20	31
	G2	800	‡‡	‡‡	‡‡	0.9	0.91	0.14	5.6	4.5	462	112	78	52	3.47	8.8	‡‡	39.4	1.110	102	0.25	35
PW26	A1	120	‡‡	‡‡	‡‡	0.32	5.83	0.74	4.7	4.0	2796	532	680	174	21.77	39.1	‡‡	55.6	1.711	88	0.20	25
	A2	450	67	19	15	0.44	4.69	0.62	5.3	4.2	1546	88	360	66	11.24	25.0	73.7	45.0	2.041	134	0.53	22
	BC	767	‡‡	‡‡	‡‡	‡‡	1.42	0.22	4.9	4.4	910	58	320	48	7.57	33.7	‡‡	22.5	1.559	95	0.43	23
PW27	O1	100	n/a	n/a	n/a	0.4	12.40	2.10	5.3	4.1	564	124	98	50	4.17	37.0	‡‡	11.3	0.609	75	0.20	38
	O2	500	n/a	n/a	n/a	0.42	5.58	0.96	5.8	4.7	940	148	200	64	7.02	27.0	‡‡	26.1	1.050	69	0.20	41
	O3	1000	n/a	n/a	n/a	0.39	7.29	1.22	6.0	5.0	606	76	114	54	4.41	28.2	‡‡	15.7	0.930	67	0.38	33
PW28	A1	150	22	42	38	‡‡	5.02	0.76	5.9	4.8	1232	152	170	72	8.28	25.0	21.7	33.1	1.326	117	2.05	58
	A2	450	36	36	28	‡‡	1.37	0.22	5.7	4.5	894	106	114	64	5.97	13.9	21.5	42.9	0.821	96	2.68	44
	AB	600	39	31	29	‡‡	2.09	0.38	5.9	4.5	782	142	90	72	5.34	15.3	18.6	34.8	1.068	85	0.95	56
	B	1000	47	29	22	‡‡	0.82	0.16	6.0	4.8	626	134	66	62	4.29	15.3	19.4	28.0	0.868	80	0.25	42
PW32	A1	100	8	51	34	0.37	4.06	0.61	5.20	4.19	622	132	152	58	4.97	30.4	14.6	16.3	1.038	91	0.30	53
	A2	280	40	35	25	0.46	3.33	0.48	5.20	4.19	318	70	96	36	2.73	17.5	11.0	15.6	0.883	58	0.18	24
	G1	370	‡‡	‡‡	‡‡	0.74	2.34	0.33	5.91	4.53	518	88	136	40	4.12	17.6	‡‡	23.4	0.690	53	0.13	26
	G2	550	52	23	25	0.78	2.34	0.33	5.91	4.53	518	88	136	40	4.12	17.6	16.7	23.4	0.690	53	0.13	26
	G3	940	40	38	23	0.84	0.93	0.16	5.91	4.60	380	106	62	58	2.94	13.0	12.9	22.5	0.653	58	0.10	35

†Hor – South African Soil Classification master horizons (Soil Classification Working Group, 1991)

‡LD – lower depth, BD – bulk density, OC – soil organic carbon, pHw – soil pH in water, pH KCl soil pH by KCl, ExchC – sum of exchangeable cations (Ca, K, Mg, Na), CEC – cation exchange capacity; BS – base saturation, P – labile phosphorus, Fe_d, Mn_d and Al_d are dithionite citrate extractable iron, manganese and aluminium respectively.

††EC – exchangeable cations per kg clay for every one per cent of organic carbon (Soil Classification Working Group, 1991)

‡‡ Missing values of particles size analysis, CEC, EC, BS, SOC results were either omitted because of high or too low values observed or samples spilled off from storage.

n/a is for a peat soil where texture of peat was determined by feel method.

APPENDIX 2C: SELECTED SOIL PROFILES PHOTOGRAPHS OF TYPICAL SOILS OF BOKONG

Figure 1 Melanic A in PD11

Figure 2 Non–diagnostic yellow brown apedal in PD01

Figure 3 Profile PW21 which was previous identified as “Wetland 2” in the study by Marneweck and Grundling (1999).

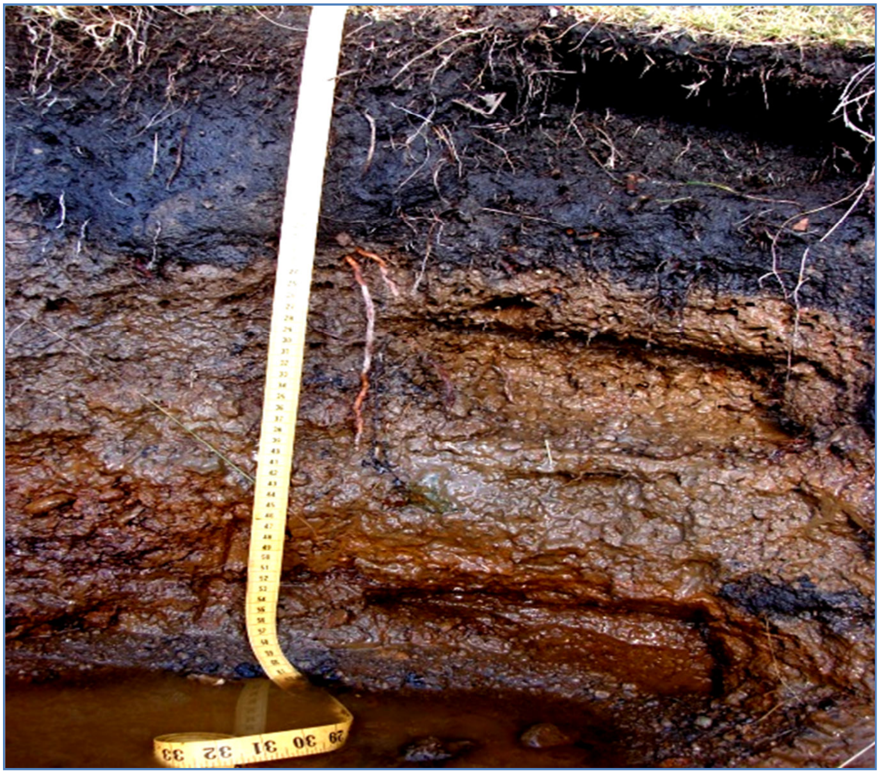

Figure 4 Profile PW06 with shallow peat depth.

Figure 3 Profile PW07 with deeper peat depth.

Figure 3 Landscape position of hillslope seeps and bogs of Bokong PW06 and PW07.

Figure 7-6 Valley head fens of Bokong (PW26)

APPENDIX 3: WATER TABLE LEVELS

	PW06					PW07					PW08				
Date	5	25	50	75	100	5	25	50	75	100	5	25	50	75	100
7-Sep-09	5	9.8	6.7	14.9	56.9	5	0		0	45	5	6.8	7.5	0	0
21-Sep-09	5	11	15	11	20.5	5	0	6	0	0	5	7	8	0	0
7-Oct-09	5	25	50	16	8	5	25	50.0	75	100	5	25	50	75	100
21-Oct-09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Nov-09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Nov-09	5	25	50	31	8	0	0	0	0	0	0	0	0	0	0
10-Dec-09	2	7	0	7	90	0	25	50	16	48	0	1	8	3	9
21-Jan-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Feb-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-Feb010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
07-Mar010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-Mar010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Apr-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-Apr-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-May-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-May-10	5	25	26	5	12	0	0	0	0	0	5	25	12.5	22	22
7-Jun-10	5	25	25	12	65	5	0	31	28	25	5	12.5	11	14.5	0
22-Jun-10	5	25	20	60	100	5	25	50.0	75	100	5	25	50	75	100
7-Jul-10	5	25	50.0	75	100	5	25	50.0	75	100	5	25	13	35	90
23-Jul-10	5	25	50.0	75	100	5	25	50.0	75	100	5	25	50.0	75	100
20-Aug-10	5	25	50.0	75	100	5	25	50.0	75	100	5	25	50.0	75	100
7-Sep-10	5	25	50.0	75	100	5	25	50.0	75	100	5	25	50.0	75	100
21-Sep-10	5	25	25.5	20.5	25.5	5	25	50.0	75	100	5	25	50	70	100
7-Oct-10	5	25	25.5	20.5	25.5	5	25	50.0	75	100	5	25	50	70	100
22-Oct-10	0	0	0	0	0	0	0	0	0	0	5	18.9	19.8	0	17
7-Nov-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Nov-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-Oct-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23-Oct-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Nov-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23-Nov-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Dec-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Dec-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Jan-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Jan-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Feb-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Feb-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Mar-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Mar-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Apr-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Apr-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-May-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-May-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Jun-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Jun-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Jul-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Jul-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Aug-11	0	10	2	11	21	0	0	0	0	0	0	0	0	0	0
21-Aug-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX 3 CONT…

	PW19					PW21					PW24				
Date	5	25	50	75	100	5	25	50	75	100	5	25	50	75	100
7-Sep-09	3	25	7	4.4	10.6	5	25	36	37	30.5	5	25	22.5	37	21.2
21-Sep-09	5	0	7	24	19	5	25	50	45	40	5	25	25	38.5	35
7-Oct-09	5	0	7	24	19	5	25	37	23.5	26	5	3	0	0	10
21-Oct-09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Nov-09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Nov-09	0	0	0	0	0	0	12	8	13	5	0	0	0	0	0
10-Dec-09	0	0	0	0	0	0	8	20	10	15	0	23	10	31	25
21-Jan-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Feb-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-Feb010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
07-Mar010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-Mar010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Apr-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-Apr-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-May-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-May-10	0	5	7	4.5	10.6	5	25	46.5	45.6	38	5	17.2	18.3	12.6	84.6
7-Jun-10	0	8	8	3	0	5	25	50	45	70	0	0	0	20	0
22-Jun-10	5	0	7	24	19	5	25	37	23.5	26	5	3	0	0	10
7-Jul-10	0	8	8	3	0	5	17	15	18	36	0	0	0	8	0
23-Jul-10	5	25	50	75	100	5	25	50.0	75	100	5	25	50	75	100
20-Aug-10	5	25	50.0	75	100	5	25	50.0	75	100	5	25	50	75	100
7-Sep-10	5	25	50.0	75	100	5	25	50.0	75	100	5	25	50.0	75	100
21-Sep-10	0	25	50	16	100	5	0	9	19	5	5	0	23	21	100
7-Oct-10	0	25	50	16	100	5	0	9	19	5	5	0	23	21	100
22-Oct-10	0	8.1	7	0	0	5	25	38	35	33	0	0	0	15.1	0
7-Nov-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Nov-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-Oct-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23-Oct-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Nov-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23-Nov-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Dec-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Dec-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Jan-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Jan-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Feb-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Feb-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Mar-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Mar-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Apr-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Apr-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-May-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-May-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Jun-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Jun-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Jul-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Jul-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Aug-11	0	0	0	0	0	0	0	0	0	0	0	23	10	31	25
21-Aug-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX 3 CONT…

	PW25					PW26					PW27				
Date	5	25	50	75	100	5	25	50	75	100	5	25	50	75	100
7-Sep-09	0	5	3	0	0	5	25	22.5	37	21.2					
21-Sep-09	0	0	11	5	3	5	25	22.5	37	21.2	0	0	0	0	0
7-Oct-09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Oct-09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Nov-09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Nov-09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10-Dec-09	0	0	0	0	0	0	0	0	12	17	0	5	0	0	0
21-Jan-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Feb-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-Feb010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
07-Mar010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-Mar010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Apr-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-Apr-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-May-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-May-10	0	2	0	0	9.5	0	0	0	10	10	**5**	0	1	0	3.3
7-Jun-10	0	10	0	9	17	0	0	0	0	0	0	0	37	36	34
22-Jun-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Jul-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23-Jul-10	5	25	50.0	75	100	5	25	50.0	75	100	5	25	50.0	75	100
20-Aug-10	5	25	50.0	75	100	5	25	50.0	75	100	5	25	50.0	75	100
7-Sep-10	5	25	50.0	75	100	5	25	50.0	75	100	5	25	50.0	75	100
21-Sep-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Oct-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22-Oct-10	0	6	0	0	2	0	0	0	0	0	0	0	0	0	0
7-Nov-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Nov-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9-Oct-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23-Oct-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Nov-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23-Nov-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Dec-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Dec-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Jan-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Jan-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Feb-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Feb-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Mar-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Mar-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Apr-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Apr-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-May-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-May-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Jun-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Jun-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Jul-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21-Jul-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7-Aug-11	0	0	0	0	0	0	0	0	0	0	0	0	19	17	25
21-Aug-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX 3 CONT…

	PW32				
Date	5	25	50	75	100
7-Sep-09	0	4.5	0	0	0
21-Sep-09	0	0	5	28	15
7-Oct-09	0	0	50	14	91.5
21-Oct-09	0	0	0	0	0
7-Nov-09	0	0	0	0	0
21-Nov-09	0	0	0	0	0
10-Dec-09	0	25	15	21	21
21-Jan-10	0	0	0	0	0
7-Feb-10	0	0	0	0	0
22-Feb010	0	0	0	0	0
07-Mar010	0	0	0	0	0
22-Mar010	0	0	0	0	0
7-Apr-10	0	0	0	0	0
22-Apr-10	0	0	0	0	0
7-May-10	0	0	0	0	0
22-May-10	0	0	0	11	14.5
7-Jun-10	0	0	0	5	7
22-Jun-10	0	0	50	14	91.5
7-Jul-10	0	25	50	75	100
23-Jul-10	5	25	50.0	75	100
20-Aug-10	5	25	50.0	75	100
7-Sep-10	5	25	50.0	75	100
21-Sep-10	0	8	50	11	10
7-Oct-10	0	8	50	11	10
22-Oct-10	0	0	0	30	36
7-Nov-10	0	0	0	0	0
21-Nov-10	0	0	0	0	0
9-Oct-10	0	0	0	0	0
23-Oct-10	0	0	0	0	0
7-Nov-10	0	0	0	0	0
23-Nov-10	0	0	0	0	0
7-Dec-10	0	0	0	0	0
21-Dec-10	0	0	0	0	0
7-Jan-11	0	0	0	0	0
21-Jan-11	0	0	0	0	0
7-Feb-11	0	0	0	0	0
21-Feb-11	0	0	0	0	0
7-Mar-11	0	0	0	0	0
21-Mar-11	0	0	0	0	0
7-Apr-11	0	0	0	0	0
21-Apr-11	0	0	0	0	0
7-May-11	0	0	0	0	0
21-May-11	0	0	0	0	0
7-Jun-11	0	0	0	0	0
21-Jun-11	0	0	0	0	0
7-Jul-11	0	0	0	0	0
21-Jul-11	0	0	0	0	0
7-Aug-11		0	0	0	0
21-Aug-11	0	0	0	0	0

APPENDIX 4: COMPARISON OF SOIL ORGANIC CARBON DETERMINATION METHODS.