

Spatial Variability of Hydric Soil Properties to Delineate Khalong-la-Lithunya Wetlands

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Thesis

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in Soil Science and Resource Conservation in the Faculty of Agriculture, Department of
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DECLARATION

I declare the thesis hereby submitted by me for Master of Science Degree in Soil Science at the National University of Lesotho as my own work and that to the best of my knowledge contains no work submitted previously as thesis for any degree at any other university. I further more cede copyright of the thesis in favour of the National university of Lesotho.

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CERTIFICATION

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DEDICATION

Thanks go to my dear wife, Matlhohonolofatso, our daughters, Tlhohonolofatso and Retlotliloe for their steady support. Thanks to my late parents Mapakiso and Makeoane Rasekoele. Dream big and work hard! My parents modelled simple values and a steady work ethic that will remain a treasured gift always.

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BIOGRAPHICAL SKETCH

Motlalepula Gerard Rasekoele was born on October 07th, 1985, at Rankakala village, in Qacha'snek district Lesotho. The author did C.O.S.C at Rankakala High School in 2005. In 2006 he was hired as a private teacher at Rankakala High School. Thereafter, he went to National University of Lesotho in 2007 where he was awarded Bachelor of Science in Agriculture with option in Soil Science and Resource Conservation. The author joined the National University of Lesotho as teacher assistant in 2013. Upon successful completion of the degree programme, he enrolled in Post Graduate Diploma in Education (PGDE) at the National University of Lesotho in 2013/14. In 2014, the author was awarded a scholarship from Regional University Forum (RUFORUM) to study for Master of Science with option in Soil Science and Resource Conservation at the National University of Lesotho. The author joined the National University of Lesotho as teacher assistant in 2015 while pursuing his Master of Science degree in Soil Science and Resource Conservation.

ABSTRACT

Spatial variability in wetland soils provide insight into underlying ecosystem processes and may itself give an indication of wetland condition. The study was conducted to characterise and delineate soil variability of wetlands of Khalong-la-Lithunya from hydric soil properties. Sampling was carried on three sub catchments within Khalong-la-Lithunya catchment. In each sub catchment, soil samples were dug at 100m interval along three transects that were 200m apart. Detailed soil profile description of 36 pits was done using USDA-NRCS (2010) manual. Field data included detailed description of redoximorphic features. Soil samples were collected at the depth of 0-15, 15-30, 30-45, 45-60, 60-75 and 75-90cm for determination of chemical and physical soil properties. Soil samples were analyzed for moisture content, soil organic carbon (SOC), soil organic matter (SOM), base cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+) and CEC, available P (Av-P), available Nitrogen (Av-N), and soil pH particle size analysis (sand, clay and silt).

Mean soil properties were 3.5mg/kg Av-p, 3.0mg/kg Av-N, 28.3% SOC, pH 5.1, bulk density 0.7g/cm^3 and the texture is sandy. The means base cations were 2.8, 1.8, 7.9 and 2.3cmol/kg for Na, K, Ca and Mg respectively with CEC 82.5cmol/kg included. Av-P was the most variable property with CV ranging from 115 and 162% in different soil depths while pH was the least variable with CV ranging from 6 and 12%. The Nugget/Sill ratios were less than 56%, indicating random heterogeneity. The semivariograms indicated moderate spatial dependence ($25\% < \text{DSD} \leq 75\%$) for soil properties including SOC, Av-P, Av-N, pH in water and sand. Most properties indicate moderate spatial dependence and hence easily managed. The physical properties were least variable; however, silt and silt/clay ratio had weak spatial dependence and thus not easily managed.

All soil properties were not significantly different between depths and showed inconsistent trends down the profile except for Av-N which was significantly higher at 45-60cm depth. Homogeneous profile and inconsistent trend of properties down the profile indicates the influence of biogeochemical processes that take place within the wetland. Amongst the identified hydric field indicators, Histosols (**A1**) and histic epipedon (**A2**) indicators were frequent in many profiles.

The occurrence of these unique properties within the landscape is therefore used to delineate wetlands and can be used as indicators of wetland conditions. Soils were classified as Humic Dystrudepts, Typic Cryaqualfs, Histic Cryaquolls, Fibric Haplohemists, Cumilic Cryaquolls

and Fluvaquentic Cryofibrists. There is a need for future research focusing on verifying and adding more soil indicators within the highland ecosystems to develop hydrologic criteria that will be used to further characterise soils of such highland wetlands. Facing the intensification of land-use conversion, wetlands soil management and careful land use planning are needed to take into account the spatial variability of soil properties, delineating management zones and conservation practices and other efforts to introduce conservative and protective measures to control soil erosion. Future research is needed to seek for appropriate approaches with regard to wetlands use management and more especially the grazing system of Lesotho in the highlands agro-ecological zone.

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LIST OF ACRONYMS

Av-N.....	Available Nitrogen
Av-P.....	Available Phosphorus
BD.....	Bulk Density
CEC.....	Cation Exchange Capacity
CV.....	Coefficient of Variation
DWAF.....	Department of Water Affairs
FAO.....	Food Agricultural Organisation
NRCS.....	Natural Resource Conservation services
NTCHS.....	National technical committee for hydric soils
SOC.....	Soil Organic Carbon
USDA.....	United States Department of Agriculture
DSD.....	Degree of Spatial Dependence
MSE.....	mean square error
G.....	Goodness-of-Prediction Criterium

CHAPTER ONE: INTRODUCTION

1.1 Background

Wetlands are dynamic ecosystems with a complex interrelationship of hydrology, soils and vegetation (Dabrowska- Zielinska *et al.*, 2015). Characteristically, wetland soils are saturated with water during all or significant portions of the year, resulting in poor oxygen penetration and chemically reducing conditions. The Ramsar Convention (1971:246) regards wetlands as “*area of marsh, fens, 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*”. According to Mokuku *et al.* (2002), Lesotho is among signatory countries that adopted Ramsar wetlands definition. Inventories on the wetlands of Lesotho, classifies wetlands as palustrine, sub-class alpine-mire as peatlands (Grundling, 1999). The classification was adapted from the “Cowardin” wetland classification developed in USA (Cowardin *et al.*, 1979), which uses vegetation types to classify wetlands.

Wetlands are found in a wide range of ecological conditions and are classified into *palustrine, riverine, lacustrine, estuarine* and *marine* wetlands based on their ecological systems. *Palustrine, lacustrine* and *riverine* wetland systems are found in Lesotho with the *palustrine wetlands* being the dominant type and these include mires (bogs and fens) most of which are found at high altitude, at valley heads and at the upper reaches of rivers. These have been referred to as “sponges”; *lacustrine system* consisting of artificial impoundments for water supply and/or soil conservation work; *riverine systems* along the rivers and streams (ORASECOM 2000). These wetlands are a unique environmental resource making significant contributions to the region’s ecological diversity, and they are inextricably linked to the water supply of the major river basins as well as naturally regulating flow in the Senqu/Orange River Basin (ORASECOM, 2000).

The wetlands of Lesotho are primarily important for their hydrological functions. They have been used for livestock grazing since the 1880’s (Centre for Environmental Management, 2010) and have also been a source of medicinal, building and craft material. However, the alpine rangelands have been severely overgrazed (Marake *et al.*, 1998; MDTP, 2007). The effect has been to cause serious erosion in both uplands and wetlands; the gulley erosion in

wetlands is effectively draining them. Consequently, the social, economic and ecologic functions of the highland watersheds are threatened.

Degradation of wetland systems in Lesotho has been identified as one of the environmental problems facing the country (Government of Lesotho, 2010; MDTP, 2007). Due to the problems perceived to be emanating from degraded wetland conditions, the Department of Water Affairs has conducted background assessments which provided the basis for formulating the Wetlands Restoration and Conservation (MCA-Lesotho, 2009).

Spatial variability cannot only provide ecosystem underlying processes but also is an indication of the wetland conditions (Nkheloane *et al.*, 2012). There is sparse information regarding quantification of spatial variability of soil properties in wetlands of Lesotho. Additionally, Bruland and Richardson (2005) show that the combined action of processes such as surface runoff, erosion and overbank flooding, sediment deposition, groundwater inputs, fire, animal burrowing, litter production, and root activity contribute to a high degree of spatial variability in wetlands. The more the SOM content and its variability in an area, the more one could expect biological diversity which ultimately adds to the soil variability due to the physical activities of animals and or chemical reactions enhanced by microbes.

In studying soil spatial variability in wetlands of Lesotho in both Tsakholo and Thaba-Putsoa wetlands, Nkheloane *et al.* (2012) reported that, the soil chemical properties yielded much higher coefficient of variation (CV) values than the physical properties, and thus indicate their high degree of variability. The CV values for SOC exceeded 20%, which indicated considerable variability. Soil organic carbon and texture could be used for the sustainable management of the wetlands of Lesotho (Nkheloane *et al.*, 2012).

In Lesotho, studies revealed that anthropogenic pressures and climate variability are among other factors that induce spatial variability in wetland soil properties (Olaleye *et al.*, 2012). Spatial variability of soil chemical properties like pH, organic matter content, available potassium, phosphorus and nitrogen and total micronutrients have been studied by different researchers in different soils under different management systems across the world (Li *et al.*, 2011).

Understanding the spatial variability of soil properties in the wetland soils of Lesotho is important for evaluation of wetland in terms of degradation and health status for management decisions (Behera and Shukla, 2014). The aim of this study therefore was firstly to delineate

Khalong-la-Lithunya wetland through soil spatial variability of hydric and secondly to evaluate wetland health status.

1.2 Statement of the problem

The current wetland delineation uses satellite imagery which is based on vegetation and soil wetness. However, limited attention has been paid to the use of hydric soil spatial variability to evaluate ecological functioning of wetlands. The link between wetland hydrology and ecological functioning is normally established by developing the wetland water budget, which is affected by land use and soil types. However, because of insufficient hydrological data, it is difficult to define minimum hydrological thresholds for wetland ecological functioning. Therefore, the study was intended to supplement available hydrological data with the use of hydric soil indicators to assess wetland functioning.

Previous studies on wetlands of Lesotho were based on classical statistics which provided soil information measured at single points in space, and thus were not sufficiently analysed spatially as there is a need of soil information of the entire catchment. Quantification of spatial variability of soil properties in wetlands of Lesotho is poorly understood. Furthermore, limited attention is paid to the use of hydric soil spatial variability to evaluate ecological functioning of wetlands.

Many parts of the world have now experienced wetland loss or degradation on a huge scale, reducing the ability of wetlands to provide goods and services for human and environmental needs. The mountain wetlands of Lesotho play a pivotal role in substantiating the indefinite water flow and regulating the water quality of the major Senqu-Orange River system (ORASECOM, 2000). They serve as an economic trade in quality water between South Africa (SA) and Lesotho (Treaty on the Lesotho Highlands Water Project, 1986). The wetland catchments also provide livestock grazing (Turpie & Malan, 2010). However, all wetlands and surrounding catchments exhibit evidence of degradation with gullies draining the wetlands (Sieben & Morris, 2010). According to these authors, constituents that lead to the wetlands and catchment degradation include soil erosion due to the high altitude system, steep topography, and increased grazing pressure. Nonetheless, there is little published scientific information on the status of spatial variability of hydric soil properties of wetlands in Lesotho and digitalised soil mapping data format on hydric soil properties that can be used to design efficient monitoring and management schemes by wetland managers as indicated by

Nkheloane *et al.* (2012), hence, the goal of this study is to delineate the Khalong-la-Lithunya wetland.

1.3 Justification

The Khalong-la-Lithunya wetland is subjected to a severe degradation that is triggered by accrued soil erosion and anthropogenic activities such as grazing of the land; as a consequence, the ecological functioning of the wetland is impacted negatively. This study intends to close a gap on lack of information regarding the quantification or measurement of the level of degradation and health status of the Khalong-la-Lithunya wetland. The study employed the use of geostatistics which allowed determination of spatial dependency and variability of soil properties and permitted estimation of values at un-sampled wetlands area by taking into account the spatial correlation between estimated and sampled points and minimizing the variance of estimation error. The examinations made on spatial dependency and variability of the hydric soil properties based on geostatistical analysis will address issues such as where exactly in a wetland do the conservation management intervention strategies need to be applied (for rehabilitation or restoration).

1.4 Hypothesis

Vertical and spatial variability that occur systematically can be used for wetland delineation and help to predict wetland functioning. Redoximorphic features such as mottling (redox concentration, redox depletion, gleying and reduced soil matrix) can be used to assess wetlands conditions.

1.5 Objectives

Generally, this study was intended to delineate and evaluate Khalong-la-Lithunya wetlands conditions through soil selected vertical and spatial variability of hydric soils.

Specific objectives

- To determine the spatial variability and dependence and heterogeneity of soil physical and chemical properties of the wetlands.
- To determine vertical distribution of physico chemical properties.
- To determine hydric soil redoximorphic features and delineate the wetland.

CHAPTER TWO: LITERATURE REVIEW

2.1 Wetland soils

Soil is the unconsolidated natural material present at the earth's surface that supports vegetation. Soil is an independent body (soil type) having specific properties and morphological characteristics that can be used to differentiate it from adjacent soil types. The properties and characteristics of each soil type are influenced by such soil forming factors as climate, parent material and time, topography and living organisms. The key soil properties that are important in the identification of wetland soils include horizonation, organic matter content, texture, permeability, drainage, and colour (MCA-Lesotho, 2010). Wetland soils are hydromorphic soils, or hydric soils that for a significant period of the growing season have reducing conditions (soil is virtually free of oxygen) in the major part of the root zone and are saturated within the 250mm of the surface. They are either organic or mineral soils. The organic soils are commonly termed peat. They are isolated on the basis of the organic carbon content (Richardson & Vepraskas, 2001).

Organic soils generally have higher organic matter content, lower bulk density and higher water holding capacity and higher porosity (Richardson & Vepraskas, 2001). Anaerobic soil conditions promote the accumulation of organic matter by impeding decomposition. Consequently, those wetland zones subject to the longest wet periods generally have the highest organic matter content as indicated by Barnal (2008). Process of decomposition limits oxygen (O₂) availability thus prohibiting aerobic respiration and partly decomposed organic material is accumulated in the top soil giving the soil dark brown or black colours (Richardson & Vepraskas, 2001). Davidson & Janssens (2006) adds that low temperatures also promote organic matter accumulation, so much that for a given water regime, more organic matter will accumulate in a cool climate than in a warmer one. The minimum proportion of organic carbon (OC) required for soil material to be classified as organic ranges from 12 to 18% (Kotze *et al.*, 1996; De Brogniez *et al.*, 2015). According to Huang *et al.*, (2008), the variable OC limits are based on the observation that a given proportion of organic matter modifies the properties of a sandy material more than it does to those of clay material. An organic soil must either have at least 400mm of organic material within the upper 800mm of the soil or organic material of any thickness extending from the soil surface to rock or gravel (Soil Survey Staff, 1975). The bulk density of organic soils is less than 0.6g/cm³ compared to 1.0 – 2.0g/cm³ of mineral soils (Mitsch & Gosselink, 1993; Kogelbauer, 2010)

however, Köchy *et al*, (2015) show that low bulk density is associated with organic soils (high Organic carbon mass) and (a change from, 0.1 to 0.2cm³ leads to a doubling of soil organic carbon stock and mass). Variation within the range of bulk density typical of mineral soils, for instance, 1.2–1.8g/cm³, is less consequential. Hydric mineral soils vary greatly with regard to properties such as texture, pH and mineralogy.

Most hydric soils are either very poorly drained or poorly drained and have properties that reflect dominant colours in the matrix called mottles. The mottles are formed as a result of anaerobic conditions that affect chemical state of elements in the soil leading to reduced (low) soil redox potential (Eh, mV) conditions (Pezeshki & DeLaune, 2012). Reduction-oxidation reactions in soils are controlled by the aqueous free electron activity pE often expressed as Eh redox potential and high levels of Eh redox potential are encountered in dry, well aerated soils, while soils with a high content of organic matter or subject to waterlogging tend to have low Eh values. These reactions include physical, chemical and biological processes. Consequently, low Eh values generally promote the solubility of heavy metals. Physical processes include restriction of atmospheric gas diffusion in the soil leading to depletion of soil oxygen and accumulation of carbon dioxide. Shortly after flooding, the limited supply of oxygen in soil pore spaces is depleted rapidly by roots, microorganisms, and soil reductants (Pezeshki & DeLaune, 2012). This process leads to oxygen depletion and reduction in soil oxidation reduction potential (Eh) followed by a chain of soil chemical changes. The processes that follow include reduction of iron, manganese and sulfate, and changing soil pH and Eh. For example, in a typical series of reductions Mn⁺⁴ is reduced to Mn⁺² and Fe⁺³ to Fe⁺² (depending upon pH).

Process of mottling can result in the formation of mottles of reddish or blackish, yellowish or orange colour. Redoximorphic features can be redox concentrations, redox depletions, or reduced matrices. Redox concentrations occur when reduced iron and manganese dissolve in the soil, precipitate out, accumulate and typically form bright areas in soils that are alternately wet and dry. Redox concentrations become redder and depletions have chroma of 2 or less pale, and if there is no mottling the chroma is 1 or less. Areas where iron and manganese have been dissolved and removed are referred to as redox depletions (MCA-Lesotho 2010). A reduced matrix occurs when ferric iron, which under normal oxygen concentrations exhibits yellowish to reddish colors, is reduced and the soil appears grey. Grey, and to lesser extent blue and green colours predominate in gleyed soil material (Nell *et al.*, 2005; Kogelbauer, 2010). Periodic saturation results in the soil material being alternately anaerobic when wet

and aerobic when dry. Repeated re-precipitation of reduced iron in localized areas in the mineral soil material each time the soil is aerobic results in the formation of yellow, orange, red or black mottles (Pezeshki & DeLaune, 2012). Mineral soils that are permanently saturated are usually uniformly gleyed throughout the saturated area and show less mottling development, usually along root channels (Vepraskas, 2001).

2.2 Indicators of hydric soils

The identification of hydric soils, hydrophytic vegetation, and wetland hydrology are the three factors necessary for the delineation of wetlands (Army Corps of Engineers, 2008). The delineation of wetlands is a vital aspect of land use planning and resource development as supported by Berkowitz & Sallee, (2011). In order to identify hydric soils, Vasilas *et al.* (2010) indicated that Field Indicators of Hydric Soils were developed. These indicators typically focus on the morphologic features that result from prolonged and repeated anaerobic soil conditions in upper portions of a soil profile. The occurrence of these unique properties within the landscape is used as indicators of wetland conditions (MCA-Lesotho, 2010). Morphological indicators of hydric soils include accumulation of organic matter, redox concentrations, and redox depletions including colour changes as a result of reduction and translocation of redox sensitive species and can be used to delineate wetland (Berkowitz & Sallee, 2011).

Preliminary determination of hydric soils can be done by excavating a soil pit to 500mm of the soil surface according to DWAF (2005) and within 300mm for both as posited USDA-NRCS (2010) and Australia (Bryant *et al.*, 2008). These depths comprise the rhizosphere of the most hydrophytic vegetation in the respective areas. Thick, dark surface layers indicate an accumulation of organic matter. Redoximorphic features seen in hydric soils include contrasting colors of redox depletions or reduced iron and zones of reddish iron that result in unique mottling. Similar features can be seen in the lower horizons of upland soils but are still not considered wetlands because there is no further evidence of a wetland environment (Brady & Weil, 2007). Matrix chroma, degree of mottling and presence of sulphur and other soil morphological features can be used to delineate wetlands.

The hydric soil field indicators in the United State 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 National Technical Committee for Hydric Soils (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 & 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. Gley and cumulative saturation representing hydric indicators such as histisols, histic epipedon, umbric surfaces, loamy gleyed matrix can be used to determine the duration and frequency of the water table in the landscape and these hydric indicators can be used to delineate wetlands, though, more indicators can be developed (Mapeshoane, 2013). 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, Mapeshoane, 2013).

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 and it is the zone that is used by the USDA-NRCS (2010) to develop the hydric soil indicators. The existence of indicators in the temporary zones also assumed that soils in the interior of the wetland also are hydric. It is vital for delineators using these tools to sample only the edge of the wetland (Mapeshoane, 2013).

2.3 Spatial soil information and soil survey

Spatial variability in soils occurs naturally as a result of complex interactions between geology, topography and climate (Panagopoulos *et al.*, 2015). Moreover Wang & Shao, 2013 support that the spatial variability of soil properties, which influence soil susceptibility to erosion, is highly related to anthropogenic factors such as grazing. The susceptibility of land degradation depends largely on various inherent soil properties, namely chemical, physical, biological and mineralogical properties (Panagopoulos *et al.*, 2015). Wetland degradation is a global problem. Best management of degraded land can be done by evaluating the spatial variability of soil properties including chemical properties of degraded land and mapping such variations as proposed by Zhao *et al.* (2013). Thus, understanding the patterns and processes of soil spatial variability is a key to efficient soil resource management (Ziadat and Tamimeh, 2013).

Stolt *et al.* (2001) illustrated that several processes can influence soil spatial patterns at a particular location. In line with these authors Bruland & Richardson (2004) showed that

wetland type may strongly affect spatial pattern. The uneven distribution of soil characteristics such as nutrient availability, organic content, and mineral content implicitly reflects the processes that occur within the larger ecosystem (Corstanje *et al.*, 2006).

Classical statistics and geostatistics methods have been widely applied in studies about spatial distribution of soil properties (Tesfahunegn *et al.*, 2011). According to Wilding and Drees (1978) the coefficient of variation (CV) for a particular property is considered low if it is <15%, moderate if it is 15–30%, and high if it is >35%. Nkheloane *et al.* (2012) added that, of the soil chemical properties, soil pH was reported to have low variability (CV <15%) in two contrasting wetlands and thus more homogenous. Available P showed extreme variability at both sites, with CV values in the highly variable range (CV >35%). The SOC was moderately variable with CV values mostly 15–33% and highly variable in other site showing more heterogeneity. The soil physical properties such as textural fractions had low to moderate variable in both wetlands. Omotoso & Akinbola (2007) found silt, clay and gravel, organic C, total N, available P, Mn, and K to be highly variable (CV>35%) while sand, Ca, Mg, and N were moderately variable (CV 15-35%). The soil pH was in line with the one reported by Nkheloane *et al.*, (2012) with least variable of (CV<15%). The variance ratio test indicate that some properties which are most influenced by management significantly ($p<0.01$) affected the variability of the soil.

Today different geostatistical and geographic information systems (GIS) spatial analysis techniques are used widely for prediction of spatial variations of the soil properties (Gao *et al.*, 2011). Increasingly, detailed soil data from multiple counties and states are being viewed and analyzed together. To address resource issues ranging from local to global scales, environmental scientists and policymakers are seeking soil information that is more specific (soil properties) and more detailed (spatially explicit). These user's needs represent a challenge for soil scientists to provide new spatial soil information, particularly in a digital format that is readily incorporated into (GIS) and can be analyzed with other spatial data as proposed by Lagacherie & McBratney (2007).

Geostatistical techniques based on predictions and simulations have been used to describe areas where predicted information is established by a limited number of samples (Panagopoulos *et al.*, 2015). Geostatistics provides tools for analyzing spatial variability structure and distribution of soil properties and evaluating their dependence (Panagopoulos *et al.*, 2014). These authors used the biplot methodology for analyzing spatial variability of soil

properties. This multivariate statistical technique allows the graphical representation of a large data matrix, whereby it is possible to interpret the relations between individuals (samples) and variables, as well as between both. Gallego-Álvarez *et al.* (2013) added that Biplot can also give an indication of clustering of units with close characteristics, designating inter-unit distances as well as displaying variances and correlations of the variables.

Knowledge of spatial dependency and distribution of soil properties is crucial for natural resource evaluation and environmental management of un-surveyed locations. Soil properties vary spatially from a wetland to a larger regional. Behera & Shukla (2014) observed that variation is a gradual change in soil properties as a function of landforms, geomorphic elements, soil forming factors and soil management scale affected by both intrinsic (soil forming factors) and extrinsic factors such as soil management practices. Strong spatial dependence of soil properties can be attributed to intrinsic factors such as soil properties and mineralogy, whereas, weak spatial dependence is due to extrinsic factors such as anthropogenic activities. Behera & Shukla (2014) added that moderate spatial dependence is owing to both intrinsic and extrinsic factors. The variation of soil properties should be monitored and quantified to understand the effects of land use and management systems on soils. Classical statistics like coefficient of variation (CV) could not identify the spatial variability of soil properties at the un-sampled sites. Geostatistical analysis, however, permits examination and understanding of spatial dependency and prediction of spatial variability of soil properties (Liu *et al.*, 2006). Additionally, geostatistical estimation aids in predicting values at unsampled location by taking into account the spatial correlation between estimated and sampled points and minimizing the variance of estimation error and implementation costs (Saito *et al.*, 2005).

Behera & Shukla (2014) stated that range value is a measure of the spatial extension within which autocorrelation exists. Estimates of range tend to depend on landscape and may also indicate the distance across distinct soil types. Samples separated by distances closer than the range are spatially related, and those separated by distances greater than the range are not spatially related. These authors further showed that a large range value of a soil property gives an indication that the value of measured soil property is influenced by natural and anthropogenic factors over greater distances. Different ranges of measured soil properties in wetland soils may be due to combined effect of parent material, hydrologic and climatic conditions and land management practices adopted in different wetland.

The formation of soil organic matter (SOM) is influenced by soil temperature, precipitation, land management, vegetation, biological activity and other bio-inputs. As stipulated by Behera & Shukla (2014) the high the SOM content and its variability in an area, the more one could expect biological diversity which ultimately adds to the soil variability due to the physical activities of the animals and sometimes chemical reactions due to the microbes. Therefore, it is important to understand and manage the existing wetland variability of soil properties for efficient and sustainable environmental functions.

CHAPTER THREE

SPATIAL VARIABILITY AND DISTRIBUTION OF THE SELECTED SOIL PROPERTIES

3.1 Introduction

Spatial variability is the considerable differences in space in soil properties that can be attributed to systematic or random factors that exist within a wetland area (Stolt *et al.*, 2001; Wilding & Drees, 1983). In wetland systems, this variability are due to numerous factors, including micro-relief, animal activity, any human activity, and the effect of individual plants on soil microclimate and precipitation chemistry (Panagopoulos *et al.*, 2015; Kavianpoor *et al.*, 2012). Baharom *et al.* (2015) add that spatial variation includes horizontal variation across a landscape and vertical variation with horizon depth. However, the variability of soil properties in space and time presents a challenge for wetlands assessment and the detection of changes within or among wetlands. Spatial variability is vital when considering the environmental and ecological functioning and delineation of wetland while spatial investigation of soil variability is essential for best wetland management (Stolt *et al.*, 2001; Kavianpoor *et al.*, 2012; Zhao *et al.*, 2013).

Baveye & Laba (2015) suggest that soil spatial variability studies with an objective to evaluate the “ecosystem services” are most relevant to the decision-making process. In addition, Zhao *et al.* (2013) ascertained that best management of degraded land can be done by evaluating the spatial variability of soil properties. Zhao *et al.* (2007) reported that spatial variability of soil chemical and physical properties are affected by graze intensity and heavy grazing decreases soil water content and soil organic carbon but increases bulk density and shear strength.

Soil properties with strong spatial dependence are more readily managed as shown by Nkheloane *et al.* (2012). These authors, together with Bruland & Richardson 2005; Grunwald *et al.* (2006) state that wetland ecosystems processes are dynamic and heterogenic, and exhibit substantial spatial and temporal variability in soil properties. This variability can have important consequences on wetlands biogeochemistry. There are several factors that control the spatial relationships in wetland systems such as pedogenic effects, parent material, elevation, erosional or depositional environment, frequency of flooding, vegetation, groundwater inputs, animal burrowing, root activity, litter production and hydrology (Bruland

& Richardson, 2005; Panagopoulos *et al.*, 2015). It is vital to recognise random effects and isolating them from systematic effects in order to understand spatial relationships in wetland soils (Wilding & Deers, 1983; Nkheloane *et al.*, 2012; Zhang *et al.*, 2014). Stolt *et al.* (2001) indicated that stratified sampling design may be crucial in quantifying soil variability.

Classical statistics and geostatistical methods have been widely applied in studies about spatial distribution of soil properties such as coefficient of variation and range (Tesfahunegn *et al.*, 2011). According to Nkheloane *et al.* (2012), of the soil chemical properties, soil pH was reported to have low variability (CV <15%) in two contrasting wetlands and thus more homogenous.

Today different geostatistical and geographic information systems (GIS) spatial analysis techniques are used widely for prediction of spatial variations of the soil properties (Lagacherie & McBratney, 2007; Gao *et al.*, 2011; Panagopoulos *et al.*, 2014; Panagopoulos *et al.*, 2015). Geostatistical analysis permits determination of spatial dependency and variability of soil properties and predict values at un-sampled location by taking into account the spatial correlation between estimated and sampled points and minimizing the variance of estimation error (Saito *et al.*, 2005; Liu *et al.*, 2006; Panagopoulos *et al.*, 2014). Furthermore Panagopoulos *et al.* (2014) showed that Geostatistical methods use mathematical and statistical functions for interpolation and their basis is statistical characteristics of data.

Silt percentage had strong spatial dependence according to the results of Cambardella *et al.*, (1994), Lopez-granados *et al.*, (2002); Weindorf & Zhu, (2010). Emadi (2008) reported a weak spatial dependence of nitrogen, phosphorus and sand while bulk density had moderate spatial dependence similar to what had been illustrated in the study by Cambardella *et al.* (1994). The ratio of nugget to sill (C_0/C_0+C) reflects the spatial autocorrelation generally. Variables with strong spatial structure and very low nugget effect have high continuous distribution in this area. Strong spatial dependence is due to the inherent variability of soil properties such as soil texture, mineralogy and less spatial dependence by non-intrinsic factors such as grazing (Davatgar *et al.*, 2000). Kriging uses the semivariogram to predict values at unobserved location using minimization of errors (Weindorf & Zhu, 2010).

Numerous studies have examined spatial variability in upland and wetland soils (Hammer *et al.*, 1987; Reese & Moorland, 1996; Bruland & Richardson, 2004; Corstanje *et al.*, 2006; Cohen *et al.*, 2008; Nkheloane *et al.*, 2012; Mapeshoane & van Huyssteen, 2016). Some studies have made spatial comparisons between soils of uplands and adjacent wetlands and

weak spatial dependence and variability has been observed in wetlands soils (Hammer *et al.*, 1987). Nkheloane *et al.* (2012) studied soil spatial variability in wetlands and found that soil chemical properties had more spatial variability than physical properties. In wetland soils, phosphorus availability is critical and it is influenced by iron through adsorption, retention, and release (Baldwin & Mitchell 2000; Aldous *et al.*, 2005); aluminium can likewise influence P availability (Darke & Walbridge, 2000). Additionally, Sims *et al.* (2002) found low or very low available P for created wetlands and low to medium for natural wetlands. Page *et al.* (2005) observed a gradual decrease of soil available phosphorus content as the elevation or slope increased in the two different first-order sub catchments. Soil organic matter/carbon is a natural spatial and temporally variable property in soils, however, in wetlands it has high spatial dependency (Vepraskas *et al.*, 2001).

Strong spatial dependence of soil properties can be attributed to intrinsic factors such as soil properties and mineralogy, whereas, weak spatial dependence is due to extrinsic factors such as anthropogenic activities. Moderate spatial dependence is owing to both intrinsic and extrinsic factors (Behera & Shukla, 2014). Corstanje *et al.* (2006) argued that the uneven distribution of soil characteristics such as nutrient availability, organic content, and mineral content implicitly reflects the processes that occur within the larger ecosystem. For example, the spatial variability of soil properties, which influences soil susceptibility to erosion, is highly related to anthropogenic factors such as grazing (Wang & Shao, 2013). The susceptibility of land degradation depends largely on various inherent soil properties, namely chemical, physical, biological and mineralogical properties (Panagopoulos *et al.*, 2015). Knowledge of spatial dependency and distribution of soil properties is crucial for natural resource evaluation and environmental management of un-surveyed locations. Best management of degraded land can be done by evaluating the spatial variability of soil properties including chemical properties of degraded land and mapping such variations as shown by Zhao *et al.* (2013). Thus, understanding the patterns and processes of soil spatial variability is a key to efficient soil resource management (Ziadat & Tamimeh, 2013). Knowledge of soil spatial variability is also necessary to locate homogenous sites that need careful management for sustainable development.

Based on the literature, the current study intended to determine spatial dependence and variability of soil properties using classical and geostatistical methods in the Khalong-la-Lithunya wetlands in Lesotho,

3.2 Material and methods

3.2.1 Study description

The study was conducted on three wetlands found within Khalong-la-Lithunya catchment. The catchment (Fig 1) is located at latitude 28°53'50.84"S and longitude 28°48'02.57"E in the mountain agro-ecological zone of Lesotho at an elevation ranging from 3100 to 3175m above sea level and has the national topographic map scale of 1: 50 000 with topographic number 2828DD. The catchment also forms part of sub catchments of a main quaternary sub catchment draining into Motete River which feeds into the Katse dam. Khalong-la-Lithunya wetlands cover an area of about 3280 hectares while the restored part is about 1332 hectares (Department of Environment, 2009).

The geology of the catchment is Lesotho formation with compact and amygdaloidal tholeiitic basalt (Schmitz & Rooyani, 1987). The basalt is an igneous rock that covered the Clarens Formation about 120 million years ago when Gondwana began to breakup. Basaltic colluvium and alluvium are the geologic material for the deep soils of the mountain valleys and accumulation glacia as stated by Schmitz & Rooyani. (1987). The soils, at altitude, are mostly shallow and have more or less even proportions of gravel, coarse sand, fine sand, silt and clay particles. The breakdown of organic matter is a slow process due to the long periods of very low temperatures. Especially in the peatlands, the accumulation of peat is the result of the decaying roots of the various plants species present on these wetlands. The peat has a high water-retention. Moroke series (local name) or Lithic Cryoborolls (USDA) covers the hillslopes and Oxbow Series (local name) or Hydric Cryohemists (USDA) covers the wetlands. The catchment is characterised by grasses: *Festuca caprina*, *Merxmüllera disticha* and *Pentaschistis oreodoxa*; shrubs and woody plants: *Chrysocoma ciliata*, *Erica dominans* and *Euryops evansii* (Olaleye *et al.*, 2012).

The rodents (ice rats) play a major role in the destruction of the vegetation thus showing lower yields. The impact is more evident at the start of winter when the vegetation dies back, and seemingly the ice rat “harvest” increases as the rodent collects and stores food in preparation for the winter chill. When there is precipitation, the convincible soils on the burrows erode easily and this would eventually result into gullies. The rodents also contribute in the bioturbation leading to soil surface heterogeneity. On an undisturbed peatlands, these ice rats’ (*Otomys sloggettii*) dens, runways and tunnels are limited to the peat land fringes and drier areas. The desiccation of the peat lands results in the encroachment of these rodents

onto the drier parts, especially around those areas near erosion gullies. Their tunnels contribute to the erosion and triggering the desiccation of a peat and changing of the wetlands conditions. The catchment is mainly used as rangeland and is sparsely populated by herd boys who live in the animal posts and people on work camps. The mean annual rainfall that is often recorded is 1000-3000mm. The temperature for the catchment ranges from 7.6 - 22.4°C and snowfalls are common in winter.

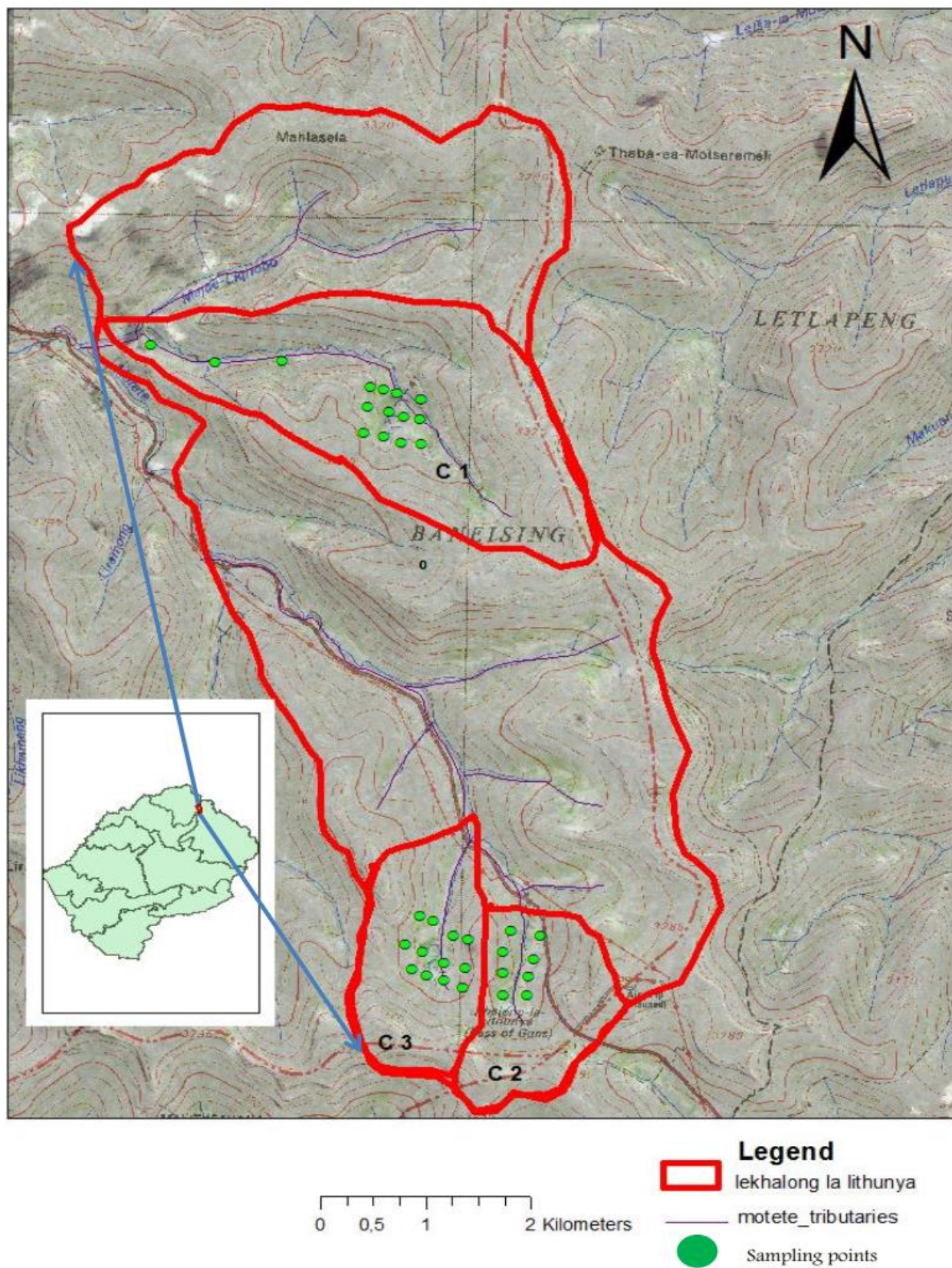


Figure 1: Location of Khalong-la-Lithunya in the Map of Lesotho and Sampling points in three sub-catchments

3.2.2 Soil sampling and analysis

A reconnaissance soil survey was used to map transects for soil profile description and soil sampling. In each wetland, three transects were marked at 200m intervals. The profile pits were dug along each transect at 50m along a transect (Fig 2). The GPS coordinates were recorded for each pit. A detailed soil profile description with reference to USDA-NRCS (2010) was done. Soil samples were collected at the depth of 0-15, 15-30, 30-45, 45-60, 60-75 and 75-90cm. Only the depth of 15cm was considered for spatial analysis (semivariogram determination). All depths were used for vertical distribution. Only a depth of 45cm was used for identification of redoximorphic features (redox concentration, redox depletion and gleying) and for soil hydric field indicators. Soil properties described included colour, horizon boundary, structure, consistency, texture, mottles, and roots density. A total of 184 soil samples were collected from the three wetlands which made up 36 pits. The samples were then carefully labelled and transferred to the laboratory. Bulk density and moisture content were determined using the core method.

The soil samples from each wetland were air-dried and crushed to pass through a 2-mm sieve, and analyzed for the following parameters, soil organic carbon (SOC) using the Walkley and Black (1934) method. Base cations (Ca^{2+} , Na^+ , Mg^{2+} , K^+) and CEC were measured using atomic absorption spectrophotometry. Available P was determined following Bray & Kurtz (1945), and available Nitrogen by the Kjeldahl digestion method (Bremner, 1965). Soil pH in water was measured using a glass electrode pH meter in 1: 2.5 soils: water ratio. Particle size analysis was carried out using Bouyoucos (1962) hydrometer method.

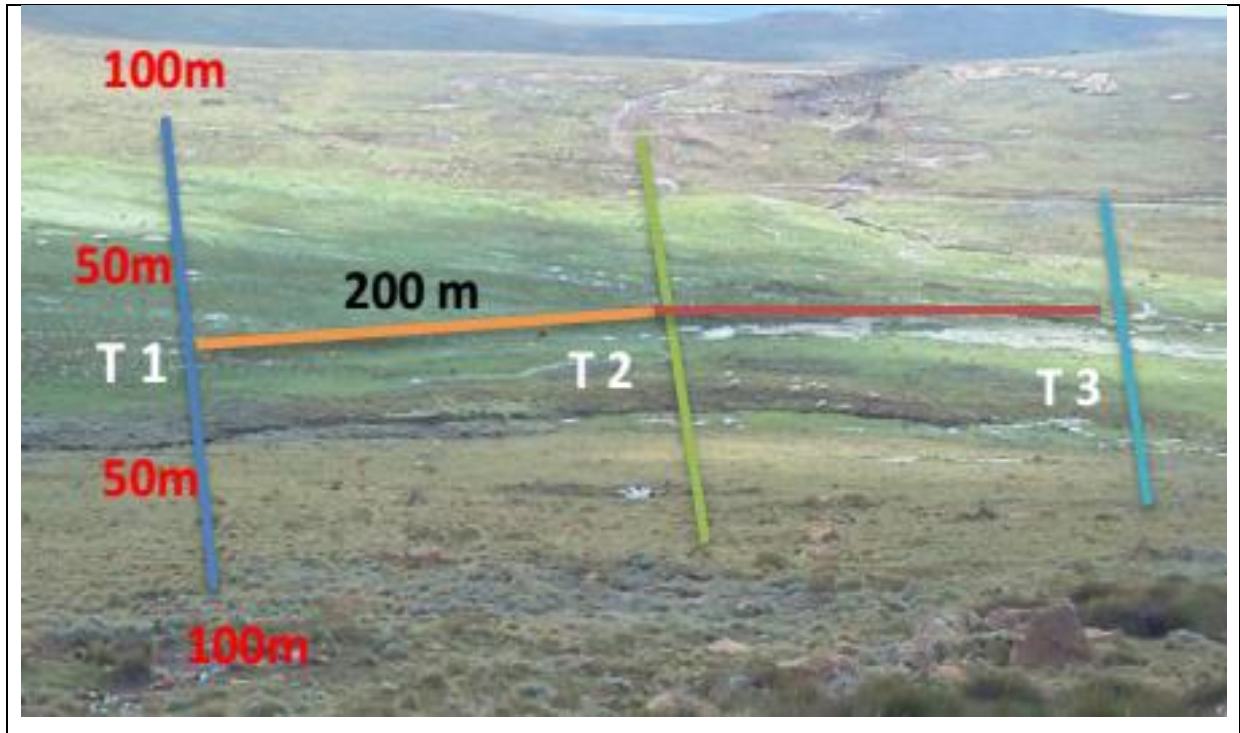


Figure 2: Sampling design showing transection demarcation within sub catchment (wetland)

3.2.3 Data Analysis

The General linear model procedure (Prog GLM SAS Inst., 1999) was carried out to establish statistical difference between depths. Mean separation was carried out using Duncan's Multiple Range Test (DMRT) at 5% significance level. Pearson correlation analysis was performed to examine the possible relationship between selected soil properties. The coefficient of variation (CV) was used to assess degree of variability for each soil property within each depth. The following equation was used

$$CV (\%) = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100.$$

3.2.4 Statistical and geostatistical analysis

The data on soil parameters were imported to the Geostatistical Analyst tool (ArcGIS 10.2.2) environment and subjected to descriptive analysis to obtain descriptive statistics, namely the mean, minimum and maximum; standard deviation (SD); skewness and kurtosis of each soil parameter. Prior to using geostatistics to obtain prediction maps, a preliminary analysis of data was done to check data normality and global directional trends. Normal quantile–quantile (Q–Q) plots were produced for observed values against the values expected for a normal distribution (Fu *et al.*, 2010). The Q–Q plot is a graphical technique that can be used to determine if two datasets come from populations with a common distribution, location and

scale or to check if the distribution of data for a given variable in a data set follows a normal distribution. Non-normal data were transformed to stabilize the variance. Then normality tests were recalculated using the transformed data, since asymmetry in the distribution of data has an important effect on the geostatistical analysis (Kerry & Oliver, 2007). Data transformation for normal distribution was necessary for some soil properties. Natural Logarithm and Box-Cox methods in geostatistical analysis tools were used to transform the data.

Trend analysis was also carried out to examine the presence of any global directional trend in data. This is the variation where properties vary as a function of their coordinates. According to McCormick *et al.* (2009), trend in the variation signals a departure from the intrinsic hypothesis in which the process is assumed to be random and it violates the assumptions on which geostatistics is based on. Kerry & Oliver (2007) suggested that when trend is removed, the variation will possibly be modelled more accurately because spatial analysis will not be influenced by trend.

Global trend exists if a curve that is not flat (i.e., a polynomial equation) can be fitted to the data. So, where necessary, the trend removal was done using geostatistical analysis tools to more accurately model the variation (Panagopoulos *et al.*, 2006). The semivariogram analyses were conducted before the application of ordinary Kriging interpolation on the soil parameters data. This is because the semivariogram model determined the interpolation function. According to Ayoubi *et al.* (2007), the geostatistical methodology is based on the creation of a semivariogram, a graphical representation defined by (Equation 2) that describes how samples are related to each other in space.

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(X_i + h) - Z(X_i)]^2 \quad (2)$$

Where $\gamma(h)$ is the experimental semivariogram value at a distance interval h , $N(h)$ is the number of sample value pairs within the distance interval h , $Z(X_i)$, $Z(X_i + h)$ are sample values at two points separated by the distance h .

Using the Geostatistical Analyst tool (ArcGIS 10.2.2) and selecting the Ordinary Kriging methods, a semivariogram was created for each measured property. Several semivariogram functions were evaluated to choose the best fit with the data. In the Kriging method, different semivariogram models can be used. These are Gaussian, Exponential, Spherical,

Pentasppherical, Circular, Rational Quadratic, Hole-Effect, K-Bessel, J-Bessel, Stable, and Tetraspherical Models. The selection was performed by employing the cross validation technique, which permitted the evaluation of the prediction accuracy. Semivariogram parameters were analysed to better understand the spatial structure and dependence of each variable. Burgess & Webster (1980) defined the fitted experimental semivariograms in the following equations:

The Gaussian model is presented as:

$$\gamma(\mathbf{h}) = \mathbf{c}_0 + \mathbf{c}_1 \left[1 - \exp\left(-\frac{h^2}{a^2}\right) \right]. \quad (3)$$

The exponential model is given by

$$\gamma(\mathbf{h}) = \mathbf{c}_0 + \mathbf{c}_1 \left[1 - \exp\left(-\frac{h}{a}\right) \right]. \quad (4)$$

The spherical model is presented as

$$\begin{aligned} \gamma(\mathbf{h}) &= \mathbf{c}_0 + \mathbf{c}_1 \left[\frac{3h}{2a} - \frac{h^3}{2a^3} \right] \text{ when } \mathbf{h} \leq \mathbf{a} \\ &= \mathbf{c}_0 + \mathbf{c}_1 \text{ when } \mathbf{h} \geq \mathbf{a}, \end{aligned} \quad (5)$$

for $0 \leq h \leq a$, and $\gamma(h; \theta) = C_0 + C_1$, for $a < h$. The pentasppherical model is

$$\gamma(\mathbf{h}) = \mathbf{c}_0 + \mathbf{c}_1 \left[\frac{15h}{8a} - \frac{5}{4} \left(\frac{h}{a}\right)^3 + \frac{3}{8} \left(\frac{h}{a}\right)^5 \right]. \quad (6)$$

The circular model is portrayed as

$$\gamma(\mathbf{h}) = \frac{2C_0 + C_1}{\pi} \left[\frac{h}{a} \sqrt{1 - \left(\frac{h}{a}\right)^2} + \arcsin \frac{h}{a} \right]. \quad (7)$$

Rational-Quadratic model is given by

$$\gamma(\mathbf{h}) = \mathbf{c}_0 + \mathbf{c}_1 \frac{19\left(\frac{h}{a}\right)^2}{1 + 19\left(\frac{h}{a}\right)^2}, \quad (8)$$

for all h ; Hole-Effect, 0 for $h=0$ and

$$\gamma(\mathbf{h}) = \mathbf{c}_0 + \mathbf{c}_1 \frac{1 - \sin\left(\frac{2\pi h}{a}\right)}{\sin\left(\frac{2\pi h}{a}\right)}, \quad (9)$$

for $h \neq 0$. The K-Bessel model is

$$\gamma(\mathbf{h}) = \mathbf{c}_0 + \mathbf{c}_1 \left[1 - \frac{\left(\frac{\Omega_{\theta_k}}{a}\right)^{\theta_k}}{2^{\theta_k-1} \Gamma(\theta_k)} k_{\theta_k} \left(\frac{\Omega_{\theta_k}}{a}\right) \right], \quad (10)$$

for all h , in which Ω_{θ_k} is a value found numerically so that

$\gamma(a) - 0.95 (C_0 + C_1)$ for any θ_k , $\Gamma(\theta_k)$ is the gamma function,

$$(\gamma) = \int_0^\infty (xy^{-1}) \exp(-x) dx,$$

and $K_{\theta k}$ is the modified Bessel function of the second kind of order θ_k ;

The J-Bessel model is given by

$$\gamma(h) = c_0 + c_1 \left[1 - \frac{2^{\theta_k-1} \Gamma(\theta_d)}{\left(\frac{\Omega_{\theta_d}}{a}\right)^{\theta_d}} J_{\theta_d} \left(\frac{\Omega_{\theta_d} h}{a}\right) \right], \quad (11)$$

for all h , in which $C_0 + C_1 \geq 0$, $a \geq 0$, $\theta \geq 0$, $\Omega_{\theta d}$ must satisfy $B = a$, $B > 0$,

$\gamma(B) = C_0 + C_1$, $\gamma'(B) = C_0 + C_1$, $\gamma'(B) < 0$, and $J_{\theta d}$ is the J-Bessel function;

and the stable model is given as,

$$\gamma(h) = c_0 + c_1 \left[1 - e^{(-3\left(\frac{h}{a}\right)^{\theta_e})} \right], \quad (12)$$

for all h , in which $C_0 + C_1$ and $0 \leq \theta_e \leq 2$.

$$\gamma(h) = \frac{2c_1}{\pi} \left[\sin^{-1}(h) + h\sqrt{1-h^2} + \frac{2h}{3} (1-h^2)^{\frac{3}{2}} \right] \quad (13)$$

$$\text{for } \gamma(h) = 1, h > 1,$$

where C_0 is the nugget, C_1 is the partial sill, and a is the range of spatial dependence to reach the sill ($C_0 + C_1$). Nugget is the variance at distance zero and reflects the sampling error. Sill is the semivariance value at which the semivariogram reaches the upper bound and flattens out after its initial increase; it is the variance in which the samples are no longer spatially related to the study area. The ratio $C_0/(C_0 + C_1)$ and the range are the parameters that characterize the spatial structure of a soil property. The $C_0/(C_0 + C_1)$ relation is the proportion in the dependence zone, and the range defines the distance over which the soil property values are correlated with each other. A low value for the $C_0/(C_0 + C_1)$ ratio and a high range generally indicates that high precision of the property can be obtained by Kriging (Parfitt *et al.*, 2009). The classification proposed by Cambardella *et al.* (1994), which considers the degree of spatial dependence (DSD = $C_0/(C_0 + C_1) \times 100$) as strong if it is less than or equal to 25%. If the ratio is between 25 and 75%, spatial dependent of variable is moderate and if it is greater than 75%, spatial dependent of variable is weak (Cambardella *et al.*, 1994). Semivariogram models were chosen by using the cross validation technique to compare statistical values estimated from the semivariogram models and actual values. The mean square error (MSE) can be used to assess the prediction accuracy of models (Utset *et al.*, 2000). The MSE can be presented as:

$$\mathbf{MSE} = \frac{\sum_{i=1}^n [Z(x_i, y_i) - Z^*(x_i, y_i)]^2}{n} \quad (14)$$

where n is the number of observation for each case (soil property), $z(x_i, y_i)$ is estimated soil property value, $z^*(x_i, y_i)$ is observed soil property value, and (x_i, y_i) are sampling coordinates. The goodness of prediction criterium G was also employed as criteria to check and compare interpolated map accuracies (Agterberg, 1984). The G criterium was computed as:

$$G = 1 - \frac{MSE}{MSE_{av}} \times 100\%, \quad (15)$$

where MSE_{av} is the mean square error obtained from a catchment average value as an estimate for all test data, applying exploratory statistics. The positive G value indicates that the map obtained by interpolating data from the samples is more accurate than a catchment average. The negative and close to zero G value indicates that the catchment scale average predicts the values at unsampled locations as accurately as or even better than the sampling estimates (Tesfahunegn *et al.*, 2011).

Once the cross-validation process was completed, interpolation maps of spatial distribution for each soil variable were produced according to the semivariogram model selected using ArcGIS software (Kaviapoor *et al.*, 2012). Ordinary Kriging was selected as the preferred method for soil properties spatial interpolation since it was more reliable than the other interpolation methods based on the mean squared error which compares the measured values with the predicted ones and assumes that variables close in space tend to be more similar than those further away as observed by Tesfahunegn *et al.* (2011). Ordinary Kriging has also an additional advantage of minimizing the influence of outliers (Triantafilis *et al.*, 2001).

3.3 Results and Discussion

3.3.1 Descriptive statistics of the soil properties in top 15cm depth

The descriptive statistics of the soil properties within the top 15cm depth are given on Table 1. A wide range was observed for SOC, which ranged from 1.95 to 81.57 with a mean of 25.41%. Av-N ranged from 0.91 to 5.56 with a mean of 4.01mg/kg and Av-P ranged from 0.05 to 21.27 with a mean of 2.40mg/kg. The low contents of available P may be attributed to high contents of Al and Fe-oxides coupled with a low pH (Mapeshoane, 2013). Low and high Av-N may be explained by wetland conditions as under anaerobic condition, soil organic matter (SOM) decomposition was low and hence more of the N fraction increased (Varennnes, 2003). Mineralization of nitrogen under aerobic conditions enhanced an increase in Av-N but quickly taken by plants and others are lost through denitrification and leaching.

The percentage range for sand, silt, clay and silt to clay were 42.12 to 85.01, 8.00 to 42.35, 6.00 to 24.00 and 0.61 to 4.96, respectively. The maximum values of chemical properties were obtained at the interior of the catchment. The pH_w ranged from 4.37 to 5.88 indicating very strong acid to medium acidity. This is a reflection of leaching characteristic of high rainfall areas. Similar soil pH levels were reported by Mapeshoane (2013) for Bokong wetlands soils in Lesotho.

Table 1 Statistics of soil properties in the 0–15cm soil depth across Khalong-la-Lithunya catchment

Variable	N	Min	Max	Mean	SD	CV	Skewness	Kurtosis
SOC %	35	1.95	81.57	25.41	15.97	63	1.19	5.58
Av- P (mg kg ⁻¹)	35	0.05	21.27	4.01	4.62	115	2.00	7.54
Av-N (mg kg ⁻¹)	35	0.91	5.56	2.40	1.13	47	0.94	3.48
Ca (cmol kg ⁻¹)	31	352.8	3014.0	1652.6	648.1	39	0.19	-0.76
Mg (cmol kg ⁻¹)	7	147.2	463.8	294.0	120.2	41	0.17	-1.07
K (cmol kg ⁻¹)	26	173	2662.7	1102.3	792.5	72	0.46	-1.25
Na (cmol kg ⁻¹)	20	249.8	1512.7	831.1	341.5	41	0.29	-0.47
CEC (cmol kg ⁻¹)	7	67.8	97.4	85.2	12.2	14	-0.83	- 1.15
pH _w	35	4.37	5.88	5.00	0.33	7	0.12	3.29
BD (g cm ⁻³)	35	0.24	1.37	0.58	0.30	52	1.17	0.49
SAND %	35	42.12	85.01	60.34	10.29	17	0.54	2.52
CLAY %	35	6.00	24.00	16.16	4.42	27	-0.56	2.39
SILT %	35	8.00	42.35	23.50	8.28	35	-0.18	2.57
SILT / CLAY	35	0.61	4.96	1.57	0.91	58	2.62	10.29

† N = number of observations; Min = minimum. Max = maximum. SD = standard deviation. CV = coefficient of variation (%). Skewness provides an indication of symmetry, and a value of 0 indicates perfectly symmetrical distribution and values between -1 and +1 is considered approximately symmetric (normally distributed) for field data (Ott, 1977).

‡ SOC – Soil organic carbon; Av-P – Available Phosphorus; Av-N – Available Nitrogen; pH water – soil pH in water; BD = - bulk density; Ca -Calcium; Mg - Magnesium; K - Potassium; Na - Sodium; CEC – Cation exchange capacity.

Schmitz & Rooyani (1987) attributed the high levels of organic matter in the mountain soils of Lesotho to the lower temperatures and evaporation. Nkheloane *et al.* (2012) reported very high means of soil organic carbon of 17.2 percent from the upper 500mm 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 25.41% (Table 1).

According to classification of coefficient of variation proposed by Wilding & Dress (1978), all soil chemical properties had high coefficient of variation (CV) except for CEC, Av-N, percentage sand, clay and silt with moderate variability. Soil pH had least variability with CV of 7%. The findings with regard to obtained pH_w were in line with the results obtained by several studies (Panagopoulos *et al.*, 2015; Kavianpoor *et al.*, 2012; Zhang *et al.*, 2009). Av-P was the most highly variable soil property with CV of 115%. In general, the study revealed that chemical soil properties appeared to be more variable compared to physical soil properties. Nkheloane *et al.* (2012) also reported similar observation from two contrasting wetlands of Lesotho. Highest variation can be elucidated by inherent heterogeneity in the parent material, differences in physiography, soil depth and anthropogenic activities such as grazing (Akinbola *et al.*, 2006).

The descriptive statistics of the soil properties of the study sub catchments also revealed moderate to high skewness for some soil properties. SOC, Av-P, BD, and silt to clay ratio were highly skewed while others were approximately normally distributed. The local distribution was indicated by highly skewed soil properties with mostly low values and some high values at some sampling points (Tesfahunegn *et al.*, 2011). Soil properties with high skewness portrayed high kurtosis values exceeding a range between -3 to 3 for normal distribution as depicted in Table 1. The normal or non-normal distribution of soil properties may be attributed to topography, vegetation cover, anthropogenic activities such as grazing and other management practices that may impose the variability.

3.3.2 The normal Q–Q plot of the top 15cm depth

A set of Q–Q plots used to determine whether the soil properties are normally distributed. Normal distribution of a variable is reflected by data points clustering around a straight line. Sand, silt and clay values followed a near straight line shape as depicted on Figure 3. A convex shape was displayed for in all other parameters. Low values were mostly obtained in the margin and higher values in the central part of the catchment. This may be attributed to

topographic factor, vegetation cover and level of erosion in the outer part of the catchment. Similar findings were observed and reported by Tesfahunegn *et al.* (2011).

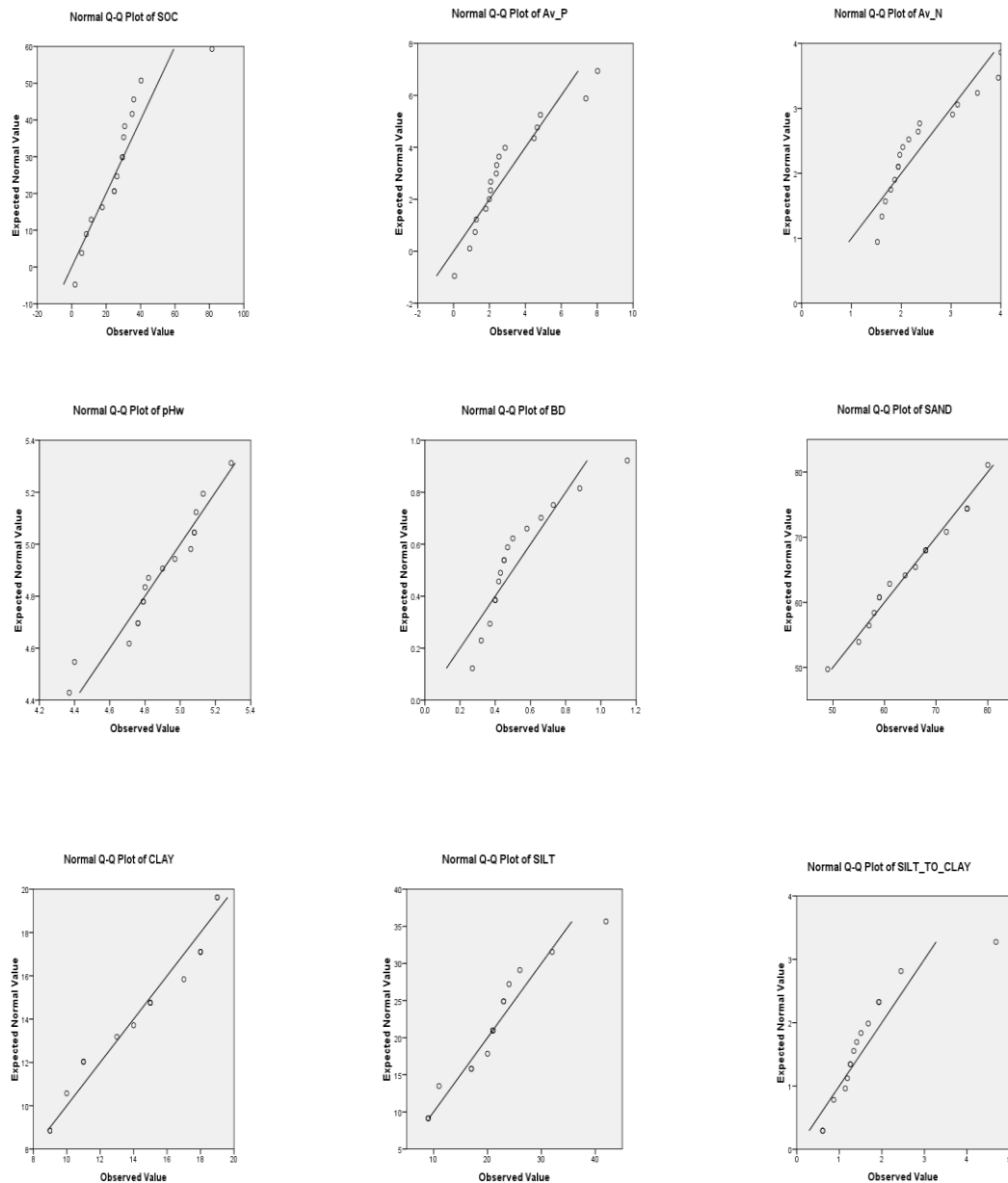


Figure 3: Normal Q–Q plot for selected soil parameter data of sub catchment one

3.3.3 Trend analysis of soil properties at study catchment

The Trend Analysis tool provides a three-dimensional perspective of the data. The locations of sample points are plotted on the x, y plane. Above each sample point, the value is given by the height of a stick in the z-dimension. Some soil properties of the study catchment illustrated that, some had a trend and some did not show a trend (Fig 4). The flat curve through projected points designated no existence of trend. The definite pattern to polynomial

upward and downward curve designated the existence of trend in the data. The accentuated trend demonstrated a strong upside-down U shape which suggested that strongest influence is from the centre of the region toward all the borders and hence shows that, the highest values occurred in the central part, while lower values occur near the edges. This was exhibited in Av-N, pHw, clay silt and silt to clay ratio. However, Av-P and sand showed the opposite pattern with low value at the centre and higher values towards the borders.

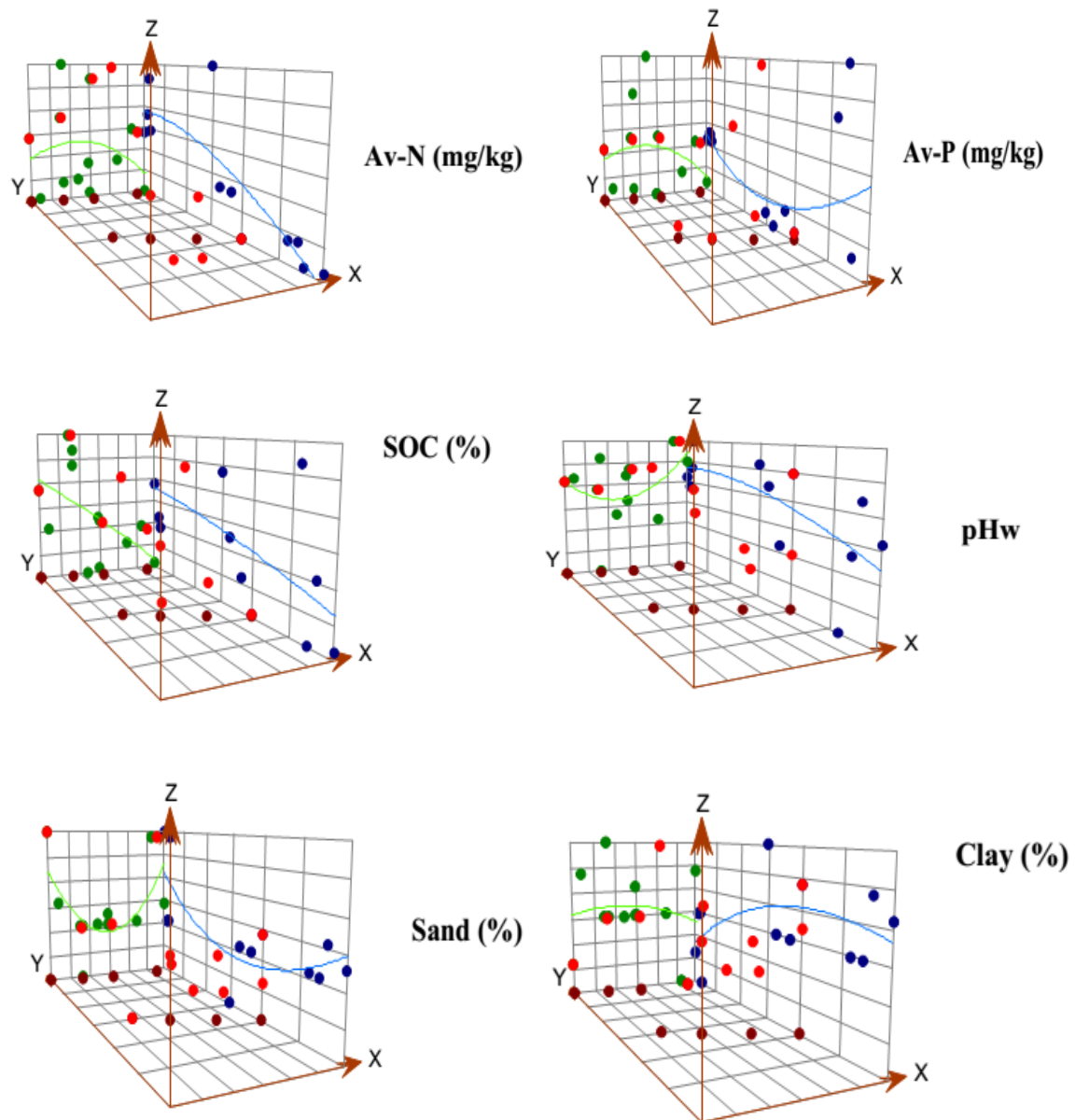


Figure 4: Trend analysis showing selected soil properties sampled at the study catchment

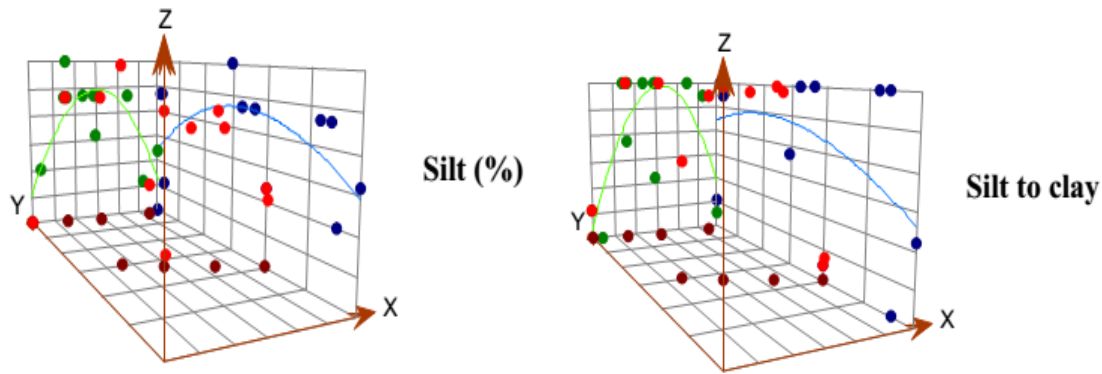


Figure 4: continued

3.3.4 The spatial dependency and distribution of soil properties

The results of geostatistical analyses of the soil properties showed their spatial dependence and fitted to different models (Table 2). In sub catchment 1, soil properties such as SOC, Av-P and pHw best fitted with Circular model whereas Av-N, BD, moisture content and sand fitted best with Exponential model. Clay and silt to clay fitted best with Gaussian model. Silt fitted best with Stable model. The selection of the model for each soil property was chosen based on the least mean squared error (the model with low error value). In sub catchment 2, SOC and Av-N fitted best with Rational Quadratic model. Soil pHw and all physical properties fitted best with Stable model except for BD which fitted best with Spherical model. In sub catchment 3, Av-P, Av-N and sand fitted best with Hole-Effect model. SOC and silt to clay fitted best with stable model. The soil pHw, clay and silt fitted best with Circular, K-Bessel and Tetraspherical model respectively.

All measured soil properties exhibited smaller range values, ranging from 0.001 to 0.025m and this indicated that the soil was more disturbed. Tesfahunegn *et al.* (2011) reported that soil variables with smaller range are good indicators of the more disturbed soils. However, large range indicates that the measured soil parameter value is influenced by natural and anthropogenic factors over greater distances than parameters which have smaller ranges (Ayoubi *et al.*, 2007). The different ranges of the spatial dependence among the soil properties may be attributed to differences in response to the erosion–deposition factors, land cover, topography and parent material and human and livestock interferences in the catchment.

Table 2: Model parameters used to find the best semivariogram to predict soil parameter in the three sub catchments in Khalong-la-Lithunya

SUB CATCHMENT 1								
Variable	Model	C ₀	C ₁	C ₀ + C ₁	Range	DSD (%)	MSE	G (%)
SOC	C [*]	301.91	120.23	422.14	0.002	72	20.2	62
Av- P	C [*]	4.58	1.16	5.74	0.012	80	2.13	92
Av-N	E ^{**}	0.36	0.80	1.16	0.025	31	1.00	53
pHW	C	0.04	0.05	0.09	0.007	44	0.21	16
BD	E ^{**}	0.00	0.16	0.16	0.003	0	0.25	4
MOISTURE	E ^{**}	0.00	0.16	0.16	0.003	0	75.5	19
SAND (%)	E	77.00	14.01	91.01	0.002	85	8.74	11
CLAY (%)	G	8.49	14.43	22.92	0.007	37	3.23	12
SILT (%)	S ^{**}	72.26	0.00	72.26	0.025	100	9.03	59
SILT / CLAY	G ^{**}	0.28	0.00	0.28	0.004	100	0.97	48
SUB CATCHMENT 2								
SOC	R-Q	17.15	30.56	47.71	0.005	36	6.71	4
Av- P	E [*]	0.00	1.82	1.82	0.011	0	1.17	12
Av-N	R-Q	0.001	1.37	1.37	0.005	0	0.65	39
pHW	S	0.25	0.00	0.25	0.021	100	0.54	0
BD	Sp	0.15	0.00	0.15	0.021	100	0.43	0
SAND (%)	S ^{**}	170	0.00	170.00	0.021	100	14.30	36
CLAY (%)	S	38.89	0.00	38.89	0.021	100	6.83	0
SILT (%)	S	113.08	0.00	113.08	0.021	100	11.65	0
SILT / CLAY	S [*]	2.37	0.00	2.37	0.021	100	1.69	3
SUB CATCHMENT 3								
SOC	S	147.30	37.50	185	0.005	80	12.38	6
Av- P	H-E	4609	0.00	4609	0.005	100	26	61
Av-N	H-E	9.60	17.63	27.23	0.003	35	1.49	40
pHw	C [*]	0.07	0.01	0.08	0.004	88	0.27	7
SAND (%)	H-E	616	785	1401	0.005	44	7.90	3
CLAY (%)	K-B	221	297	518	0.003	43	3.00	11
SILT (%)	T	2630	5558	8188	0.003	32	5.37	14
SILT / CLAY	S	0.05	0.00	0.05	0.005	100	0.23	1

* Log and ** Box-Cox transformation for normal distribution. Av-P = Available Phosphorus (mg/kg), Av-N = Available Nitrogen (mg/kg), SOC soil organic carbon (%), pHw = pH in water. BD = Bulk density (g/m⁻³), S= Stable, H-E =Hole-Effect, C = Circular, G = Gaussian, Sp = Spherical, K-B = K-Bessel, J-B =J-Bessel, T = Tetraspherical, E = Exponential, R-Q = Rational Quadratic. C₀= nugget effect; C₁= partial sill, C₀+C₁= sill; DSD = C₀/(C₀+ C₁) DSD: degree of spatial dependence; strong DSD (DSD ≤ 25%); moderate DSD (25 < DSD ≤ 75%); weak DSD (DSD > 75%) according to Cambardella et al. (1994). MSE = mean square error.

The nugget, which is an indication of micro variability, was higher for SOC, sand and silt in comparison with other soil properties (Table 2). The soil pH, BD, Av-N, and silt to clay ratio had lowest nugget which indicated low spatial variability within small distances. Tesfahunegn *et al.* (2011) also reported low nugget value for soil pH. The degree of spatial dependence of soil properties is defined by nugget-to-sill ratio. Av-P and clay had moderate nugget to sill ratio. This indicated high spatial variability within short distances of soil properties.

The Kriging cross-validation technique was employed to select which of the semivariogram models could result with most accurate predictions of the unknown values of different sub catchments. The mean square error (MSE) values were used in this validation test as illustrated on Table 2. Low values (0.21 to 20.2) in sub catchment 1 were obtained and thus indicating that Kriging predictions of soil properties were closer to measured values. The accuracy of the Kriged soil properties spatial maps were not validated only with MSE but also with G values (Table 2). The G value for soil properties indicated the prediction capacity of the data sets using Kriging from the sampling points against catchment average values. The G value of 92% for Av-P in sub catchment 1, for instance, indicated that the Kriged Av-P map was 92% more accurate than the value obtained using the catchment scale average. Similarly, all other soil properties had similar trend (Kriged maps) with varying degree of accuracy when compared to values of the catchment scale average. The positive G values indicated that Kriging was more accurate than the catchment-scale average values and this suggested the use of interpolation technique was suitable for constructing the soil property maps that can help as to where exactly in the wetland appropriate management intervention should be initiated.

In this study, the semivariograms in sub catchment 1 indicated strong spatial dependence ($DSD \leq 25\%$) for soil properties such as BD (0%) and moisture content (0%) as depicted on Table 2.2. Similarly, Av-P (0%) and Av-N (0%) also exhibited strong spatial dependence in sub catchment 2 and none of the soil properties exhibited strong spatial dependence in sub catchment 3. The strong spatial dependence of the properties may be controlled by the intrinsic variations in soil features including texture and mineralogy (Cambardella *et al.*, 1994). In sub catchment 1, SOC (72%), Av-N (31%), pH_w (44%) and clay (37%) exhibited moderate spatial dependence ($25 < DSD \leq 75\%$). SOC (39%) and sand (36%) in sub catchment 2 and Av-P (61%) and Av-N (40%) in sub catchment 3 also exhibited moderate spatial dependence. The moderate spatial dependence of the soil properties may be controlled

by extrinsic variations brought about by anthropogenic factors (management practices). In sub catchment 1, Av-P (80%), sand (85%), silt (100%) and silt/clay (100%) exhibited weak spatial dependence ($DSD > 75\%$). Similar patterns were observed in all physical soil properties (100%) in sub catchment 2 exhibiting a weak spatial dependence and in sub catchment 3, weak spatial dependence was exhibited in SOC (80%), Av-P (100%), pHw (88%) and silt/clay (100%).

The overall catchment spatial dependency and distribution of soil properties such as SOC and Av-P best fitted with an Exponential model whereas Av-N, clay and silt/clay fitted best with Rational Quadratic model (Table 3). Silt and sand fitted best with J-Bessel model. The soil pH in water fitted best with Circular model.

In this study, the semivariograms indicated moderate spatial dependence ($25 < DSD \leq 75\%$) for soil properties such as SOC, Av-P, Av-N, pHw and sand; and the silt and silt/clay exhibited weak spatial dependence ($DSD > 75\%$). The moderate spatial dependence of the soil properties may be controlled by extrinsic variations brought about anthropogenic factors (management practices). Clay exhibited a strong spatial dependence ($DSD \leq 25\%$). The strong spatial dependence of the properties may be controlled by the intrinsic variations in soil features including texture and mineralogy (Cambardella *et al.*, 1994).

Table 3: Model parameters used to find the best semivariogram to predict soil parameter in Khalong-la-Lithunya catchments

Variables	Model	C ₀	C ₁	C ₀ + C ₁	RANGE	DSD (%)	SDL	MSE	G (%)
SOC	E*	141.48	190.23	331.71	0.001	43	Moderate	15.41	52
AV- P	E*	14.76	15.67	30.43	0.013	49	Moderate	4.38	56
AV-N	R-Q	0.50	1.30	1.8	0.007	28	Moderate	1.00	1
pHW	C	0.05	0.09	0.14	0.009	36	Moderate	0.31	7
Sand	J-B	42.99	43.22	86.21	0.002	50	Moderate	8.54	7
Clay	R-Q	6.24	20.75	26.99	0.012	23	Strong	3.72	6
Silt	J-B	52.72	16.92	69.64	0.001	76	weak	7.78	14
Silt/clay	R-Q*	0.82	0.05	0.87	0.017	94	weak	0.95	3

* Log and ** Box-Cox transformation for normal distribution. Av-P = Available Phosphorus (mg/kg), Av-N =Available Nitrogen (mg/kg), SOC soil organic carbon (%), pHw = pH in water. BD = Bulk density (g/m⁻³), S= Stable, H-E =Hole-Effect, C = Circular, G = Gaussian, Sp = Spherical, K-B = K-Bessel, J-B =J-Bessel, T = Tetraspherical, E = Exponential, R-Q = Rational Quadratic. C₀= nugget effect; C₁= partial sill, C₀+ C₁= sill; DSD = C₀/(C₀+ C₁) DSD: degree of spatial dependence; strong DSD (DSD ≤ 25%); moderate DSD (25 < DSD ≤ 75%); weak DSD (DSD > 75%) according to Cambardella et al. (1994). MSE = mean square error.

3.3.5 Ordinary Kriged map of soil properties

Spatial analysis indicated spatial variability of soils across fields in the catchment. The semivariogram parameters were used for kriging that produced an interpolation map of the soil properties as shown on Fig. 5, 6 and 7 for sub catchment 1, 2 and 3 respectively. From the spatial distribution map, SOC ranged from 5.9 to 49.8%, with higher values in the eastern part (upper slope) and lower values in mid slope of sub catchment 1. In both sub catchments 2 and 3, higher values of SOC were obtained in the central part of the catchments ranging from 5.6 to 20.0% and 18.2 to 47.8% for sub catchment 2 and 3. Low SOC values were associated with severe degradation due to erosion and triggered SOC losses by enhancing high rate of decomposition. Loss of organic matter is expected as a result of soil aging and normal decomposition by a diverse community of invertebrates, microbes and physical processes (Yang *et al.*, 2011). Higher SOC values in the central part indicated wetter area (anaerobic condition) with low soil organic matter decomposition. The higher the soil organic matter content and its variability in an area, the more one could expect biological diversity which ultimately adds to the soil variability due to the physical activities of the animals and sometimes chemical reactions due to the microbes (Behera & Shukla, 2014). Therefore, it is important to understand and manage the existing wetland variability of soil properties for efficient and sustainable environmental functions.

High value of Av-N were obtained at central to bottom slope with a decreasing trend from upper slope in all sub catchments ranging from 1.58 to 4.00, 0.96 to 3.10 and 1.03 to 5.24mg/kg for sub catchment 1, 2 and 3 respectively. This may be explained by leaching of Av-N leading to high content of such properties in the central to bottom part of the catchment. Under anaerobic condition, which is the case of the central part (wetter), soil organic matter decomposition was low and hence more of the N fraction increased (Varennnes, 2003).

The mineralization of nitrogen under aerobic conditions enhances an increase in Av-N but quickly taken by plants and others are lost through denitrification and leaching. Lower values were also attributed to high soil erosion that triggered organic matter decomposition and hence loss of nitrogen. Hammer *et al.* (1987) compared soil variability within three landscape units; first-order bottomlands, sloping landscapes and level uplands. Soils on bottomlands were found to have the most spatial variability. Reese & Moorland (1996) observed significant differences in organic matter and clay content between the wetland and surrounding upland rim.

Soil phosphorus exists in different forms of organic, fixed and orthophosphates and alteration of fixed P into soluble ortho-P is controlled by oxidation reduction reaction. The spatial distribution of Av-P exhibited low values at the central part and high values were obtained at upper and bottom part of sub catchments ranging from 0.30 to 5.41, 0.41 to 3.05 and 1.1 to 20.3mg/kg for sub catchment 1, 2 and 3 respectively. Generally, Av-P depicted a decreasing trend with slope. Lower values at the bottom suggested that the wetland released less phosphate into the river bodies and thus implying good performance of the wetlands.

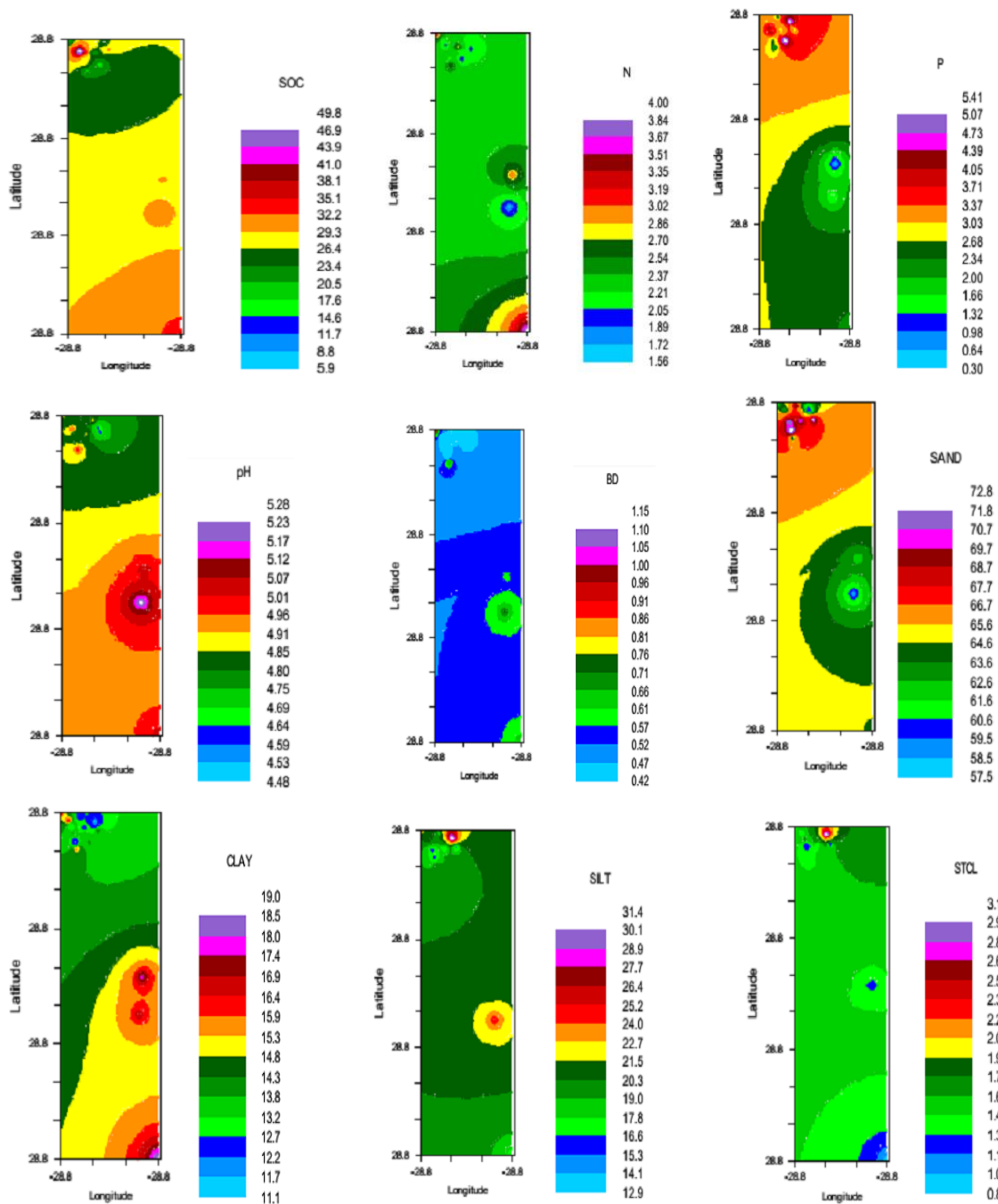
Ewing *et al.* (2012) observed increased solubility of excess P in a drained wetland as compared to natural wetland soils. However, increased solubility of residual P when wetland hydrology and anaerobic soil conditions are restored may degrade water quality. Low contents of available P may be attributed to high contents of Al and Fe-oxides coupled with a low pH that could lead to adsorption and precipitation of P. According to Fiedler *et al.* (2004), under reduced conditions P is mobilised and accumulated above the water table. This is due to increased solubility of Fe upon reduction, thereby releasing higher concentrations of adsorbed and precipitated P to the soil solution.

High pH values occurred in the middle of sub catchment 1 and 2 while low pH values occurred in the borders of sub catchments parts with sub catchment 3 having irregular soil pH

distribution. Low soil pH in hydric soils may be associated with H^+ dissociation from organic acids during aerobic phase of ferrolysis (Webster & McLaughlin, 2010; Behera *et al.*, 2016). Generally, the soil pH ranged from 4.47 and 5.86 in the study catchment. Bulk density varied considerably within the catchment and low and high values were obtained in different parts of the catchment ranging from 0.42 to 1.15 and 0.34 to 1.34 g/cm³. The central parts of sub catchment were dominated by fine textured soils (silt and clay) while the upper and bottom slope were dominated by coarse textured soils (high percentage sand). The coarse texture soils allow for more leaching, thus under similar conditions the soil pH of coarse textured soil is usually lower than that of the fine texture soils.

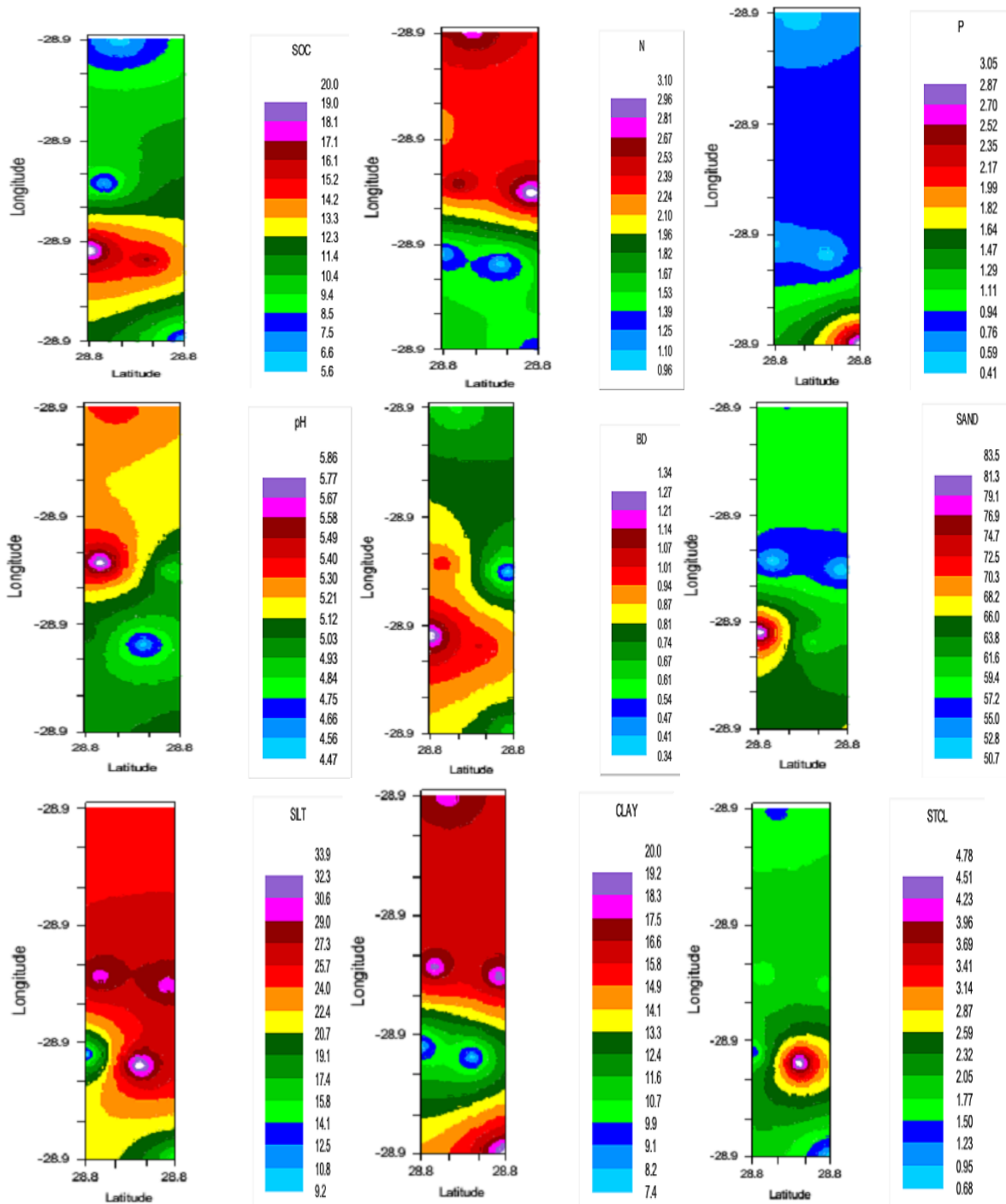
Geostatistical analysis is the key for studying the spatial variability of soil properties for sustainable wetlands soil resource management. The present study revealed that the measured soil properties had large variability in spatial distribution pattern in the study catchment. The Kriged distribution maps for different soil properties providing quantitative information about soil properties is of great use for environmentalist, wetlands managers, extension officers and farmers. This will help in visualizing soil properties distribution for planning appropriate intervention conservation management strategies as to where exactly should the intervention applied (Behera *et al.*, 2012).

NORTHING
DISTANCE/
BOTTOM
SLOPE



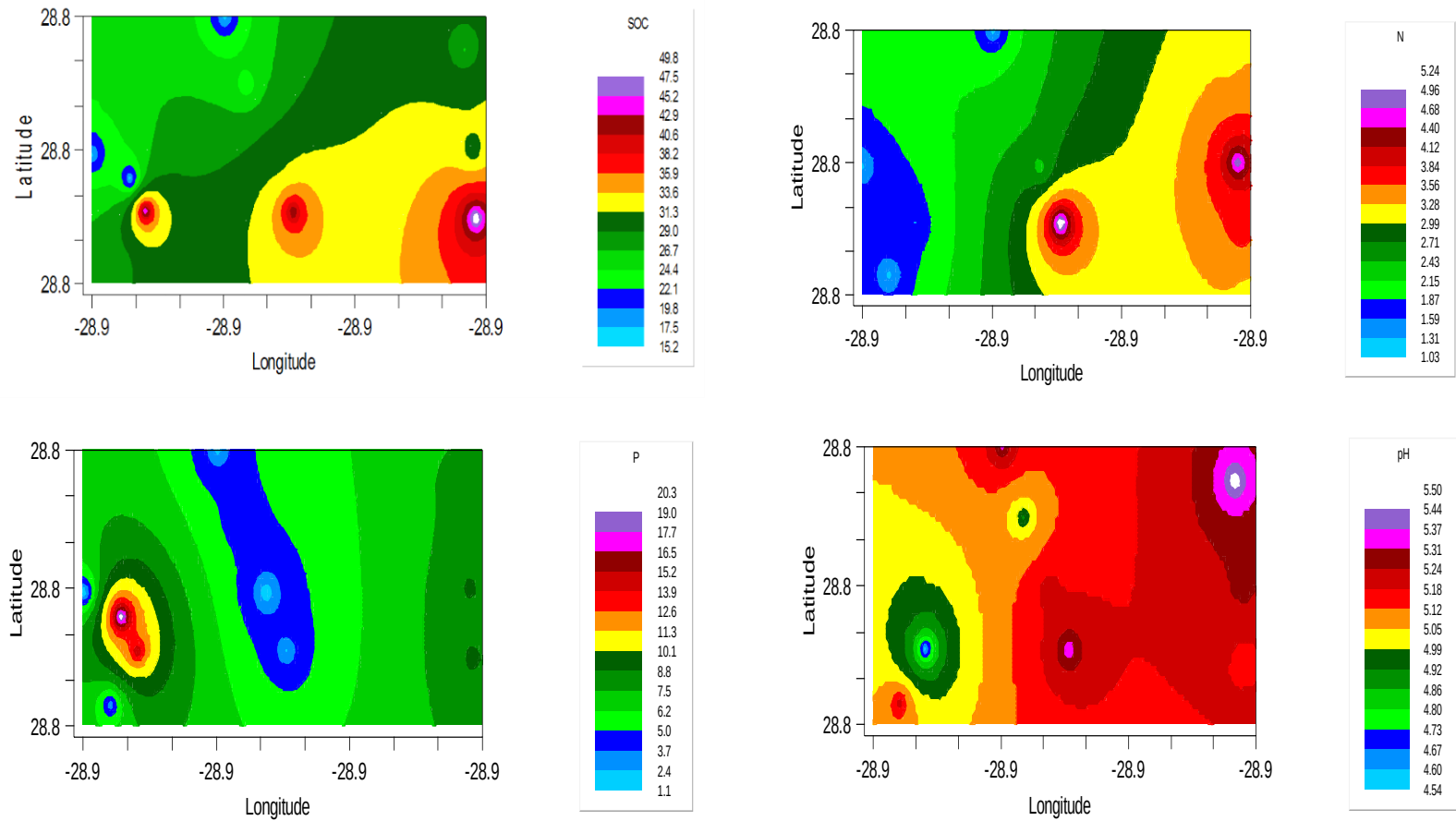
WESTING DISTANCE

Figure 5: Ordinary Kriged maps of soil properties in sub catchment 1 at Khalong La Lithunya



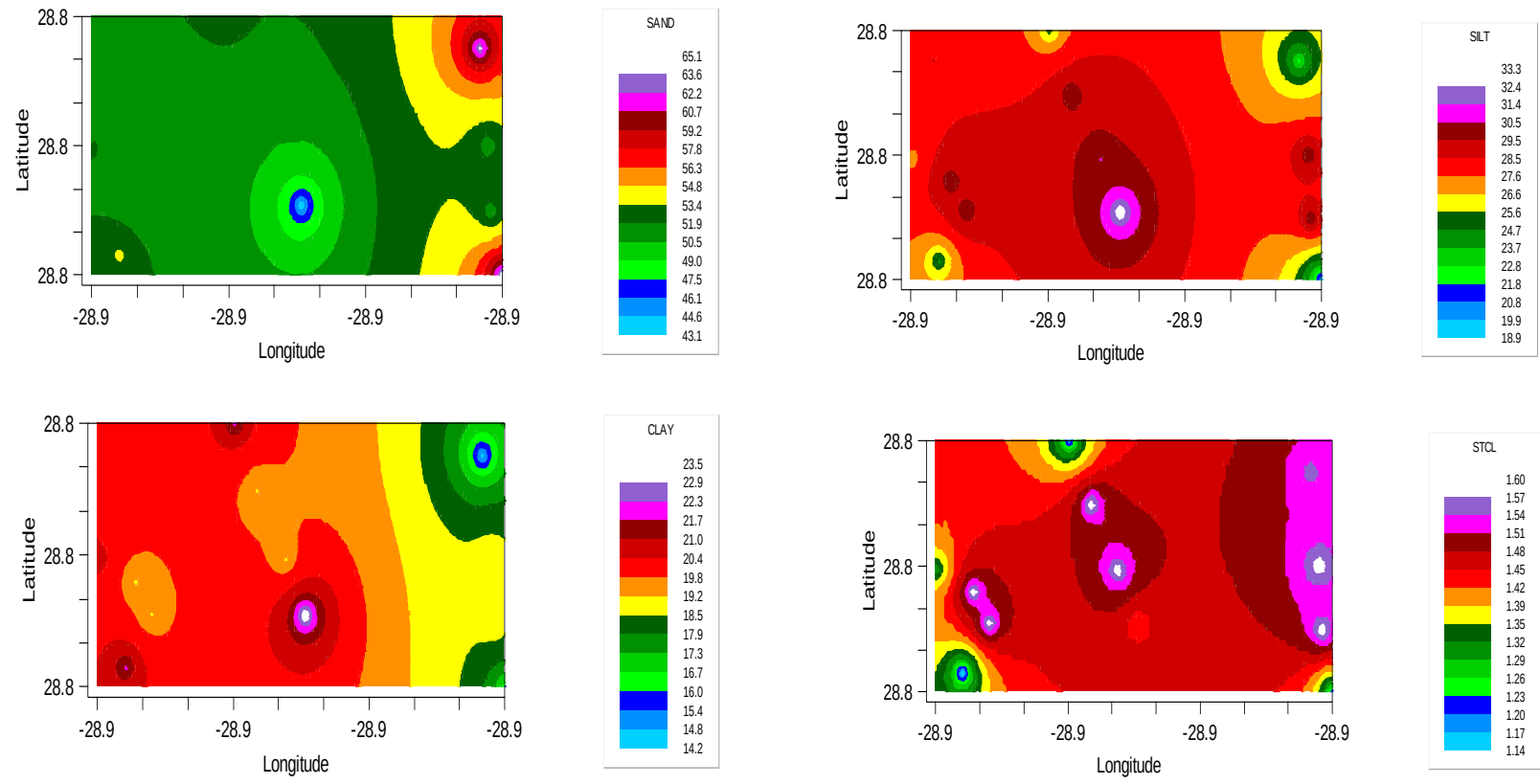
SOURTHING DISTANCE (UPPER SLOPE)

Figure 6: Ordinary Kriged maps of soil properties in sub catchment 2 at Khalong La Lithunya



EASTING DISTANCE

Figure 7: Ordinary Kriged maps of soil properties in sub catchment 3 at Khalong La Lithunya



EASTING DISTANCE

Figure 7: continued

3.3.6 Vertical distribution of selected soil properties in the catchment.

The mean, standard deviation and coefficient of variation of SOC, Av-P, Av-N, pHw, BD and base cations (Na, K and Ca), as well as sand, clay, silt and silt/ clay at 15cm depth increment from 0 to 90cm are presented in Table 4. Soil organic carbon was not significantly different throughout the profile. The profile has the mean SOC of 28.3%. High levels of SOC were associated with partial decomposition of organic material due to anaerobic conditions that slow down the decomposition rate leading to accumulations and formation of peat (Mapeshoane, 2013). However, SOC exhibited high variation within each depth with CV higher than 60%.

The Av-P profile mean was 3.5mg/kg. Av-P was not significantly different between depths. However, it showed inconsistent trend and it tends to increase at lower depths. The distributions and dynamics of P forms in soil, especially in wetlands, can be significantly impacted by various biogeochemical and environmental factors such as soil moisture, soil organic matter, and clay content (Bai *et al.*, 2010). Yang *et al.* (2011) also observed high P values in topsoil to decrease with depth and reach their minima at 60cm depth and increase again. Aldous *et al.* (2005) revealed that, under aerobic conditions, which are in the case of topsoil, available P is subjected to iron adsorption and retention but down the profile the conditions turn into anaerobic and thus enhance the release of more phosphates. Av-P was the most highly variable soil property within depths. Av-N profile mean was 3.0mg/kg and it is significantly higher in the middle depth of 30-45cm. It exhibited moderate to high variability with CV ranging between 35 to 46% within depths.

The mean soil pH of the profile is 5.1. It increased slightly from 5.0 to 5.2 from the surface layer down the profile. The pH was strongly acidic (Osuaku *et al.*, 2014). This could be explained by constant leaching by rainfall which leaves the soil saturated with more Al^{3+} and H^+ . An increment in soil pH in deeper horizons indicated accumulation of bases. Soil pH was the least variable soil property and similar results for pH were also registered by Panagopoulos *et al.* (2015); Amuyou *et al.* (2013); Kaviapoor *et al.* (2012); and Zhang *et al.* (2009).

Table 4: Summary statistic for soil physical and chemical properties for study area

Depth (cm)	0-15	15-30	30-45	45-60	60-75	75-90	Profile
SOC Mean (%)	25.4a	28.9a	29.7a	28.6a	29.5a	27.6a	28.3
N	36	35	36	33	27	17	184
CV (%)	63	62	64	66	63	73	64
Av-P Mean(mg/kg)	4.0a	3.3a	2.6a	2.5a	4.3a	4.9a	3.5
N	35	36	36	33	27	17	184
CV (%)	115	152	162	152	140	131	140
Av-N Mean (mg/kg)	2.4b	2.8ab	3.2a	3.4a	3.0ab	3.0ab	3.0
N	36	35	36	33	27	17	184
CV (%)	46	39	38	35	40	43	40
pH Mean (1:2.5)	5.0a	5.0a	5.1a	5.1a	5.1a	5.2a	5.1
N	36	33	34	32	26	17	178
CV (%)	6	10	10	10	12	10	10
BD Mean (g/cm)	0.6a	0.7a	0.7a	0.7a	0.6a	0.7a	0.7
N	25	25	24	24	18	11	127
CV (%)	50	57	43	57	50	71	57
Sand Mean (%)	63.0a	64.8a	64.7a	65.0a	66.5a	69.7a	65.0
N	27	24	26	23	16	9	125
CV (%)	18	17	17	16	16	11	16
Clay Mean (%)	15.1a	16.2a	16.2a	17.3a	16.4a	14.4a	16.1
N	27	24	26	23	16	9	125
CV	34	31	31	25	32	34	30
Silt Mean (%)	21.9a	18.9a	19.1a	17.8a	17.1a	15.9a	18.9
N	27	24	26	23	16	9	125
CV	44	41	45	51	59	45	47
Silt/clay Mean (%)	1.5a	1.2a	1.2a	1.3a	1.4a	1.1a	1.3
N	25	24	24	23	18	11	125
CV	87	58	75	62	71	45	69
Na Mean (Meq/100g)	3.1a	2.2a	2.5a	3.0a	3.2a	3.1a	2.8
N	32	29	29	26	24	15	155
CV (%)	106	86	108	93	106	68	100
K Mean (Meq/100g)	2.3a	1.7a	1.7a	1.7a	1.7a	1.7a	1.8
N	33	32	31	26	25	17	164
CV	91	106	100	124	129	135	111
Ca Mean (Meq/100g)	8.3a	8.8a	7.8a	7.9a	7.5a	6.9a	7.9
N	32	31	30	30	26	17	166
CV	39	44	45	41	40	49	43
Mg Mean (Meq/100g)	2.7a	2.2a	2.3a	2.2a	2.0a	2.3a	2.3
N	6	6	6	6	5	4	33
CV	48	45	13	32	30	39	35
CEC Mean (cmol/kg)	80.7a	71.2a	80.4a	84.6a	100a	80.4a	82.5
N	6	6	6	6	5	4	33
CV	15	23	32	30	27	32	27

Means with same letter in one row are not significantly different at 5% according to Duncan multiple range test (DMRT).

† CV= Coefficient of variation; <15 – Least variable, 15 – 35 – Moderately variable, >35 – Most variable (Wilding & Dress, 1978).

‡BD = Bulk density, SOC= Soil Organic Carbon, Av-P = available Phosphorus, Av-N= Available Nitrogen. Base cations: K= Potassium, Na =Sodium, Ca =Calcium, and Mg =Magnesium.

††CEC = Cation Exchange Capacity

‡‡N is the number of observations

Bulk density was not significantly different throughout the profile. The mean bulk density for the profile was 0.7g/cm³. Sand had percentage mean of 65 with CV ranging from 11 to 18% exhibiting weak to moderate variability. Percentage clay had a mean 16.1 with CV ranging from 25 to 34% exhibiting moderate variability. Silt percentage mean was 18.9 with CV

ranging from 41 to 59%, indicating high variability within depth. Therefore, the soils of the study area have sandy texture. The mean silt/clay ratio of the profile was 1.3 and it was highly variable with the highest CV value of 87%. That is, silt/clay ratios are relatively higher in the surface and subsurface horizons and decrease with increase in pedon depth. Van Wambeke (1962) registered that “old” parent materials usually have a silt/clay ratio below 0.15 while silt/clay ratios above 0.15 indicate “young” parent materials. On the contrary, FAO (1990) reported that soils with silt/clay ratios of less than 0.20 indicate a low degree of weathering. Results of this study show that, all the soils have silt/clay ratio above 0.15 or 0.20 indicating that the soils are relatively young with high degree of weathering potential. The silt to clay ratio obtained in this study suggested that soils in study area are moderately weathered.

Base cations mean across the profile is 2.8, 1.8, 7.9 and 2.3cmol/kg for Na, K, Ca and Mg respectively and they were highly variable with Na and K being the most variable bases. Possible reasons for low base cations could be that the parent material on which soil has developed had low base content (Zgorelec *et al.*, 2013). The comparatively high coefficients of variation of Na and K reflect additional source of these bases since lithology is not expected to be heterogeneous (Ekwueme, 2003; Kumar *et al.*, 2012). The mean profile CEC is 82.5cmol/kg with moderate CV ranging from 15 to 32 within depth. The base cations and CEC is not significantly different between depths. There are apparently higher levels of K, Ca and Mg in the surface layers, while CEC and Na are higher in sub-surface horizons at 60-75cm.

All the soil properties were moderate to highly variable except the soil pH. AV-P was the most variable property followed by Na and K. Only Av-N differs significantly between depths. Bastviken, (2006) studied factors influencing spatial and temporal variations, and revealed that available nitrogen, is influenced by environmental factors, such as alternate period of wetting and drying, level of water table, pH, water chemistry and other wetland conditions, such as climate, water depth and water flow. The essential factors are the absorption of plant's root and microbiological activities. In the study by Yang *et al.* (2006), the results designated significant declines in available N and P concentration in soil solution have occurred with increase in depth, and reached their minima at 60cm depth, except for available N, which increased with depth. Most nutrients changed much from 20 to 40cm along the depth. Yang *et al.*, (2006) further show that soil at 0–60cm depth is active

rhizoplane, with strong capability to remove the nitrogen and phosphorus in aquatic-terrestrial ecotone.

However, high water table also explains the variability in available nitrogen, pH and SOC and subsequently reduce the amount of organic matter decomposition. SOC and available nitrogen were higher in wetter sites. Several studies reported a decline in SOC with depth. According to the results obtained in Stolt *et al.* (2001) available nitrogen and SOC showed a decreasing trend with depth from the surface. The SOC was high at the surface and decreased to a relatively stable concentration (Elgin, 2012). Accumulation of organic matter on the surface and the near surface horizons occurred as the results of additions of organic matter from plant roots leading to higher available nitrogen values (Elgin, 2012). Several studies on vertical soil variability revealed that soil pH increases with depth and it was the least variable soil properties, irrespective of depth. Studies also revealed that variability of soil organic carbon, available phosphorus and nitrogen, base cations and CEC increased with depth and ranged in an interval of a total change categorised as moderate to high. However, a vital question is to what extent are soil properties different along the profile depths in different wetlands parts of study sites. The knowledge on the vertical distribution of soil properties along profile depth could assist to predict the proneness of such soils to erosive impact. Understanding of their variability is necessary in applying location-specific wetland conservation management interventions.

3.3.7 Vertical distribution of soil properties in the three sub-catchments

The graphical presentation of vertical distribution of soil properties in the three sub-catchments is presented in Figure 8. SOC was the highest in sub catchments 1 and 3 with mean of 31 and 30% respectively while in sub catchment 2 the mean was 11%. The results show that soil organic carbon was relatively lower in the upper depth. The low SOC content in the upper depth may be due to oxidized microzones created around plant roots, allowing degradation by aerobic bacteria in the root zone. Some loss of organic matter is also expected as a result of soil aging and normal decomposition by a diverse community of invertebrates, microbes and physical processes (Yang *et al.*, 2011). Nutrient loading may also enrich the soil and tends to decompose organic matter than it is stored (Tiner, 2005). Av-N and percentage sand were higher in sub catchment 1 than in sub catchments 2 and 3. This indicated that sub catchment 1 was the most having Av-N and were easily leached due to coarse textured soil and more of the nitrates discharged into river water bodies.

Silt to clay ratio, BD and Ca were higher in sub catchment 2 than in sub catchments 1 and 3. Low Ca values in sub catchments 1 and 3 may be due to parent materials on which soil has developed were poor in bases (Zgorelec *et al.*, 2013). The silt to clay ratio is an indicator of wetland degradation and thus showed that sub catchment 2 was highly degraded and that was explained by higher silt to clay. Higher level of compaction was attributed in sub catchment 2 with bulk density of 1.0g/cm^3 while in sub catchments 1 and 3 had 0.6 and 0.8g/cm^3 respectively. 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.

In sub catchment 3, most soil properties exhibited higher values including Av-P with mean 7.3mg/kg , pH with mean 5.3, silt with mean 24%, clay with mean 19%, Na with mean 3.9 and K 3.2cmol/kg . High Av-P is associated with high pH that decreases the solubility of Al and Fe leading to more release of the adsorbed phosphates. However, low contents of available P may be attributed to high contents of Al and Fe-oxides coupled with a low pH.

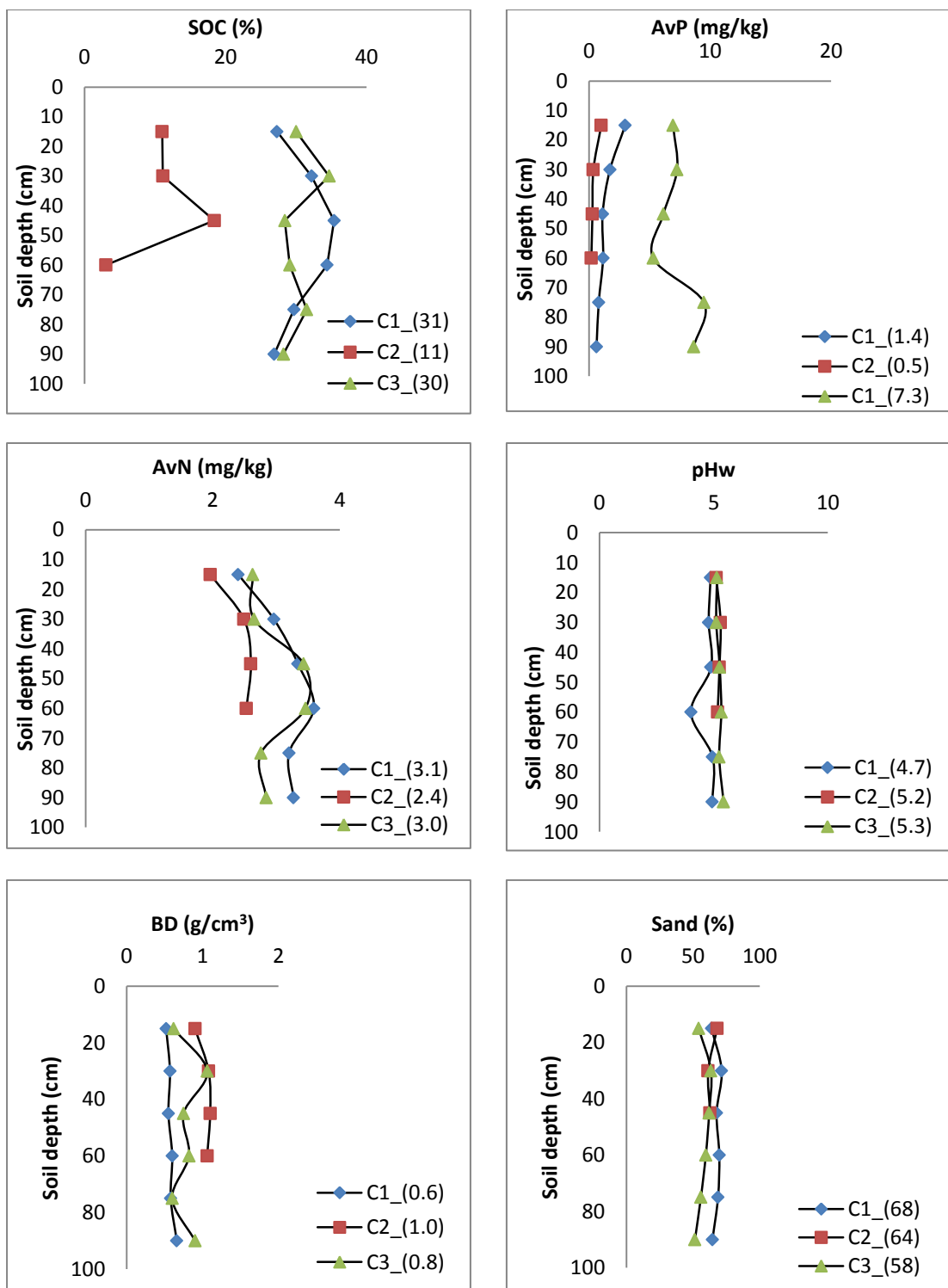


Figure 8: Variation of selected soil properties with depth in three sub catchments at Khalong-la-Lithunya wetlands

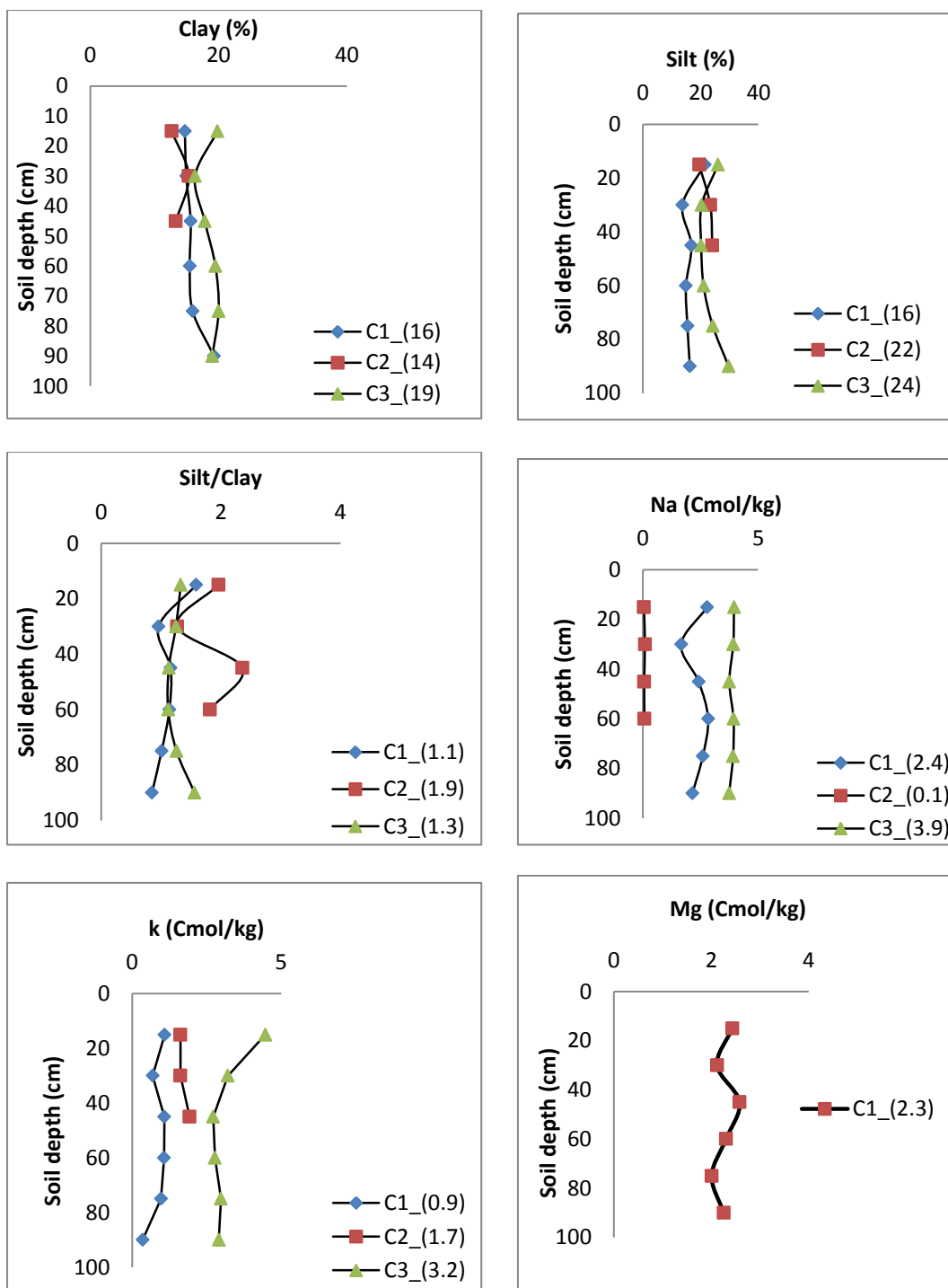


Figure 8: continued

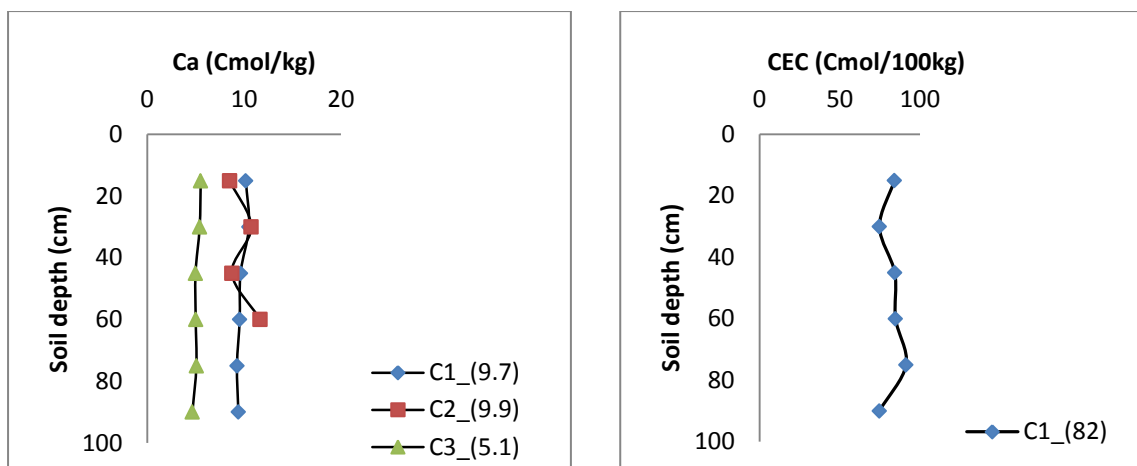


Figure 8: continued

3.3.8 Effect of slope on selected soil properties

The results of the study showed that topography affects and changes the overall soil properties of a given landscape. A considerable difference in soil parameters can exist within a wetland area, even if the change in elevation is minimal. The profile showed a decrease in Av-P and K content down slope (Table 5). The decrease in Av-P with slope suggested that, less of the phosphates were discharged into water bodies and thus indicating good performance of the wetlands.

Similarly, silt to clay ratio decreased down slope. This could be explained by the transportation and deposition of weathering parent materials from the upper slope to the bottom slope by the erosive agent of water (Brady & Weil, 2007). The relative magnitude of silt/clay at different depths has special significance in terms of the degree of weathering.

On the contrary, soil pH, Av-N, Ca, percentage clay and BD increased down slope with the bottom slope having the highest values, while soil organic carbon and sand were highest in the middle slope. Organic matter accumulation is often favoured at the midslopes as conditions were wetter than at upper-slope and bottom-slope positions (Brady & Weil, 2007).

Table 5 Duncan grouping of means of selected soil properties across different slope in the catchment

Slope	DB	Av-P	Av-N	Na	K	Ca
	(g/cm)	-----mg/kg-----			-----Cmol/kg-----	
Upper	0.7b	4.3a	2.5b	2.7ab	1.7b	8.5b
Middle	0.7b	2.0b	3.1a	1.9b	1.4cb	6.7c
Bottom	0.9a	0.8b	3.4a	3.1ab	0.7c	12.0a

Slope	SOC	Sand	Clay	Silt/clay	pH
		-----%-----			
Upper	24.4b	60.5c	17.8a	1.3a	5.1b
Middle	32.1a	71.4a	13.9b	1.3a	4.8c
Bottom	19.2b	60.3c	19.6a	1.0a	5.3a

Means with same letter in one column are not significantly different at 5% according to Duncan multiple range test (DMRT).

3.3.9 Relationship between soil properties

Pearson's correlation analysis was conducted to examine the levels of association between the soil properties within each sub catchment as summarised in Table 6. Positive correlation reveals that, as one soil property increases in value, the second soil property also increases in value. Similarly, as one soil property decreases in value, the second soil property also decreases in value and the opposite is negative correlation which means that as one soil property increases in value, the second soil property decreases in value.

SOC had a significant negative correlation with pH, BD, clay, silt and Ca. Soil microbes use carbon compounds found in organic matter as an energy source. However, the rate at which organic carbon is utilized by soil microbes is considerably lower under lower soil pH conditions as microbes die off. Therefore, under low soil pH, partially decomposed organic matter may accumulate and this suggested high content of percentage SOC. Soil organic matter tends to increase as the clay content increases. The increase depended on the bonds between the surface of clay particles and organic matter that retarded the decomposition process. It relied also on soils with higher clay content that increased the potential for aggregate formation. Macro aggregates physically protect organic matter molecules from further mineralization caused by microbial attack (Rice, 2002). However, positive significant correlation existed between SOC and percentage sand.

Av-P correlated significantly and negatively with Ca. This could be explained by the fact that, Av-P formed insoluble compound with Ca and thus hindered its availability. The results revealed a significant positive correlation between Av-P and pH, Na and K. An increase in soil pH improved availability of phosphorus as Fe and Al decreased in the soil solution and then *vice versa*. Monovalent also improved availability of Av-P. Significant negative correlation existed between Av-N and silt, silt/clay and Na. However, Av-N has significant positive correlation with clay.

Soil pH has a significant positive correlation with BD, clay, silt and K but exhibited a negative significant correlation with sand. The results further indicated that BD has a positive significant association with clay and silt while it has a significant negative correlation with sand. Sand showed a significant negative correlation with clay, silt, silt/clay, Na and K. Clay has significant negative correlation with silt/clay but it has a significant positive correlation with K. Significant positive correlation was observed between silt and silt/clay, Na and K. Na is positively and significantly correlated with K but it is negatively significantly correlated

with Ca. Generally, SOC, pH and sand were the main factors influencing the variation in other physico-chemical properties and similar results were registered by Zhang *et al.* (2013).

Table 6: Correlation matrix of soil properties for three sub catchment

Variable	SOC	Av-P	Av-N	pH	BD	Sand	Clay	silt	Silt/clay	Na	K	Ca
SOC	1.00											
Av-P	0.03	1.00										
Av-N	0.14	-0.09	1.00									
pH	-0.37**	0.19*	0.04	1.00								
BD	-0.36**	-0.17	-0.02	0.39**	1.00							
Sand	0.47**	-0.16	0.09	-0.59**	-0.36**	1.00						
Clay	-0.20*	0.08	0.20*	0.52**	0.22*	-0.58**	1.00					
silt	-0.46**	0.15	-0.22*	0.43**	0.33**	-0.89**	0.14	1.00				
Silt/clay	-0.12	0.001	-0.29**	-0.05	0.20	-0.27**	-0.54**	0.63**	1.00			
Na	-0.08	0.24**	-0.17*	0.16	0.09	-0.28**	0.04	0.30**	0.12	1.00		
K	-0.14	0.40**	-0.10	0.43**	0.09	-0.32**	0.26**	0.25**	-0.03	0.23**	1.00	
Ca	-0.28**	-0.41**	-0.09	0.05	0.14	-0.04	-0.04	0.06	0.07	-0.04	-0.25**	1.00

*P<0.05, **P<0.01

3.5 Conclusion

The spatial variability and distribution of soil physical and chemical properties in three sub catchments were assessed. The results on classical statistics showed that soil physical and chemical properties had a total change varying from least to high variation and in that regard, soil pH was the least variable and Av-P was the most highly variable. The results of the study showed that soil chemical properties showed more spatial variability than physical properties. The semivariogram analysis showed the presence of a strong ($\leq 25\%$) to weak ($> 75\%$) spatial dependence of soil properties. In conclusion, soil physical and chemical properties exhibited heterogeneous pattern and thus varied with space. In addition, depending on soil physical property, maps produced by Kriging showed either good or poor spatial distribution. The physical properties were least variable. However, silt and silt/clay ratio had weak spatial dependence and thus not easily managed. Homogeneous profile and inconsistent trend of properties down the profile indicated the influence of biogeochemical processes that take place within the wetland. The understanding of soil properties' behaviour in this study addressed as to where exactly are proper conservation management interventions needed to be applied.

The results of the coefficient of variation showed that the overall physico-chemical properties in the study catchment varied from low to high with the smallest and highest average CV of 10 and 140% for soil pH and Av-P, respectively. This variability was probably due to catchment soil characteristics. Av-N and Av-P had inverse relationship in the sense that as depth increases Av-N increases while Av-P decreases. Both of them showed a turning point of trend at depth of 60cm. SOC was relatively lower on the surface horizons and with inconsistent trend down the profile. All other soil properties exhibited inconsistent trend down the soil profile. Among all studied physico-chemical properties, Av-N alone differed significantly with depth and hence indicating that sampling at different depth brought variation. The results showed that there was existence of an association between some soil properties with significant correlation with each other, with SOC being the soil parameter having the most diverse relationships with other soil parameters. SOC is followed by soil pH and sand, respectively. Soil pH in the study catchment showed acidity rated as moderately to strongly acidic. This acidity was thought to be explained by constant leaching due to rainfall which leaves the soil saturated with more Al^{3+} and H^+ . High percentage values of sand were obtained in the middle topographic unit with the least in the upper and bottom slope. The results revealed that topography influences the distribution of soil physical and chemical properties across the different slope positions. Therefore, the results of the study indicated that physico-chemical properties exhibited heterogeneity with depth and hence such soils are difficult to manage. However, soil pH and sand were least variable with depth. The heterogeneity in this study catchment, more especially on the upper soil depth, may be associated with wetlands use such as rangelands for animal grazing. The study catchment is also subjected to burrowing by ice rat leading to pedoturbation.

CHAPTER FOUR

APPLICATION OF HYDRIC SOIL FIELD INDICATORS TO DELINEATE WETLANDS

4.1 Introduction

Wetlands are considered as areas that have hydrophytic vegetation, hydric soils, and wetland hydrology (United States Army Corps of Engineers, 1987; National Water Act 36 of 1998). Wetland delineation is the application of a technical and procedural methodology to identify the boundary of a wetland area (United States Army Corps of Engineers, 1987; Kotze *et al.*, 1996; DWAF, 2005). The procedure begins with identifying the presence or absence of wetland indicators and establishing boundaries that group together sets of points that share the same status of each indicator.

The three factors necessary for the delineation and assessment of wetland performance are wetland hydrology, hydric soils and hydrophytic vegetation and they are indicators of a wetland (Vepraskas, 2008). However, the direct evidence of saturation to delineate wetlands is affected by the seasonality of wetland hydrology. Furthermore, the use of vegetation as an indicator is limited to sites where hydrology changes have not occurred. Therefore, soils have been regarded as an important feature in most delineation manuals hence hydric soils are key attributes for wetlands inventory (Tiner, 1999). In areas where there was hydrologic alteration and the vegetation has been removed, hydric soil serves as verification of the presence of wetlands hydrology (Kotze *et al.*, 1996; Mapeshoane, 2013). Field indicators of hydric soils have been developed in the United States of America by Vasilas *et al.* (2010). These indicators are the morphologic features that result from prolonged and repeated anaerobic soil conditions in upper portions of a soil profile.

The morphological changes include mottles which are spots or blotches of different colours or shades of colours interspersed within the dominant colour in a soil layer, usually resulting from the presence of periodic reducing soil conditions that cause reduction and translocation of redox sensitive species (Army Corps of Engineers, 1987; Vepraskas, 2000; Bohn *et al.*, 2001; Pezeshki & DeLaune, 2012).

Process of mottling can result in the formation of redox concentrations, redox depletions, reduced matrices and gleying (Vepraskas, 2001; Hurt *et al.*, 2002; Berkowitz & Saltee, 2011). Redox concentrations occur when reduced iron and manganese dissolve in the soil,

precipitate out, and accumulate and typically to form yellow, orange, red or black spots in soils that are alternately wet and dry mottles (Kotze *et al.*, 1996; Pezeshki and DeLaune 2012). However, redox concentrations such as root channel and pore lining masses and decreasing matrix chroma are just used as indicative of a wetland soil and require verification of the hydrology (Bryant *et al.* 2008, Mapeshoane, 2013). Redox depletions have chroma of 2 or less pale, and if there is no mottling, the chroma is 1 or less. A reduced matrix occurs when ferric iron is reduced and the soil appears gray. Grey, and to lesser extent blue and green colours predominate in gleyed soil material (Richardson *et al.*, 2001; Nell *et al.*, 2005).

Hydric soils are soils that for a significant period of the growing season have reducing conditions (soil is virtually free of oxygen) in the major part of the root zone and are saturated within 250mm of the surface. Wetland soils are either organic or mineral soils. Mineral soils that are permanently saturated are usually uniformly gleyed throughout the saturated area and show less mottling development, usually along root channels (Vepraskas, 2001). Soils are separated on the basis of the organic carbon content (Richardson *et al.*, 2001). The minimum proportion of organic carbon (OC) required for soil material to be classed as organic ranges from 12 to 18% (De Brogniez *et al.*, 2015). Organic soils generally have higher organic matter content, lower bulk density and higher water holding capacity and higher porosity (Richardson *et al.*, 2001).

According to Huang *et al* (2008), the variable OC limits are based on the observation that a given proportion of organic matter modifies the properties of a sandy material more than it does to those of clay. The bulk density of organic soils is less than 0.6 compared to 1.0 – 2.0 g/cm³ of mineral soils (Mitsch *et al.*, 1993, Richardson *et al.*, 2001). However, Köchy *et al*, (2015) suggested that low bulk density is associated with high organic carbon mass and a change from, for instance, 0.1 to 0.2g/cm³ leads to a doubling of soil organic carbon stock and mass.

Anaerobic soil conditions promote the accumulation of organic matter by impeding decomposition. Consequently, those wetland zones subject to the longest wet periods generally have the highest organic matter content (Barnal, 2008). Process of decomposition limits oxygen availability thus prohibiting aerobic respiration and partly decomposed organic material is accumulated in the topsoil giving the soil dark brown or black colours (Richardson *et al.*, 2001).

Low temperatures also promote organic matter accumulation, so that for a given water regime, more organic matter will accumulate in a cool climate than in a warmer one. An organic soil must have either 400mm of organic material within the upper 800mm of the soil or organic material of any thickness extending from the soil surface to rock or gravel (Soil Survey Staff, 1975).

The occurrence of these unique properties within the landscape is used as indicators of wetland conditions (Vepraskas, 2001) and can be used to delineate wetland. The use of the delineation manual is required to identify and delineate wetland such as Corps of Engineers Wetlands Delineation Manual (United States Army Corps of Engineers, 1987) and the wetland delineation manual of South Africa (DWAF, 2005).

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 hydric field soil indicators are identified by excavating a soil pit to 500mm of the soil surface according to DWAF (2005) and within 300mm for both USDA-NRCS (2010) and Australia Bryant *et al.*, (2008). These depths comprise the rhizosphere of the most hydrophytic vegetation in the respective areas. Hydric soil indicators are observed at the wetland edge and, if these soils are hydric, assume that soils in the wetter, interior portions of the wetland also are hydric, even if they lack an indicator (DWAF, 2005; USDA-NRCS, 2010).

Lesotho adapted the USDA soil taxonomy classification (Soil Survey Staff, 2010) to classify soils. Identified hydric soil indicators of Bokong wetlands in Lesotho by Mapeshoane, (2013), were Histisol (A1), Histic Epipedon (A2), Thick dark surfaces (A12), Redox dark surfaces (F6), Depleted dark surfaces (F7), Redox depression (F8), Loamy gleyed matrix (F2) and Umbric surface (F13). The most common were Umbric surfaces (F13) and occurred on the midslopes and footslopes while histisols (A1) indicator and a histic epipedon were not common (Mapeshoane, 2013). The histisols, histic epipedon and umbric surfaces are formed due to slower organic matter decomposition and formation of peat (USDA-NRCS, 2010). In the findings of Mapeshoane (2013), indicators with prominent concentrations were not common and some profiles had the redoximorphic features occurring deeper than that required by the USDA-NRCS (2010) and thus could not meet the listed field indicators. The gleyed matrix observed occurred at 600mm depth from the surface whereas, USDA-

NRCS, (2010) recommends 300mm from the surface. However, Mapeshoane (2013) further indicated that the research which would further focus on developing more indicators for proper characterisation and classification of soils is required to identify hydric soils.

Olaleye *et al.* (2014) reported the morphological features such as grey or low chroma (<3) colours, mottles, and few Fe/Mn concretions at some parts of Khalong-la-Lithunya catchment. However, the study did not use the redoximorphic features to delineate the wetlands. The delineation of wetlands is important aspect of land use planning, conservation planning such as assessment of potential wildlife habitat and resource development (Berkowitz & Sallee, 2011). According to Mapeshoane (2013), gley and cumulative saturation representing hydric indicators such as histisols, histic epipedon, and loamy gleyed matrix can be used to determine the duration and frequency of the water table in the landscape and these hydric indicators can be used to delineate wetlands, however, more indicators can be developed.

Spatial variability is the considerable differences in space in soil properties that can be attributed to systematic or random factors that can exist within a wetland area (Wilding & Drees, 1983). In wetland systems, this variability are due to numerous factors, including micro-relief, animal activity, any human activity, and the effect of individual plants on soil microclimate and precipitation chemistry. Spatial variation includes horizontal variation across a landscape and vertical variation with horizon depth (Baharom *et al.*, 2015). However, the variability of soil properties in space and time presents a challenge for wetlands assessment and the detection of changes within or among wetlands. Spatial variability is vital when considering the environmental and ecological functioning and delineation of wetland (Stolt *et al.*, 2001).

Wetland delineation relies on field indicators and can contribute to an understanding of wetland extent within a catchment. It is thus the process of demarcating wetland areas from other adjoining areas that do not satisfy the wetland definition, based on field investigation. In practice, if the area is identified as a wetland area, the field indicators are used to determine the spatial limits of the wetland conditions being the boundary of the wetland area on the ground. Wetland area delineation involves determining its spatial limits on the ground and this is based on the field indicators of wetland conditions for the wetland criteria (TAT, 2012).

The objectives of this chapter are then to (i) determine soil redoximorphic features (ii) identify field hydric soil indicators relevant for Lesotho mountain wetlands for assessment of wetlands performance and (iii) delineate Khalong-la-Lithunya wetlands.

4.2 Material and Methods

4.2.1 Hydric soil description and soil sampling

Detailed soil profile and hydric soil description (USDA-NRCS, 2010) was carried out. Field indicators of hydric soils were determined from 0-450mm depth for mottling (redox concentrations), grey (redox depletion) and gleying (permanent saturation) following USDA-NRCS, (2010). Munsell Colour book was used to identify the colour according to Kollmorgen Instruments Corporation (2002). Areas in the soil where iron is reduced often develop characteristic bluish gray or greenish gray colors known as gley (colors with value of 4 or more on the gley pages in the Munsell color book). Areas that have lost iron typically develop characteristic gray or reddish gray colors and are known as redox depletions. If a soil reverts to an aerobic state, iron that is in solution will oxidize and become concentrated in patches as soft masses and along root channels and other pores. These areas of oxidized iron are called redox concentrations (USDA-NRCS, 2010).

4.2.2 Statistical analysis

Data were subjected to classical analysis using SPSS 16.0 software to obtain descriptive statistics. Arc GIS 10.2.2 was used to create interpolation map for spatial distribution of hydric soil indicators and redoximorphic features.

4.3 Results and Discussion

4.3.1. Soil morphological properties within 450mm soil depth from the surface and identified hydric soil indicators of Khalong-la-Lithunya wetlands

The study was carried out to characterise and classify the Khalong-la-Lithunya wetland soils in order to identify presence of hydric soils. According to Mapeshoane (2013), hydric soils definition is met only when hydric soil indicators are present. The identified hydric soil indicators of Khalong-la-Lithunya wetlands according to USDA-NRCS (2010) are presented in Table 7. Identified soil field indicators were **A1, A2, A3, A5, A7, A10, A12, A13** and **A14**.

Table 7: Description of identified hydric soil field indicators in the wetlands of Khalong-li-Lithunya (USDA-NRCS, 2010)

Hydric soil indicator	Description
Histosol (A1)	A layer with organic soil material typically 400mm or more of the upper 800mm. Organic soil materials have organic carbon contents of 12 to 18% or more, depending on the clay content of the soil.
Histic Epipedon (A2)	A histic epipedon underlain by mineral soil material with chroma of 2 or less. Most histic epipedons are surface horizons 200mm or more thick of organic soil material. Aquic conditions or artificial drainage is required.
Black Histic (A3)	A layer of peat, mucky peat, or muck 200mm or more thick that starts within the upper 150mm of the soil surface; has hue of 10YR or yellower, value of 3 or less, and chroma of 1 or less; and is underlain by mineral soil material with chroma of 2 or less. Unlike indicator A2, this indicator does not require proof of aquic conditions or artificial drainage.
Stratified Layers (A5)	Several stratified layers starting within the upper 150mm of the soil surface. At least one of the layers has value of 3 or less and chroma of 1 or less, or it is muck, mucky peat, peat, or a mucky modified mineral texture. The remaining layers have chroma of 2 or less. For any sandy material that constitutes the layer with value of 3 or less and chroma of 1 or less, at least 70% of the visible soil particles are masked with organic material, viewed through a 10x or 15x hand lens. The minimum organic-carbon content of at least one layer of this indicator is slightly less than is required for indicator A7 (50mm Mucky Mineral).
Mucky Mineral (A7)	A layer of mucky modified mineral soil material 50mm or 12 field indicators of more thick, starting within 150mm of the soil surface. The content of organic carbon is at least 5% and ranges to as high as 18%. The percentage required depends on the clay content of the soil; the higher the clay content, the higher the content of organic carbon required.
Muck (A10)	A layer of muck 20mm or more thick with value of 3 or less and chroma of 1 or less, starting within 150mm of the soil surface. This indicator requires a minimum muck thickness of 20mm. Muck is sapric soil material with a minimum content of organic carbon that ranges from 12 to 18%, depending on the content of clay.
Thick dark surface (A12)	A layer that has at least 150mm thick with a depleted or gleyed matrix that has 60% or more chroma of 2 or less starting below 300mm of the surface. The layer(s) above the depleted or gleyed matrix having value of 2.5 or less and chroma of 1 or less to a depth of at least 300mm and value of 3 or less and chroma of 1 or less in any remaining layers above the depleted or gleyed matrix. This indicator applies to soils that have a black layer 300mm or more thick and have value of 3 or less and chroma of 1 or less in any remaining layers directly above a depleted or gleyed matrix.
Alaska Gleyed (A13)	A mineral layer with a dominant hue of N, 10Y, 5GY, 10GY, 5G, 10G, 5BG, 10BG, 5B, 10B, or 5PB and with value of 4 or more in more than 50% of the matrix. The layer starting within 300mm of the mineral surface and is underlain within 1500mm by soil material with hue of 5Y or redder in the

	same type of parent material.
Alaska Redox (A14)	A mineral layer that has dominant hue of 5Y with chroma of 3 or less, or a gleyed matrix, with 10% or more distinct or prominent redox concentrations occurring as pore linings with value and chroma of 4 or more. The layer occurs within 300mm of the soil surface.

Histosol (**A1**) indicators were observed in many profiles with histic epipedon (**A2**). This was explained by slower organic matter decomposition and formation of peat (USDA-NRCS, 2010). The other soil indicators were rarely identified.

The surface diagnostic horizons observed were, histic, mollic, umbric and ochric. Cambic was identified in the subsurface. Most soil profile had histic epipedon. 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. Different soil profiles exhibited different redoximorphic features, whereas some did not have such features such as profiles 1, 6, 19, 21, 22, 31 and 34. This suggested that not all soil found in Khalong-la-Lithunya were hydric with reference to USDA-NRCS (2010). Hence this calls for further proper characterization of soils of such wetlands. The most redoximorphic features observed were of concentration rather than of depletion and gleying. Indicators with prominent concentrations were not common in all sub catchment but they were distinct and faint. However, some profiles had the redoximorphic features occurring below 500mm and thus failed to meet the listed field indicators with reference to USDA-NRCS (2010). Gleying was observed in profiles 4, 5, 17, 20, 25, 28, 30 and 33 and these profiles were situated close to the stream. This gives an indication of prolonged saturation. Soil morphological properties within 450mm soil depth from the surface and hydric soil indicators of Khalong-la-Lithunya wetlands identified in the sampled profiles are given in Table 8.

Table 8: Soil morphological properties within 450mm soil depth from the surface and hydric soil indicators of Khalong-la-Lithunya wetlands identified in the sampled profiles

Prof No	DH	Depth (mm)	Matrix col	RMFs Con	RMFs Dep	Dep col	Gleying	Indicator
1	Umbric	0-150	10YR 3/3	none	none	none	none	A2
	Cambic	150-300	10YR 3/4	none	none	none	none	A10
	Cambic	300-450	10 YR 3/2	none	none	none	none	A10
2	Ochric	0-150	7.5 YR 4/4	m/c/dyb/pr	none	none	none	A1
	Histic	150-300	10 YR 2/1	c/f/dyb/faint	none	none	none	A1
	Histic	300-450	10 YR 2/1	c/f/dyb/faint	none	none	none	A1
3	Mollic	0-150	10 YR 3/2	c/f/dyb/faint	none	none	none	A1
	Histic	150-300	10 YR 2/2	none	none	none	none	A1
	Histic	300-450	10 YR 2/1	none	none	none	none	A1
4	Histic	0-150	10 YR 2/1	f/m/ry/faint	none	none	none	A1
	Histic	150-300	10 YR 2/1	m/c/ry/pr	none	none	none	A1
	Histic	300-450	10 YR 2/1	none	c/c/g/dist	N5/	g	A1
5	Ochric	0-150	7.5 YR 4/6	m/c/ry/pr	none	none	none	A1
	Histic	150-300	10 YR 2/1	none	f/c/g/dist	N5/	g	A1
	Histic	300-450	10 YR 2/1	none	none	none	none	A1
6	Ochric	0-150	10 YR4/4	none	none	none	none	A2
	Cambic	150-300	10 YR4/4	none	none	none	none	A2
	Cambic	300-450	10 YR4/4	none	none	none	none	A1
7	Histic	0-150	10 YR 2/1	m/f/ry/pr	none	none	none	A1
	Histic	150-300	10 YR 2/1	f/f/ry/faint	none	none	none	A1
	Histic	300-450	10 YR 2/1	none	none	none	none	A1
10	Mollic	0-150	10 YR 2/1	m/f/ry/dist	none	none	none	A2
	Histic	150-300	10 YR 2/1	m/f/ry/faint	none	none	none	A10
	Histic	300-450	10 YR 2/1	none	none	none	none	A1
15	Melanic	0-150	10 YR 2/2	c/f/ry/faint	none	none	none	A1
	Melanic	150-300	10 YR 2/2	f/f/ry/faint	none	none	none	A10
	Hisitc	300-450	10 YR 2/1	f/f/ry/faint	none	none	none	A1
16	Mollic	0-150	10 YR 3/2	m/f/ry/faint	none	none	none	A3
	Mollic	150-300	10 YR 3/2	none	none	none	none	A3
	Mollic	300-450	10 YR 3/2	none	none	none	none	A3

DH= USDA soil classification diagnostic horizons (USDA-NRCS, 2010).

Matrix col = Matrix colour, RMFs Con = Redoximorphic features of concentration, RMFs Dep = Redoximorphic features of depletion,

Dep Col = Depletion colour (Chroma of < 2).

Abundance: f= few (<2%), c = common (2 to 20%), m =many (>20%).

Size: f = fine, m = medium, c = coarse, vc = very coarse.

Colour: ry = reddish yellow, yr = yellowish red, o = olive, dyb = dark yellowish brown db =dark brown, dgg = dark greenish gray, bg = bluish gray, dbg = dark bluish gray, g = gray.

Contrast: faint, dist = distinct, pr = prominent

Hydric soil indicators (USDA-NRCS, 2010): **A1** Histisols, **A2** Histic epipedon, **A3** Black histic, **A5** stratified layers, **A7** Mucky Mineral, **A10** Muck, **A12** Thick Dark Surface, **A13** Alaska Gleyed and **A14** Alaska Redox.

Table 8 continued

Prof No	DH	Depth (mm)	Matrix col	RMFs Con	RMFs Dep	Dep Col	Gleying	Indicator
17	Mollic	0-150	10 YR 3/2	f/m/ry/dist	none	none	None	A3
	Mollic	150-300	10 YR 3/2	none	f/m/dbg/pr	5B 4/1	dbg	A3
	Histic	300-450	10 YR 2/1	c/c/ry/pr	none	none	None	A3
18	mollic	0-150	2.5Y3/1	f/c/db/dist	none	none	None	A12
	Cambic	150-300	5Y2.5/1	none	none	none	None	A12
	Cambic	300-450	5Y2.5/1	none	none	none	None	A12
19	Umbric	0-150	10YR 3/4	none	none	none	None	A1
	Cambic	150-300	7.5YR 3/1	none	none	none	None	A7
	Cambic	300-450	10YR 3/2	none	none	none	None	A1
20	Mollic	0-150	10YR 3/2	none	none	none	None	A3
	Histic	150-300	2.5Y2.5/1	none	none	none	None	A12
	Cambic	300-450	2.5Y2.5/2	none	f/m/dgg/faint t	5BG 4/1	Dgg	A13
21	Ochric	0-150	10 YR4/4	none	none	none	None	A7
	Cambic	150-300	5Y2.5/1	none	none	none	None	A12
	Cambic	300-450	5Y2.5/1	none	none	none	None	A12
22	Ochric	0-150	10 YR4/4	none	none	none	None	A7
	Cambic	150-300	10 YR4/4	none	none	none	None	A14
	Cambic	300-450	10 YR4/3	none	none	none	None	A7
23	Histic	0-150	7.5 YR 2.5/1	f/f/ry/pr	none	none	None	A12
	Histic	150-300	10 YR 2/1	f/mry/pr	none	none	None	A12
	Histic	300-450	10 YR 3/1	none	none	none	None	A1
24	Histic	0-150	10 YR 2/1	f/f/ry/faint	none	none	None	A12
	Histic	150-300	10 YR 3/1	f/fyr/pr	none	none	None	A1
	Histic	300-450	5 YR 3/4	f/vc/ry/pr	none	none	None	A1
25	Histic	0-150	N 3/	f/f/o/faint	none	none	None	A12
	Histic	150-300	N 3/	none	f/m/dgg/dis	5Y 4/3	Olive	A12
	Histic	300-450	10 Y 2.5/1	none	none	none	None	A1
26	Histic	0-150	10 Y 3/1	f/f/ry/faint	none	none	None	A1
	Histic	150-300	7.5 YR 2.5/1	f/f/ry/faint	none	none	None	A12
	Ochric	300-450	7.5 YR 3/1	f/f/ry/dist	none	none	None	A5

DH= USDA soil classification diagnostic horizons (USDA-NRCS, 2010).

Matric col = Matrix colour, RMFs Con = Redoximorphic features of concentration, RMFs Dep = Redoximorphic features of depletion,

Dep Col = Depletion colour (Chroma of < 2).

Abundance: f= few (<2%), c = common (2 to 20%), m =many (>20%).

Size: f = fine, m = medium, c = coarse, vc = very coarse.

Colour: ry = reddish yellow, yr = yellowish red, o = olive, dyb = dark yellowish brown db =dark brown, dgg = dark greenish gray, bg = bluish gray, dbg = dark bluish gray, g = gray.

Contrast: faint, dist = distinct, pr = prominent

Hydric soil indicators (USDA-NRCS, 2010): **A1** Histisols, **A2** Histic epipedon, **A3** Black histic, **A5** stratified layers, **A7** Mucky Mineral, **A10** Muck, **A12** Thick Dark Surface, **A13** Alaska Gleyed and **A14** Alaska Redox.

Table 8 continued

Prof No	DH	Depth (mm)	Matrix col	RMFs Con	RMFs Dep	Dep Col	Gleying	Indicator
27	Histic	0-150	10 YR 2/1	none	None	None	none	A12
	Histic	150-300	10 YR 2/2	none	None	None	none	A1
	Ochric	300-450	10 YR 3/4	f/m/ry/dist	None	None	none	A7
28	Histic	0-150	10 YR 3/2	f/m/ry/dist	None	None	none	A1
	Histic	150-300	10 YR 2/1	none	f/m/dgg/dist	5BG 4/1	dgg	A12
	Histic	300-450	10 YR 2/1	f/m/ry/dist	None	None	none	A12
29	Histic	0-150	10 YR 3/1	f/m/ry/pr	None	None	none	A1
	Histic	150-300	11 YR 3/1	none	None	None	none	A1
	Histic	300-450	N 2.5/	none	None	None	none	A12
30	Histic	0-150	10 YR 3/1	f/f/ry/dist	None	None	none	A1
	Histic	150-300	10 YR 3/1	none	None	None	none	A1
	Histic	300-450	10 YR 3/1	none	f/f/dgg/faint	5BG 4/1	dgg	A13
31	Histic	0-150	7.5 YR 2.5/1	none	None	None	none	A12
	Histic	150-300	5 YR 2.5/1	none	None	None	none	A12
	Histic	300-450	5YR 3/1	none	None	None	none	A1
32	Histic	0-150	7.5 YR 2.5/1	c/f/yr/dist	None	None	none	A12
	Histic	150-300	N 2.5/	f/f/yr/faint	None	None	none	A12
	Histic	300-450	N 3/	none	None	None	none	A1
33	Histic	0-150	5YR 2.5/1	none	None	None	none	A12
	Histic	150-300	7.5 YR2.5/2	None	c/m/bg/dist	5PB 6/1	bgr	A12
	Cambic	300-450	7.5 YR2.5/3	None	c/m/bg/dist	5B 7/1	ligbgr	A1
34	Histic	0-150	10YR 2/1	None	None	None	none	A12
	Cambic	150-300	10YR 2/2	None	None	None	none	A1
	Cambic	300-450	10YR 3/4	None	None	None	none	A1

DH= USDA soil classification diagnostic horizons (USDA-NRCS, 2010).

Matric col = Matrix colour, RMFs Con = Redoximorphic features of concentration, RMFs Dep = Redoximorphic features of depletion, Dep Col = Depletion colour (Chroma of < 2).

Abundance: f= few (<2%), c = common (2 to 20%), m =many (>20%).

Size: f = fine, m = medium, c = coarse, vc = very coarse.

Colour: ry = reddish yellow, yr = yellowish red, o = olive, dyb = dark yellowish brown db =dark brown, dgg = dark greenish gray, bg = bluish gray, dbg = dark bluish gray, g = gray.

Contrast: faint, dist = distinct, pr = prominent

Hydric soil indicators (USDA-NRCS, 2010): **A1** Histisols, **A2** Histic epipedon, **A3** Black histic, **A5** stratified layers, **A7** Mucky Mineral, **A10** Muck, **A12** Thick Dark Surface, **A13** Alaska Gleyed and **A14** Alaska Redox.

4.3.2 Occurrences of hydric soil properties within the 450mm soil depth in the three sub catchments at Khalong-la-Lithunya

Soil organic carbon was categorised into three classes namely, a class of less than 12, between 12 and 18 and above 18%. The descriptive statistics of hydric soil properties within 450mm soil depth are given in Table 9. The results show that in sub catchments 1 and 3, most horizons had soil organic content greater than 18% with 71.8% and 75.0% frequency of occurrence. In contrary, sub catchment 2 had soil profile with soil organic content less than 12% with 86.7% of occurrence. Soil organic carbon in the category of between 12 and 18% had 13.3, 17.9 and 16.7% frequencies of occurrence for sub catchments 2, 1 and 3 respectively.

The results of this study show that in most of the horizons, there were no redoximorphic features (Redox concentrations) observed and this was explained by 48.7, 55.6 and 93.3% null results of occurrence. The occurrence of reddish yellow was 38.5 and 27.8% for sub catchment 1 and 3 respectively and 6.7% for dark brown in sub catchment 2. The results also show that 13.4 and 2.8% of occurrence for yellowish red and olive respectively were obtained in sub catchment 2 and 12.8% dark yellowish brown in sub catchment 1. The presence of redoximorphic features was not observed in most horizons for redox depletion and gleying with the same percentage of 89.7% none histic for both sub catchments 1 and 3 whereas sub catchment 2 had 93.3% for redox concentration, redox depletions and gleying for sub catchment 2. The most observed soil field indicators were **A1** (64.1%) in sub catchment 1 and **A12** for sub catchments 2 and 3 with 40.0 and 47.2% of occurrence respectively. **A7** (26.7%) occurrence was higher in sub catchment 2. In contrary, **A2**, **A3**, **A5**, **A10**, **A13** and **A14** were limited.

Table 9: Occurrences of hydric soil properties within the 450mm soil depth in the three sub catchments at Khalong-la-Lithunya

Hydric soil properties	Percentage (%) frequency of occurrence		
	Sub catchment 1	Sub catchment 2	Sub catchment 3
Soil Organic Carbon content			
< 12%	10.3	86.7	8.3
12% ≥ 18%	17.9	13.3	16.7
> 18%	71.8	0	75.0
Redox concentrations			
None	48.7	93.3	55.6
Reddish yellow	38.5	0	27.8
yellowish red	0	0	13.4
Olive	0	0	2.8
Dark brown	0	6.7	0
Dark yellowish brown	12.8	0	0
Redox Depletions			
None	89.7	93.3	86.6
5Y4/3	0	0	2.8
5BG4/1	0	6.7	5.6
5PB6/1	0	0	2.8
5B7/1	0	0	2.8
5B4/1	2.6	0	0
N/5	7.7	0	0
Gleying			
None	89.7	93.3	86.1
Olive	0	0	2.8
Bluish gray	0	6.7	5.6
Dark greenish gray	0	0	2.8
Light bluish gray	0	0	2.8
Dark bluish gray	2.6	0	0
Gray	7.7	0	0
Indicators			
A1	64.1	13.3	4.4
A2	10.3	0	0
A3	15.4	6.7	0
A5	0	0	2.8
A7	0	26.7	2.8
A10	10.3	0	0
A12	0	40.0	47.2
A13	0	6.7	2.8
A14	0	6.7	0

4.3.3 The soil classification of Khalong-la-Lithunya wetlands with reference to the USDA soil taxonomy

The means of the chemical and physical properties of the soil in three sub catchment are given in table 10. Lesotho adapted the USDA soil taxonomy classification (Soil Survey Staff, 2010) to classify soils. The current study classified the Khalong-la-Lithunya soils as Alfisols, Histisols, Inceptisols and Mollisols with cryic temperature and aquic and udic moisture regime (Table 11). The Profiles 1 and 19 were classified as Humic Dysstrudepts (Table 11). Fusi series were also observed by Mapeshoane (2013) in Bokong wetlands with a cambic horizon and were classified as Humic Dystrudepts or Humic Pachic Dystrudepts on the footslopes where the humic layer was thicker.

Profiles 2, 5, 6, 21 and 22 exhibited Typic Cryaqualfs while Histic Cryaquolls were found in profile 3, 10, 18 and 20. Histic humaquepts were not common as they were only identified in profile 15 and 34. The Khalong-la-Lithunya wetlands are dominated by Fibric Haplohemists. The description of soil taxonomic classes in the wetlands of Khalong-li-Lithunya is given in Table 12. These are hemists that have one or more layers of fibric materials with a total thickness of 250mm or more in the control section. This indicated that most profile had high content of organic matter in the upper 800mm of the soils. 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; Mapeshoane, 2013). Histisols are found in small acreages in the higher elevations of the mountain zone of Lesotho..

Table 10 Soil properties in three sub catchments at Khalong-la-Lithunya wetlands

Soil properties	Sub catchment 1	Sub catchment 2	Sub catchment 3
SOC (%)	27	11	30
Av- P (mg/kg)	3.0	1.0	7.0
Av-N P (mg/kg)	2.4	2.0	2.6
pHW	4.9	5.1	5.1
Na (Cmol/kg)	2.4	0.1	3.9
K (Cmol/kg)	1.8	1.6	3.2
Ca (Cmol/kg)	9.9	10.0	5.1
Mg (Cmol/kg)	2.3	-	-
CEC (Cmol/kg)	82.8	-	-
BD g/cm ³	0.5	0.8	0.8
SAND %	65	61	52
CLAY%	14	15	19
SILT%	20	24	28
SILT / CLAY	1.6	1.9	1.4

Cumulic Cryaquolls were not common and were observed in profiles 16 and 17. According to Rooyani & Badamchian (1986), mollisols are characterised by having a relatively dark to dark brown thick surface (mollic epipedon) and in Lesotho, they occur in a variety of landforms. Mollisols are relatively shallow on the mountain and foothill slopes. However, in depressions, at the base of slopes and in mountain valleys, they are deep and referred to as Cumulic Cryaquolls. The Matsana, Soloja and Thamathu series are well drained and moderately deep soils. However, Hapludolls (Popa series) are the most extensive and occur on the basaltic high slopes of the mountain zone (Rooyani & Badamchian., 1986). Fluvaquentic Cryofibrists were observed only in Profile 26 and these soils have, within the organic materials, either one mineral layer 50 to 300mm thick or two or more mineral layers of any thickness in the control section, below the surface tier.

Table 11: Taxonomic classes in the wetlands of Khalong-li-Lithunya

Profile no	USDA Soil Taxonomy
1	Humic Dystrudepts
2	Typic Cryaqualfs
3	Histic Cryaquolls
4	Fibric Haplohemists
5	Typic Cryaqualfs
6	Typic Cryaqualfs
7	Fibric Haplohemists
10	Histic Cryaquolls
15	Histic humaquepts
16	Cumulic Cryaquolls
17	Cumulic Cryaquolls
18	Histic Cryaquolls
19	Humic Dystrudepts
20	Histic Cryaquolls
21	Typic Cryaqualfs
22	Typic Cryaqualfs
23	Fibric Haplohemists
24	Fibric Haplohemists
25	Fibric Haplohemists
26	Fluvaquentic Cryofibrists
27	Fibric Haplohemists
28	Fibric Haplohemists
29	Fibric Haplohemists
30	Fibric Haplohemists
31	Fibric Haplohemists
32	Fibric Haplohemists
33	Fibric Haplohemists
34	Histic humaquepts

Table 12: Description of taxonomic classes in the wetlands of Khalong-li-Lithunya

Taxonomic classes	Description
Humic Dystrudepts	These soils have an umbric or mollic epipedon that is less than 500mm thick. They are otherwise like the soils of the Typic subgroup.
Histic humaquepts	These soils have a histic epipedon. They are the wettest of the Humaquepts and are intergrades to Histosols. The organic-carbon content (Holocene age) may be relatively high in the deep layers. Most of these soils support native vegetation.
Typic Cryaqualfs	Cryaqualfs are the Aqualfs that have a cryic or isofrigid temperature regime.
Histic Cryaquolls	These soils have a histic epipedon and are considered intergrades to Histosols. They are the wettest of the Cryaquolls, and the level of ground water in them fluctuate the least.

Cumulic Cryaquolls	These soils have an overthickened mollic epipedon as a result of slow accumulation of material washed from higher areas. They are subject to occasional flooding when streams are high. Cryaquolls may have an argillic or cambic horizon or a shallow calcic horizon.
Fluvaquentic Cryofibrists	These soils differ from Typic Cryofibrists because they have, within the organic materials, either one mineral layer 50 to 300mm thick or two or more mineral layers of any thickness in the control section, below the surface tier.
Fibric Haplohemists	These soils differ from Typic Haplohemists because they have one or more layers of fibric materials with a total thickness of 250mm or more below the surface tier.

Source: USDA-NRCS, 2010

4.3.4 Spatial distribution of hydric soil indicators and redoximorphic features in the three sub catchments of Khalong-la-Lithunya

Soils are categorized into organic and mineral soils. Soils with organic content by weight ranging between 12 and 18% and above 18 are considered organic and soils with organic content below 12 are regarded as mineral soils. Both sub catchments 1 and 3 were dominated by high percentage SOC greater than 12 as depicted in Figure 9. On the contrary, sub catchment 2 was dominated by mineral soil. Low SOC content may be explained by wetland degradation as a result of soil erosion.

Identified soil field indicators were **A1, A2, A3, A5, A7, A10, A12, A13** and **A14**. Histosols (**A1**) and indicators were observed in many profiles with histic epipedon (**A2**) as illustrated in Figure 10. Field indicators **A1, A2, A3** and **A10** were identified in sub catchment 1 with **A1** being the most occurring indicator. In sub catchment 2, **A1, A3, A7, A12** and **A14** were identified with **A12** being the most frequent and **A1** being the least frequent. Field indicators **A1, A5, A7, A12** and **A13** were obtained in sub catchment 3 with **A1** and **A12** dominating.

Periodic saturation results in the formation of yellow, orange, red or black mottles (Kotze *et al.*, 1996; Pezeshki & DeLaune 2012). Process of mottling can result in the formation of redox concentrations, redox depletions, reduced matrices and gleying (Berkowitz & Sallee, 2011; Vepraskas, 2001). Redox concentrations occur when reduced iron and manganese dissolve in the soil, precipitate out, and accumulate and typically form yellow to red spots in soils that are alternately wet and dry. The results on spatial distribution of redox concentration show that most horizons in the catchment did not have redoximorphic feature as depicted in Figure 11 with large area without the presence of redox concentration. These

results are in agreement with what is shown in Table 9. The observed soil mottle colours were reddish yellow, dark yellowish brown, reddish yellowish red and olive. According to Figure 12, redox depletions have chroma of two or less pale, and if there is no mottling, the chroma is 1 or less.

A reduced matrix occurs when ferric iron is reduced and the soil appears grey. Grey, and to lesser extent blue and green colours predominate in gleyed soil material (Nell *et al.*, 2005; Richardson *et al.*, 2001). Mineral soils that are permanently saturated are usually uniformly gleyed throughout the saturated area and show less mottling development, usually along root channels (Vepraskas, 2001). The results of the study in figure 13 revealed few profiles with gleying and most profiles had gleying occurring below 450mm and thus failed to meet the USDA NRCS (2010) requirements.

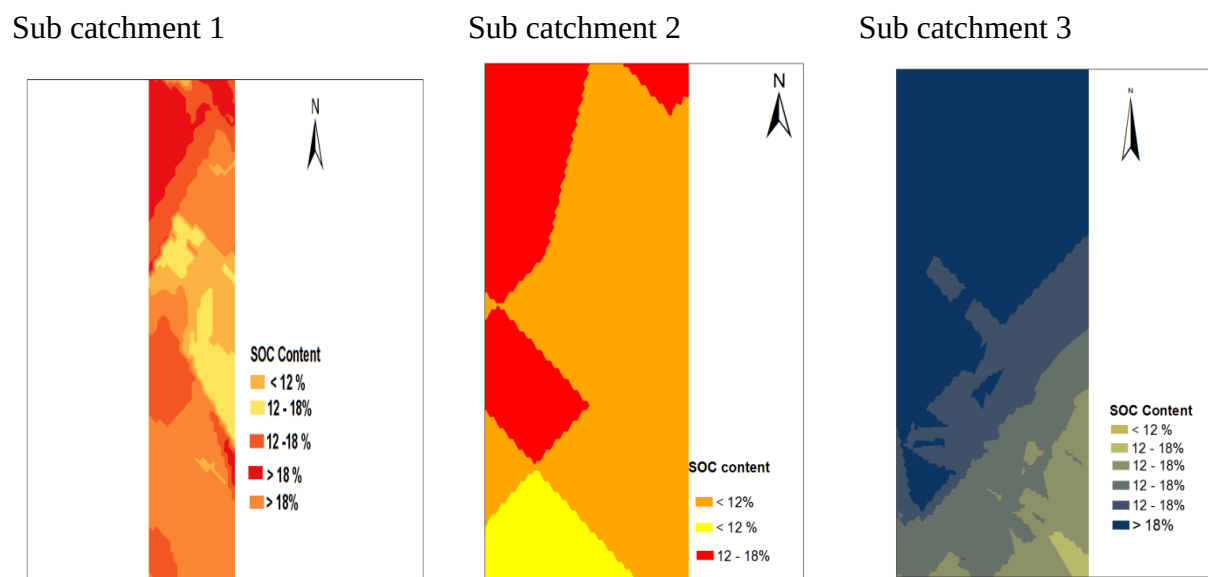


Figure 9: Ordinary Kriged maps of soil organic content classes in the three sub catchments of Khalong-la-Lithunya

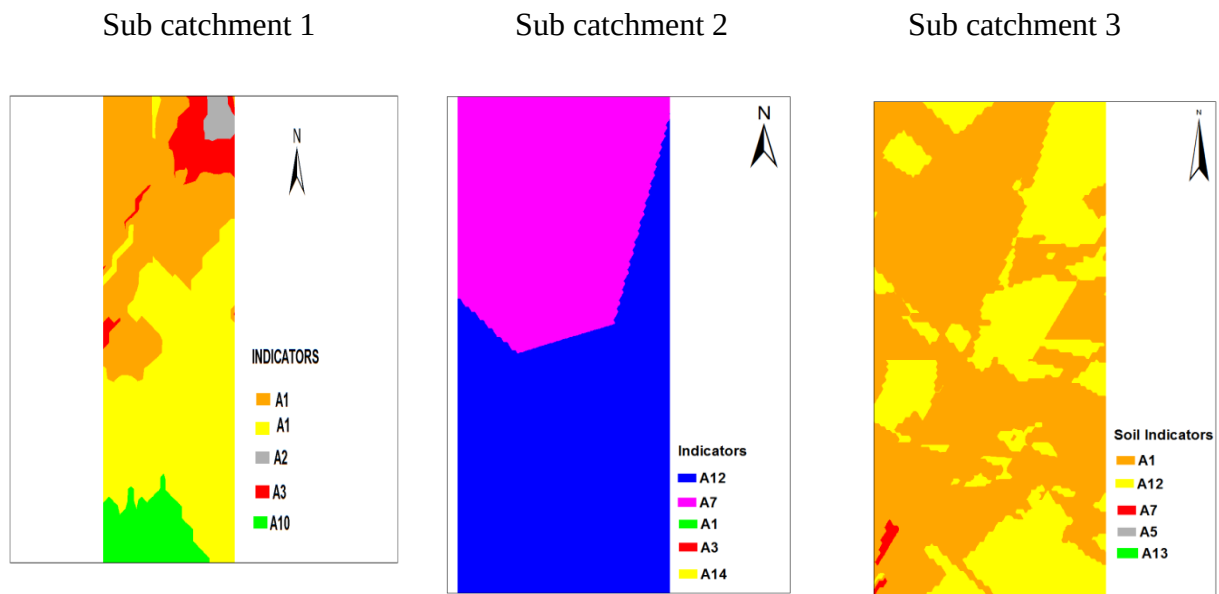


Figure 10: Ordinary Kriged maps of hydric soil field indicators in the three sub catchments of Khalong-la-Lithunya

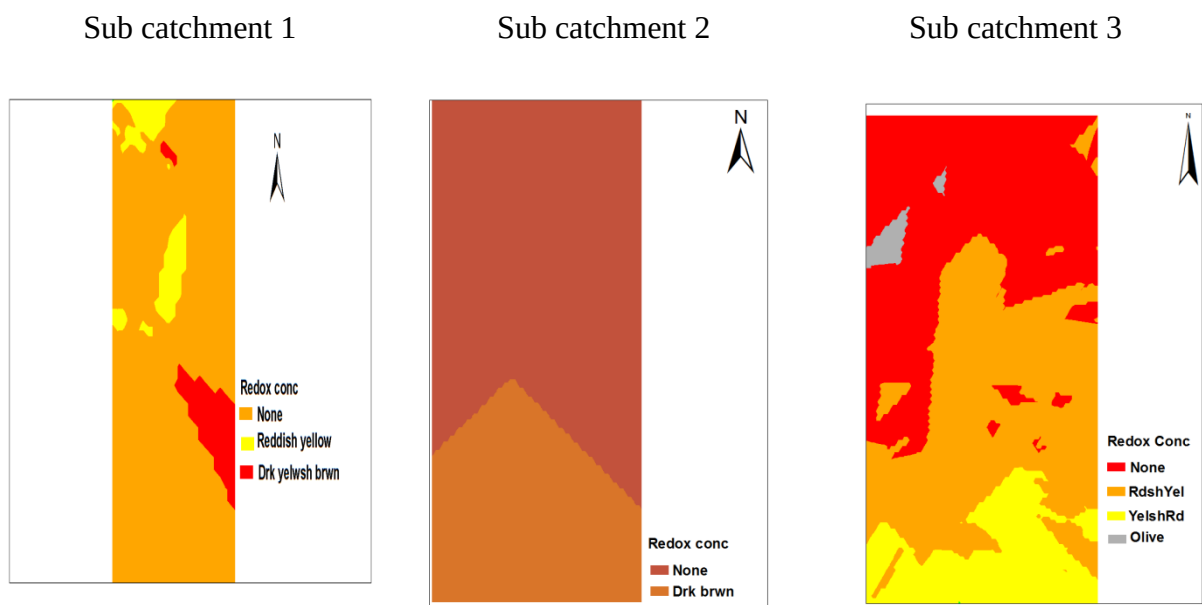


Figure 11: Ordinary Kriged maps of redox concentrations in the three sub catchments of Khalong-la-Lithunya

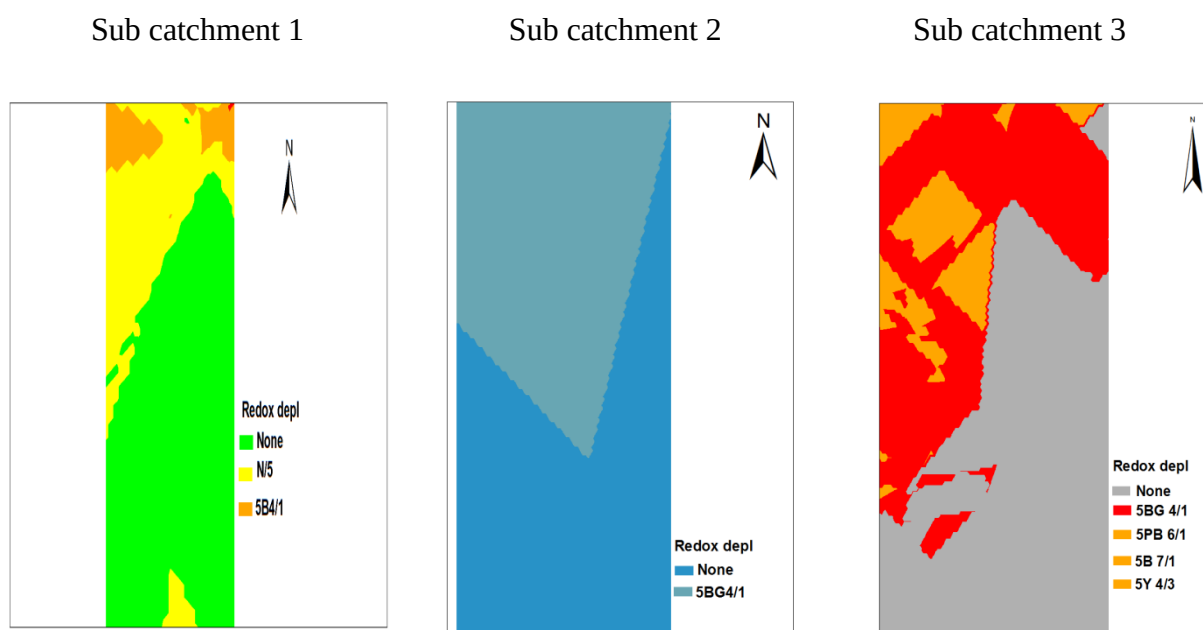


Figure 12: Ordinary Kriged maps of redox Depletion in the three sub catchments of Khalong-la-Lithunya

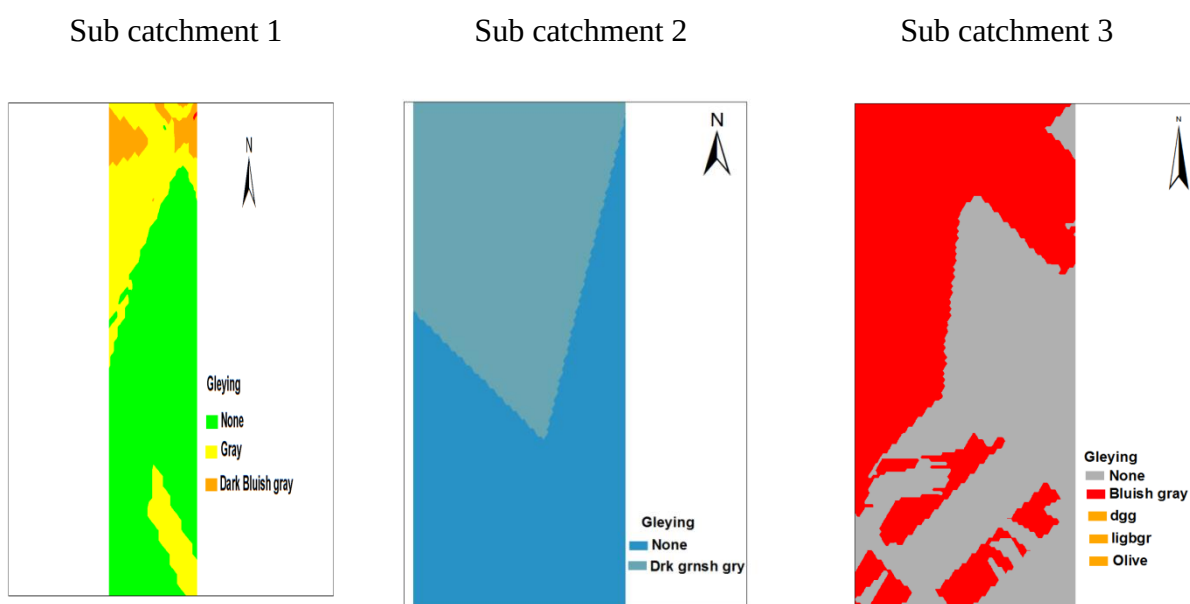


Figure 13: Ordinary kriged maps of gleying in the three sub catchments of Khalong-la-Lithunya

4.4 Conclusions

Identified soil field indicators were **A1**, **A2**, **A3**, **A5**, **A7**, **A10**, **A12**, **A13** and **A14**. Histosols (**A1**) indicators were observed in many profiles with histic epipedon (**A2**). The surface diagnostic horizons observed were, histic, mollic, umbric and ochric. Cambic was identified in the subsurface. Soils were classified as Humic Dystrudepts, Typic Cryaqualfs, Histic Cryaquolls, Fibric Haplohemists, Cumilic Cryaquolls and Fluvaquentic Cryofibrists. The most redoximorphic features observed were of concentration than of the depletion and Gleying. Some profiles had the redoximorphic features occurring below 500mm and thus failed to meet the listed field indicators with reference to USDA-NRCS (2010). Hence this calls for further research that will come up with proper characterization of soils in such wetlands.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

Knowledge on vertical, spatial variability, spatial dependence and distribution of soil properties is vital for understanding the ecosystem processes which give an indication of wetlands conditions and suitable conservation wetlands management decisions. The aims of this study were to determine the vertical and spatial variability and spatial dependence in soil physical, chemical and morphological properties, and to identify hydric soil indicator and redoximorphic features to delineate wetlands in Khalong-la-Lithunya catchment. The main factors of variability in soil properties in small catchments with uniform geology are the microclimate, topography, anthropogenic activities (road construction across wetlands and grazing); hence variability was determined vertically, horizontally and between topographic units named upper, middle and bottom slope.

Within the catchment, burrowing of ice rats and some anthropogenic activities such as grazing were found to have a great influence on soil physical and chemical properties variation more especially on the topsoil where there was high variation on small distances. Soil pH, soil texture, bulk density were relatively vertically and spatially variable with soil pH being the least variable and stable chemical property. Chemical soil properties were variable with Av-P being the most highly variable. Therefore, soil chemical properties were highly variable than soil physical properties. The solubility of Fe under anaerobic conditions resulted into mobility of Fe^{2+} accumulation within the profile due to alternating redox conditions and hence forming insoluble phosphate compounds which shows that it is less available. Therefore, this indicated that the wetlands are releasing lower phosphates content into the water bodies and suggested that the wetlands performance is good.

The classical statistics was used to measure soil properties at single points in space, even though classical statistics assume that measured data are independent, and thus were not sufficient to analyse spatially dependent variables. However, information is required for the entire catchment space, which necessitates methods that interpolate data to estimate the mean value within an area. Cognition of soil spatial variability is fundamental for wetlands management and can help in the sustainable use of soil and wetlands delineation. The

prediction maps produced with geostatistics are a vital monitoring tool, depicting the exact position of the specific soil properties in the wetland.

It is vital to know the spatial dependency and distribution of soil properties as it aids in the natural resource evaluation and environmental management even on unsurveyed areas using known points. Thus, the semivariograms indicated moderate spatial dependence ($25 < \text{DSD} \leq 75\%$) for soil properties such as SOC, Av-P, Av-N, pHw and sand; and the silt and silt/clay exhibited weak spatial dependence ($\text{DSD} > 75$). The moderate spatial dependence of the soil properties may be controlled by extrinsic variations brought about anthropogenic factors such as management practices. Clay exhibited a strong spatial dependence ($\text{DSD} \leq 25\%$). The strong spatial dependence of the properties may be controlled by the intrinsic variations in soil features including texture and mineralogy (Cambardella *et al.*, 1994).

USDA-NRCS (2010) developed more site specific hydric soil indicators for United States. The indicators of USDA-NRCS systems were adapted and used as reference to develop relevant indicators for the wetlands of Lesotho. Nine hydric indicators were identified and described. Identified soil field indicators were **A1**, **A2**, **A3**, **A5**, **A7**, **A10**, **A12**, **A13** and **A14**. Histosols (**A1**) indicators were observed in many profiles with histic epipedon (**A2**). The occurrence of these unique properties within the landscape is therefore used as indicators of wetland conditions and can be used to delineate wetland. The surface diagnostic horizons observed were; histic, mollic, umbric and ochric. Cambic was identified in the sub surface. Soils were classified as Humic Dystrudepts, Typic Cryaqualfs, Histic Cryaquolls, Fibric Haplohemists, Cumilic Cryaquolls and Fluvaquentic Cryofibrists. The most redoximorphic features observed were of concentration than of the depletion and Gleying. Some profiles had the redoximorphic features occurring below 500mm and thus failed to meet the listed field indicators with reference to USDA-NRCS (2010). Hence this calls for further proper characterization of soils of such wetlands.

5.2 Recommendations

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.

Given the common practice of the intensification of land-use conversion, wetland soil management and careful land use planning are needed to take into account the spatial

variability of soil properties, delineating management zones and conservation practices and other efforts to introduce protective measures to control soil erosion. Future research is needed to seek for appropriate approaches with regard to wetlands use management and more especially the grazing system of Lesotho in the highlands agro-ecological zone for rehabilitation.

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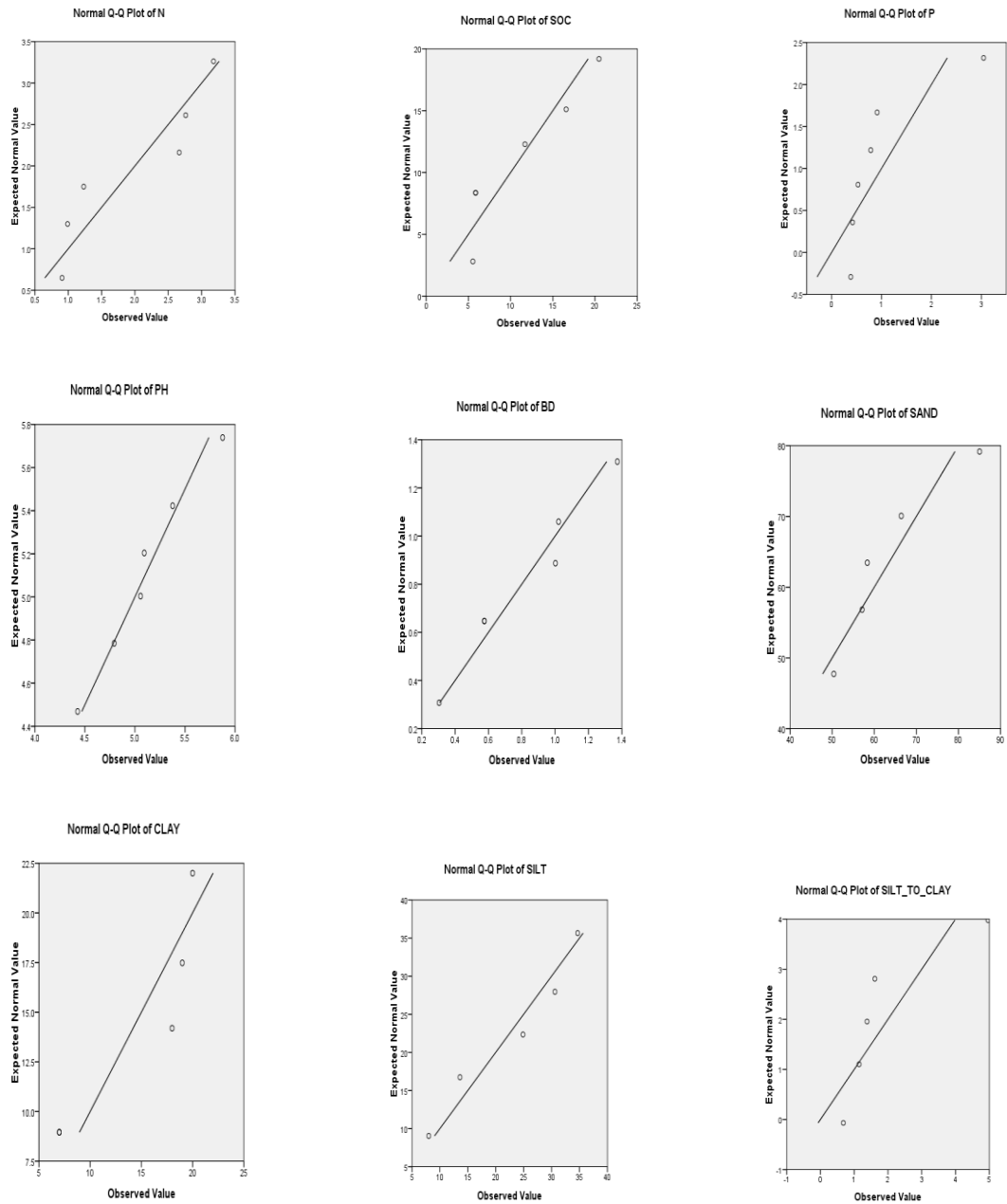
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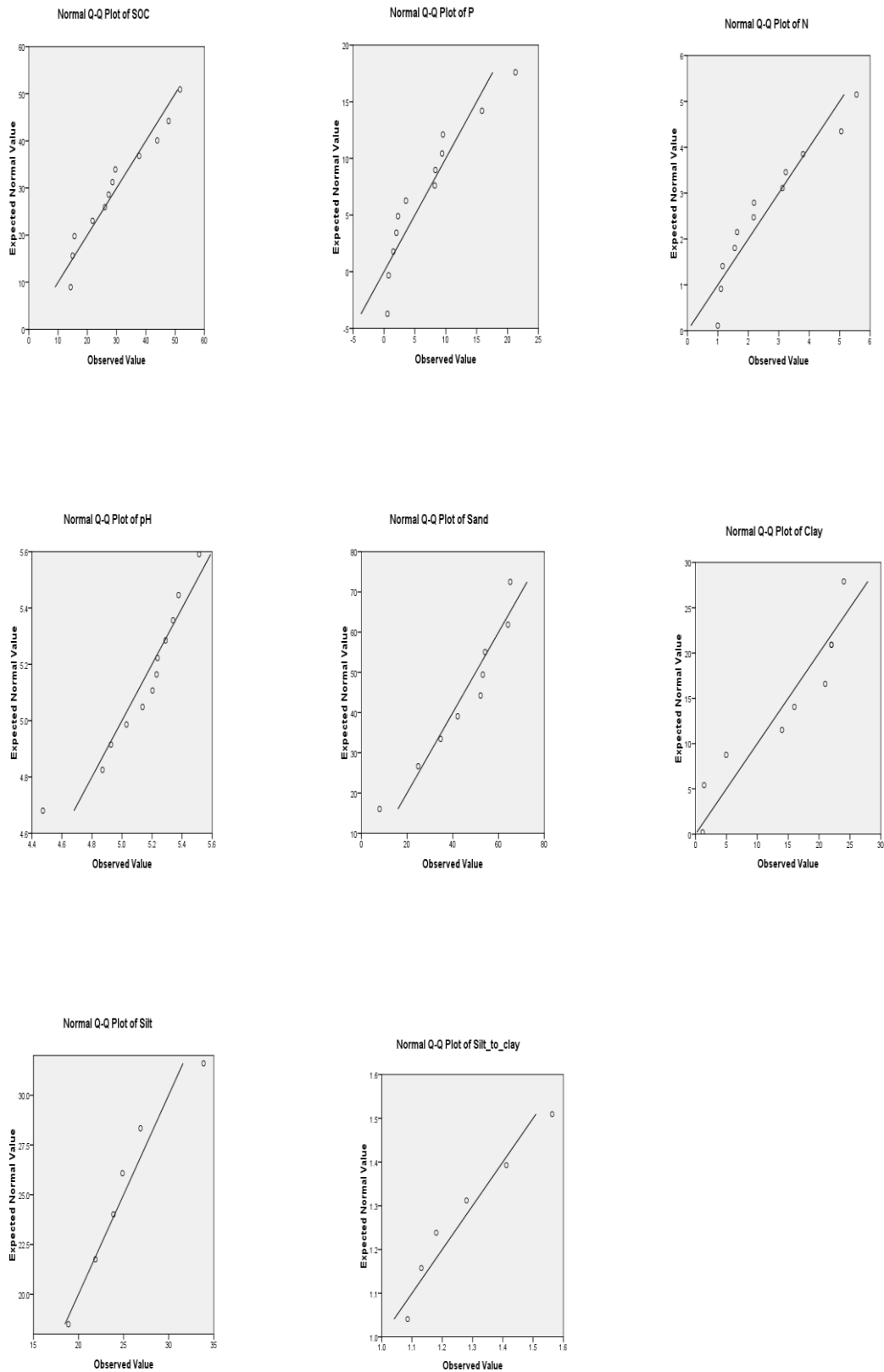
Appendices

Appendix 1 Normal Q-Q plot for selected soil physico-Chemical properties in sub catchment

2



Appendix 2 Normal Q-Q plot for selected soil physico-Chemical properties in Sub catchment 3



Appendix3. Analysis of Variance (ANOVA) for selected soil properties at a depth of 0 to 90 cm

Variable	Source	DF	Sum of Squares	Mean Square	F Value	P>F
SOC	Sub catchment	2	9030.42	4515.21	17.89	<0.001
	Transect	3	7447.44	2482.48	9.83	<0.001
	Depth	5	620.95	124.19	0.49	0.8
Av-P	Sub catchment	2	1298.13	649.07	43.73	<0.001
	Transect	3	230.92	76.97	5.19	0.001
	Depth	5	65.96	13.19	0.89	0.5
Av-N	Sub catchment	2	12.97	6.48	5.05	0.0
	Transect	3	18.22	6.07	4.73	0.0
	Depth	5	20.69	4.14	3.22	0.0
pHw	Sub catchment	2	24.89	12.45	13.46	<0.001
	Transect	3	5.15	1.72	1.86	0.1
	Depth	5	3.34	0.67	0.72	0.6
Sand	Sub catchment	2	2652	1326	18	< 0.001
	Transect	3	3222	1074	14	< 0.001
	Depth	5	444	88	1	0.3
Clay	Sub catchment	2	456	228	14	< 0.001
	Transect	3	724	241	15	< 0.001
	Depth	5	49	10	0.6	0.7
Silt	Sub catchment	2	1234	617	10	< 0.0
	Transect	3	1153	384	6	< 0.0
	Depth	5	401	80	1	0.3
Silt/clay	Sub catchment	2	14	7	10	0.0
	Transect	3	3	1	1	0.2
	Depth	5	2	0.4	0.6	0.7
Na	Sub catchment	2	199	100	16	< 0.001
	Transect	3	101	34	6	< 0.001
	Depth	5	9	2	0.3	0.9
K	Sub catchment	2	194	97	41	< 0.001
	Transect	3	32	11	4	0.00
	Depth	5	11	2	0.9	0.5
Ca	Sub catchment	2	579	289	56	< 0.001
	Transect	3	176	59	11	< 0.001
	Depth	5	31	6	1	0.3

*P <0.05 Significance level

Appendix 4 Statistics of soil properties in the 0–15 cm soil depth of three sub catchments in Khalong-la-Lithunya wetlands

Variables	Sub Catchment 1			Sub Catchment 2			Sub Catchment 3		
	N = 17			N= 6			N = 12		
	Means	CV	SKw	Means	CV	SKw	Means	CV	SKw
SOC %	27.3	65	1.42	11.00	58	0.49	29.93	43	0.38
Av- P (mg kg ⁻¹)	2.99	74	1.06	1.01	101	1.63	6.94	94	0.95
Av-N (mg kg ⁻¹)	2.40	34	0.91	1.96	52	0.06	2.63	59	0.72
Ca (mg kg ⁻¹)	2034.4	26	-0.25	631.4	86	1.6	1104.1	32	-0.26
Mg (mg kg ⁻¹)	294.0	41	0.17	††	††	††	††	††	††
K (mg kg ⁻¹)	479.2	77	1.00	1698.8	42	0.00	1746.0	36	-0.82
Na (mg kg ⁻¹)	715.9	42	0.50	††	††	††	907.9	39	0.09
CEC (cmol kg ⁻¹)	82.4	12	-0.37	††	††	††	††	††	††
pH _w	4.87	5	-0.48	5.10	10	0.25	5.14	5	-1.04
BD (g cm ⁻³)	0.52	42	1.54	0.81	48	0.16	0.79	52	0.65
SAND %	65.0	13	-0.05	61.28	21	1.07	52.76	12	0.80
CLAY %	14.3	25	-0.12	15.00	42	-0.67	19.42	14	-0.32
SILT %	20.4	42	0.78	23.72	45	-0.54	27.82	16	-0.68
SILT / CLAY	1.55	62	2.08	1.90	81	1.58	1.44	15	-0.66

† CV = coefficient of variation; <15 – Least variable, 15 – 35 – Moderately variable, >35 – Most variable (Wilding & Dress, 1978). SK= Skewness: provides an indication of symmetry, and a value of 0 indicates perfectly symmetrical distribution and values between -1 and +1 are considered approximately symmetric (normally distributed) for field data (Ott, 1977).

‡SOC – Soil organic carbon; Av-P – Available Phosphorus; Av-N – Available Nitrogen; pH_w – soil pH in water; Ca – Calcium; Mg – Magnesium; K – Potassium; Na – Sodium; CEC – Cation exchange capacity.

††N is the number of observations

††Missing values, such parameters were not measured in the particular sub-catchment

Appendix5. Summary statistics of selected soil properties at depth of 0 to 90 cm in three sub catchments

	Sub catchment 1				Sub catchment 2				Sub catchment 3			
Depth (cm)	SOC (%)											
	N	Mean	S.D	CV	N	Mean	S.D	CV	N	Mean	S.D	CV
0-15	17	27.30	17.86	65	6	11.00	6.39	58	12	29.93	12.83	43
15-30	17	32.16	14.75	46	7	11.14	7.58	68	12	34.70	17.49	50
30-45	17	35.35	13.52	38	7	18.43	11.37	62	12	28.41	16.16	57
45-60	17	34.34	14.94	44	4	3.01	2.11	70	12	29.14	20.97	72
60-75	15	29.73	14.30	48	††	††	††	††	11	31.50	23.18	74
75-90	8	26.85	18.14	68	††	††	††	††	9	28.21	23.01	82
	91	31.39	15.34	49	25	10.90	6.86	64	68	30.39	18.46	61
Av-P (mg/kg)												
0-15	17	2.99	2.20	73	6	1.01	1.02	101	12	6.94	6.52	94
15-30	17	1.73	1.54	89	7	0.36	0.49	135	12	7.27	7.03	97
30-45	17	1.12	0.90	81	7	0.28	0.30	108	12	6.15	5.95	97
45-60	17	1.16	0.96	82	4	0.19	0.12	64	12	5.30	5.25	99
60-75	15	0.80	0.69	86	††	††	††	††	11	9.49	6.64	70
75-90	8	0.62	0.47	77	††	††	††	††	9	8.65	6.80	79
	91	1.50	1.52	102	25	0.46	0.64	139	68	7.21	6.29	87
Av-N (mg/kg)												
0-15	17	2.40	0.81	34	6	1.96	1.02	52	12	2.63	1.54	59
15-30	17	2.96	1.11	38	7	2.49	0.89	36	12	2.65	1.18	45
30-45	17	3.34	1.03	31	7	2.60	1.03	40	12	3.43	1.36	40
45-60	17	3.59	1.20	33	4	2.53	1.16	46	12	3.46	1.32	38
60-75	15	3.20	1.10	35	††	††	††	††	11	2.76	1.46	53
75-90	8	3.27	1.33	41	††	††	††	††	9	2.84	1.32	46
	91	3.11	1.12	36	25	2.39	0.96	40	68	2.97	1.37	46
pHw												
0-15	15	4.86	0.26	5	6	5.11	0.50	10	12	5.14	0.28	5
15-30	17	4.78	0.44	9	7	5.30	0.62	12	12	5.11	0.36	7
30-45	16	4.88	0.47	10	7	5.25	0.56	11	12	5.26	0.41	8
45-60	17	4.00	1.20	30	4	5.17	0.74	14	12	5.33	0.46	9
60-75	15	4.95	0.44	9	††	††	††	††	11	5.24	0.61	12
75-90	8	4.94	0.22	4	††	††	††	††	9	5.43	0.65	12
	88	4.74	0.51	11	25	5.27	0.60	11	68	5.24	0.46	9
BD (g/cm ³)												
0-15	17	0.52	0.22	43	6	0.90	0.39	43	3	0.62	0.31	50
15-30	16	0.57	0.23	41	5	1.08	0.55	50	4	1.06	0.44	41
30-45	16	0.55	0.27	48	4	1.10	0.23	21	4	0.75	0.35	47
45-60	16	0.60	0.33	55	4	1.06	0.46	43	4	0.82	0.72	88
60-75	13	0.58	0.25	44	††	††	††	††	4	0.60	0.36	60
75-90	7	0.66	0.38	57	††	††	††	††	4	0.90	0.61	68
	85	0.57	0.27	47	20	1.00	0.40	40	23	0.80	0.47	59
Sand (%)												
0-15	14	63.85	8.56	13	6	68.00	12.95	19	6	54.17	7.55	14
15-30	14	71.36	8.81	12	6	61.33	10.27	17	6	63.33	5.24	8
30-45	14	67.58	10.31	15	6	62.67	12.45	20	6	62.00	7.64	12
45-60	14	69.61	8.78	13	††	††	††	††	6	59.50	12.97	22
60-75	12	68.64	11.81	17	††	††	††	††	5	55.80	10.13	18
75-90	6	64.47	11.37	18	††	††	††	††	3	51.33	7.37	14
	74	67.89	9.82	14	18	64.84	11.86	18	32	58.34	9.15	16
Clay (%)												
0-15	14	14.73	3.65	25	6	12.67	6.98	55	6	19.83	3.92	20
15-30	14	14.95	4.17	28	6	15.33	7.61	50	6	16.33	2.34	14
30-45	14	15.64	4.68	30	6	13.33	7.55	57	6	17.83	2.48	14
45-60	14	15.49	4.79	31	††	††	††	††	6	19.50	3.78	19

60-75	12	15.95	5.05	32	††	††	††	††	5	20.00	2.45	12
75-90	6	19.28	4.17	22	††	††	††	††	3	19.00	1.00	5
	74	15.65	4.46	28	19	13.42	7.01	52	32	18.69	3.06	16
Silt (%)												
0-15	14	21.42	8.40	39	6	19.50	8.07	41	6	26.00	4.24	16
15-30	14	13.70	6.41	47	6	23.33	7.17	31	6	20.33	4.55	22
30-45	14	16.78	8.52	51	6	24.00	8.88	37	6	20.17	6.52	32
45-60	14	14.91	8.38	56	††	††	††	††	6	21.00	12.63	60
60-75	12	15.41	9.48	62	††	††	††	††	5	24.20	11.52	48
75-90	6	16.25	9.56	59	††	††	††	††	3	29.67	7.23	24
	74	16.45	8.48	52	18	21.79	7.92	36	32	22.97	8.33	36
Silt/clay												
0-15	14	1.59	1.00	63	6	1.96	1.21	62	6	1.33	0.19	14
15-30	14	0.96	0.47	49	6	1.27	0.72	57	6	1.25	0.32	26
30-45	14	1.16	0.62	53	6	2.36	1.63	69	6	1.13	0.37	32
45-60	14	1.14	0.68	60	††	††	††	††	6	1.12	0.70	63
60-75	12	1.01	0.57	57	††	††	††	††	5	1.26	0.69	55
75-90	6	0.85	0.48	57	††	††	††	††	3	1.56	0.37	24
	74	1.15	0.70	61	18	1.86	1.22	66	32	1.25	0.46	37
Na ⁺ (Meq/100g)												
0-15	17	2.79	3.99	143	2	0.05	0.02	47	12	3.95	1.55	39
15-30	17	1.66	1.35	81	5	0.09	0.11	118	12	3.92	1.38	35
30-45	16	2.42	3.17	131	4	0.06	0.02	26	11	3.75	1.47	39
45-60	16	2.83	3.18	113	2	0.07	0.00	0	11	3.93	1.92	49
60-75	15	2.60	4.16	160	††	††	††	††	10	3.91	1.60	41
75-90	8	2.15	2.34	109	††	††	††	††	8	3.74	1.70	45
	89	2.43	3.17	131	13	0.07	0.06	93	64	3.87	1.54	40
K ⁺ (Meq/100g)												
0-15	17	1.09	1.30	119	4	1.62	1.39	86	12	4.47	1.61	36
15-30	17	0.69	0.74	107	4	1.62	0.73	45	12	3.21	2.02	63
30-45	16	1.08	1.14	105	4	1.93	0.63	33	12	2.72	2.21	81
45-60	15	1.07	1.45	136	††	††	††	††	12	2.78	2.52	90
60-75	15	0.97	1.48	152	††	††	††	††	11	2.98	2.77	93
75-90	8	0.35	0.23	67	††	††	††	††	9	2.91	2.63	90
	88	0.92	1.18	128	12	1.65	0.90	54	68	3.19	2.30	72
Ca ²⁺ (Meq/100g)												
0-15	17	10.17	2.69	26	2	8.50	3.54	42	12	5.52	1.76	32
15-30	17	10.50	3.80	36	4	10.73	1.40	13	12	5.41	2.18	40
30-45	16	9.62	3.18	33	3	8.74	2.02	23	12	4.98	2.22	45
45-60	16	9.54	2.01	21	2	11.66	1.60	14	12	5.00	2.29	46
60-75	15	9.26	2.17	23	††	††	††	††	11	5.07	2.31	46
75-90	8	9.40	2.51	27	††	††	††	††	9	4.66	2.29	49
Average	89	9.80	2.80	29	11	9.95	2.15	22	68	5.13	2.11	41

† CV = coefficient of variation; <15 – Least variable, 15 – 35 – Moderately variable, >35 – Most variable (Wilding & Dress, 1978).

‡SOC – Soil organic carbon; Av-P – Available Phosphorus; Av-N – Available Nitrogen; pH water – soil pH in water; Ca – Calcium; K – Potassium; Na – Sodium; ††N is the number of observations

††Missing values, such parameters were not measured in the particular sub-catchment

Appendix.6. Soil profile description in Khalong-la-Lithunya

SUB-CATCHMENT ONE

SOIL PROFILE

Profile name:	C1T1P1E150 (P_01)	Soil form	Humic Dystrudepts
Latitude + Longitude:	028.84758°S/ 028.78198°E	Surface rockiness:	None
Surface stoniness:	None	Occurrence of flooding:	None
Altitude:	3167 m	Water erosion:	None
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	East	Described by:	Rasekoele M.G
Micro-relief:	None	Date described:	20/10/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	Kaolinised
Horizon	Depth (mm)	Description	
O1	0-90	Dry state: dark yellowish brown 10YR4/4 dry colour; dark brown 10YR 3/3 moist colour; Soil organic carbon content 5%; Texture: sandy loam; weak very fine crumb structure; Consistence: loose, non-sticky, non-plastic; many medium roots; many fine pores; gradual wavy boundary.	
O2	90-190	Dry state: dark yellowish brown 10YR4/4 dry colour; dark brown 10YR 3/3 moist colour; Soil organic carbon content 15%; Texture: sandy loam moderate fine granular structure; Consistence: friable, non-sticky, non-plastic; many medium roots; gradual wavy boundary.	
O3	190-220	Moist state: dark yellowish brown 10YR4/4 dry colour; dark brown 10YR 3/3 moist colour; Soil organic carbon content 15%; Texture: sandy loam; moderate medium granular structure; Consistence: friable, non-sticky, non-plastic; common fine roots; diffuse wavy boundary.	
A	220-650	Wet state: very dark grayish brown 10YR 3/2 dry colour; very dark grayish brown 10YR 3/2 moist colour; Soil organic carbon content 17%; Texture: loam; strong medium granular structure; Consistence: friable, non-sticky, non-plastic; few fine roots; clear smooth boundary.	
A2	>650	Wet state: very dark grayish brown 10YR 3/2 dry colour; very dark grayish brown 10YR 3/2 moist colour; Soil organic carbon content 13%; Texture: sandy loam strong medium granular structure; Consistence: loose firm, slightly sticky, slightly plastic; diffuse wavy boundary.	

Profile name:	C1T1P2E100 (P_02)	Soil form:	Typic Cryaqualfs
Latitude + Longitude:	028.84739°S/ 28.78752°E	Surface rockiness:	None
Surface stoniness:	None	Occurrence of flooding:	None
Altitude:	3167 m	Water erosion:	yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	East	Described by:	Rasekoele M.G
Micro-relief:	None	Date described:	20/10/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-90	Moist state: brown 7.5YR4/4 moist colour; many coarse prominent 10 YR 4/4 dark yellowish brown concentrated mottles; weak very fine crumb structure; Consistence: loose, non-sticky, non-plastic; many coarse roots; many medium pores; clear wavy boundary
A1	90-150	Moist state: black 10YR2/1 moist colour; common fine faint 10 YR 4/4 dark yellowish brown concentrated mottles; weak very fine crumb structure; Consistence: loose, non-sticky, non-plastic; many coarse roots; many medium pores; clear wavy boundary
A2	>150	Moist state: black 10YR2/1 moist colour; common fine faint 10 YR 4/4 dark yellowish brown concentrated mottles; weak very fine crumb structure; Consistence: loose, non-sticky, non-plastic; many coarse roots; many medium pores; gradual wavy boundary

Profile name:	C1T1P3E50 (P_03)	Soil form:	Histic Cryaquolls
Latitude + Longitude:	028.84720°S/028.78707°E	Surface rockiness:	None
Surface stoniness:	None	Occurrence of flooding:	None
Altitude:	3168 m	Water erosion:	yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	East	Described by:	Rasekoele M.G
Micro-relief:	None	Date described:	20/10/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	Kaolinised

Horizon	Depth (mm)	Description
O1	0-120	Moist state: very dark grayish 10YR3/2 moist colour; common fine faint dark yellowish brown concentrated mottles; weak very fine crumb structure; Consistence: loose, non-sticky, non-plastic; many fine roots; many fine pores; clear wavy boundary
O2	120-260	Moist state: black 10YR2/2 moist colour; weak very fine crumb structure; Consistence: loose, non-sticky, non-plastic; many coarse roots; many medium pores; clear wavy boundary
A	>260	Moist state: very dark brown 10YR2/1 moist colour; weak very fine crumb structure; Consistence: loose, non-sticky, non-plastic; many coarse roots; many medium pores; clear wavy boundary

Profile name:	C1T1P4W50 (P_04)	Soil form:	Fibric Haplohemists
Latitude + Longitude:	028.84701°S/ 028.78660°E	Surface rockiness:	None
Surface stoniness:	None	Occurrence of flooding:	None
Altitude:	3164 m	Water erosion:	yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/grazing
Slope Shape:	Concave	Water table:	None
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	None	Date described:	20/10/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-100	Moist state: black 10YR2/1 moist colour; few medium faint yellowish red concentrated mottles; weak very fine crumb structure; Consistence: soft, non-sticky, non-plastic; many medium-coarse roots; many medium-coarse pores; diffuse irregular boundary.
O2	100-150	Moist state: black 10YR2/1 moist colour; many coarse prominent yellowish red concentrated mottles; weak very fine crumb structure; Consistence: soft, non-sticky, non-plastic; many medium roots; many medium pores; diffuse irregular boundary.
O3	150-450	Moist state: black 10YR2/1 moist colour; many medium distinct grey depleted mottles; weak very fine crumb structure; Consistence: slight hard, slightly sticky, slightly plastic; few fine roots; common fine pores; diffuse irregular boundary.
O3	450-600	Moist state: black 10YR2/1 moist colour; common coarse faint grey and yellowish red concentrated mottles; weak very fine crumb structure; Consistence: moderate hard, sticky, plastic; common medium roots; common fine pores; diffuse irregular boundary.
A	600-750	Moist state: black 10YR2/1 moist colour; common coarse faint grey concentrated mottles; weak very fine crumb structure; Consistence: moderate hard, sticky, plastic; common medium roots; common fine pores; diffuse irregular boundary
A2	>750	Moist state: black 10YR2/1 moist colour; common medium faint grey, yellowish red and green depleted mottles; weak very fine crumb structure; Consistence: moderate hard, sticky, plastic; few coarse roots; common fine pores

Profile name:	C1T1P5W100 (P_05)	Soil form:	Typic Cryaqualfs
Latitude + Longitude:	028.84686°S/ 028.78601°E	Surface rockiness:	Yes
Surface stoniness:	Yes	Occurrence of flooding:	none
Altitude:	3165 m	Water erosion:	yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	20/10/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-80	Moist state: strong brown 7.5YR4/6 moist colour; many coarse prominent yellowish red concentrated mottles; weak very fine crumb structure; Consistence: slightly hard, non-sticky, non-plastic; many medium roots; common fine pores; clear smooth boundary
O2	80-900	Moist state: black 10YR2/1 moist colour; few coarse distinct grey depleted mottles; weak very fine crumb structure; Consistence: moderate hard, slightly sticky, slightly plastic; few very fine roots; diffuse irregular boundary

Profile name:	C1T1P6W150 (P_06)	Soil form:	Typic Cryaqualfs
Latitude + Longitude:	028.84671°S/ 028.78550°E	Surface rockiness:	Yes
Surface stoniness:	Yes	Occurrence of flooding:	None
Altitude:	3164 m	Water erosion:	yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	20/10/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-100	Dry state: dark yellowish brown 10YR4/4 dry colour; dark brown 10YR 3/3 moist colour; weak very fine crumb structure; Consistence: loose, non-sticky, non-plastic; many medium roots; many fine pores; gradual wavy boundary.
O2	100-150	Dry state: dark yellowish brown 10YR4/4 dry colour; dark brown 10YR 3/3 moist colour; moderate fine granular structure; Consistence: friable, non-sticky, non-plastic; many medium roots; gradual wavy boundary.
A	>150	Moist state: dark yellowish brown 10YR4/4 dry colour; dark brown 10YR 3/3 moist colour; moderate medium granular structure; Consistence: friable, non-sticky, non-plastic; common fine roots; diffuse wavy boundary.

Profile Name:	C1T2P1E100 (P-07)	Soil form:	Fibric Haplohemist
Latitude + Longitude:	028.84647°S/ 028.78784°E	Surface rockiness:	None
Surface stoniness:	None	Occurrence of flooding:	Noen
Altitude:	3158 m	Water erosion:	Yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld open/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	East	Described by:	Rasekoele M.G
Micro-relief:	None	Date described:	20/10/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-100	Moist state: black 10YR2/1 moist colour; many fine prominent yellowish red concentrated mottles; weak very fine crumb structure; Consistence: soft, sticky, plastic; many medium roots; many medium pores; clear irregular boundary.
O2	100-300	Moist state: black 10YR2/1 moist colour; few fine faint yellowish red concentrated mottles; weak very fine crumb structure; Consistence: slightly hard, sticky, plastic; many medium roots; common medium pores; diffuse irregular boundary.
O3	300-450	Moist state: black 10YR2/1 moist colour; weak very fine crumb structure; Consistence: slight hard, very sticky, very plastic; many coarse roots; few fine pores; diffuse irregular boundary.
A1	450-600	Moist state: black 10YR2/1 moist colour; weak very fine crumb structure; Consistence: slight hard, very sticky, very plastic; many coarse roots; few fine pores; diffuse irregular boundary.
A2	600-750	Moist state: black 10YR2/1 moist colour; weak very fine crumb structure; Consistence: hard, very sticky, very plastic; many coarse roots; few fine pores; diffuse irregular boundary
B	>750	Moist state: black 10YR2/1 moist colour; weak very fine crumb structure; Consistence: hard, very sticky, very plastic; many coarse roots; few fine pores; diffuse irregular boundary

Profile Name:	C1T2P4W100 (P-10)	Soil form:	Histic Cryaquolls
Latitude + Longitude:	028.84580°S/ 028.78602°E	Surface rockiness:	None
Surface stoniness:	None	Occurrence of flooding:	None
Altitude:	3161 m	Water erosion:	yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	23/10/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-100	Moist state: black 10YR2/1 moist colour; many fine distinct yellowish red concentrated mottles; weak very fine crumb structure; Consistence: soft, non-sticky, non-plastic; many medium roots; many medium pores; clear wavy boundary.
O1	100-200	Moist state: black 10YR2/1 moist colour; many fine faint yellowish red concentrated mottles; weak very fine crumb structure; Consistence: soft, non-sticky, non-plastic; many medium roots; many medium pores; abrupt smooth boundary.
O1	200-300	Moist state: black 10YR2/1 moist colour; weak very fine crumb structure; Consistence: slight hard, sticky, plastic; few fine roots; few fine pores; diffuse irregular boundary.
O2	300-450	Moist state: black 10YR2/1 moist colour; weak very fine crumb structure; Consistence: slight hard, sticky, plastic; many coarse roots; few fine pores; diffuse irregular boundary.
O2	450-600	Moist state: black 10YR2/1 moist colour; weak very fine crumb structure; Consistence: slight hard, sticky, plastic; many coarse roots; few fine pores; diffuse irregular boundary.
O3	>600	Moist state: black 10YR2/1 moist colour; weak very fine crumb structure; Consistence: slight hard, sticky, plastic; many coarse roots; few fine pores; diffuse irregular boundary.

Profile Name:	C1T4P1W50 (P-15)	Soil form:	Histic humaquepts
Latitude + Longitude:	028.84149°S/ 028.77651°E	Surface rockiness:	Yes
Surface stoniness:	Yes	Occurrence of flooding:	None
Altitude:	3095 m	Water erosion:	Yes
Terrain Unit:	Bottom slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	23/10/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-70	Moist state: very dark brown 10YR2/2 moist colour; common medium faint yellowish red concentrated mottles; weak very fine crumb structure; Consistence: soft, non-sticky, non-plastic; many fine roots; many fine pores; clear smooth boundary.
O1	70-130	Moist state: very dark brown 10YR2/2 moist colour; common fine faint yellowish red concentrated mottles; Consistence: soft, non-sticky, non-plastic; many medium roots; many medium pores; clear wavy boundary.
O2	130-220	Moist state: very dark brown 10YR2/2 moist colour; few fine faint yellowish red concentrated mottles; Consistence: hard, moderately sticky, moderately plastic; common coarse roots; few fine pores; diffuse irregular boundary.
O3	220-310	Moist state: black 10YR2/1 moist colour; few fine faint yellowish red concentrated mottles; Consistence: hard, sticky, plastic; few coarse roots; few fine pores; diffuse irregular boundary.
O3	310-430	Moist state: black 10YR2/1 moist colour; many medium prominent yellowish red concentrated mottles; Consistence: soft, very sticky, very plastic; few coarse roots; few fine pores; diffuse irregular boundary.
O3	430-510	Moist state: black 10YR2/1 moist colour; few fine faint yellowish red concentrated mottles; Consistence: soft, very sticky, very plastic; few coarse roots; few fine pores; diffuse irregular boundary.
O3	>510	Moist state: black 10YR2/1 moist colour; Consistence: hard, sticky, plastic; few coarse pores; clear irregular boundary.

Profile Name:	C1T4P2W50 (P-16)	Soil form:	Cumulic Cryaquolls
Latitude + Longitude:	028.84174°S/ 028.77389°E	Surface rockiness:	Yes
Surface stoniness:	Yes	Occurrence of flooding:	None
Altitude:	3088 m	Water erosion:	Yes
Terrain Unit:	Bottom slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	23/10/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
A1	0-15	Moist state: very dark grayish brown 10YR3/2 moist colour; many fine distinct yellowish red concentrated mottles; weak very fine granular structure; Consistence: soft, non-sticky, non-plastic; Common fine roots; many medium pores; clear wavy boundary.
A2	150-300	Moist state: very dark brown 10YR2/2 moist colour; weak medium crumb structure; Consistence: soft, non-sticky, non-plastic; few fine roots; many fine pores; clear smooth boundary.
A3	300-450	Moist state: very dark brown 10YR2/2 moist colour; weak coarse crumb structure; Consistence: soft, non-sticky, non-plastic; many coarse pores; clear smooth boundary.
B	450-600	Moist state: black 10YR2/1 moist colour; moderately coarse sub angular structure; Consistence: soft, non-sticky, non-plastic; few coarse pores; diffuse irregular boundary.

Profile Name:	C1T4P3W50 (P-17)	Soil form:	Cumulic Cryaquolls
Latitude + Longitude:	028.84015 °S/ 028.76377°E	Surface rockiness:	Yes
Surface stoniness:	Yes	Occurrence of flooding:	None
Altitude:	3049 m	Water erosion:	None
Terrain Unit:	Bottom slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	23/10/15
Parent Material Solum:	Soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt and sandstone	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
A	0-100	Moist state: very dark brown 10YR2/2 moist colour; few medium faint reddish yellow concentrated 5YR 6/8 mottles; weak very fine crumb structure; Consistence: soft, non-sticky, non-plastic; many medium roots; many medium pores; clear wavy boundary.
A2	100-200	Moist state: very dark brown 10YR2/2 moist colour; few medium distinct reddish yellow concentrated 5YR 6/8 mottles; Consistence: hard, slightly sticky, slightly plastic; many medium roots; many medium pores; clear wavy boundary.
A3	200-300	Moist state: very dark brown 10YR2/2 moist colour; few medium distinct depleted reddish yellow 5YR 6/8 mottles; Consistence: hard, very sticky, very plastic; many medium roots; many medium pores; clear wavy boundary.
AB	300-400	Moist state: black 10YR2/1 moist colour; few medium prominent reddish yellow depleted mottles; Consistence: hard, very sticky, very plastic; few fine roots; many medium pores; clear wavy boundary.
B	400-540	Moist state: black 10YR2/1 moist colour; common coarse prominent reddish yellow concentrated mottles; Consistence: hard, very sticky, very plastic; many medium pores; clear wavy boundary.
B2	>540	Moist state: black 10YR2/1 moist colour; common very coarse prominent depleted dark greenish gray 5G 4/1 mottles; Consistence: hard, very sticky, very plastic many medium pores; clear wavy boundary

SUB-CATCHMENT THREE

Profile Name:	C3T1P1E100 (P-23)	Soil form:	Fibric Haplohemists
Latitude + Longitude:	S 28°53.047 E 028°49.602	Surface rockiness:	Yes
Surface stoniness:	Yes	Occurrence of flooding:	None
Altitude:	3055 m	Water erosion:	Yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	East	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	09/12/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-100	Moist state: black 7.5YR2.5/1 moist colour; few medium prominent yellowish red concentrated mottles; moderate fine angular blocky structure; Consistence: soft, non-sticky, non-plastic; few medium roots; few medium pores; gradual irregular boundary
O1	100-300	Moist state: black 10YR2/1 moist colour; few medium prominent yellowish red concentrated mottles; moderate fine sub angular blocky structure; Consistence: slightly hard, non-sticky, non-plastic; many fine roots; few medium pores; gradual irregular boundary
O2	300-500	Moist state: very dark gray 10YR3/1 moist colour; moderate fine sub angular blocky structure; Consistence: moderate hard, slightly sticky, slightly plastic; clear wavy boundary
O2	500-700	Moist state: very dark gray 10YR3/1 moist colour; moderate fine sub angular blocky structure; Consistence; hard, slightly sticky, slightly plastic; common fine roots; few medium pores clear wavy boundary
O3	>700	Moist state: very dark gray 10YR3/1 moist colour; moderate fine sub angular blocky structure; Consistence; hard, slightly sticky, slightly plastic; clear wavy boundary

Profile Name:	C3T1P2E50 (P-24)	Soil form:	Fibric Haplohemists
Latitude + Longitude:	S 28°53.641 E 028°47.556	Surface rockiness:	None
Surface stoniness:	none	Occurrence of flooding:	None
Altitude:	3055 m	Water erosion:	Yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	East	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	09/12/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-80	Moist state: black 10YR2/1 moist colour; few fine faint yellowish red concentrated mottles; weak very fine sub angular blocky structure; Consistence: soft, non-sticky, non-plastic; common very fine roots; gradual irregular boundary
O1	80-180	Moist state: black 10YR2/1 moist colour; few fine distinct yellowish red concentrated mottles; moderate fine sub angular blocky structure; Consistence: hard, non-sticky, non-plastic; few fine roots; gradual irregular boundary
O2	180-350	Moist state: very dark gray 10YR3/1 moist colour; few fine prominent yellowish red concentrated mottles; moderate fine sub angular blocky structure; Consistence: hard, non-sticky, non-plastic; few fine roots; gradual irregular boundary
O2	350-750	Moist state: dark reddish brown 5YR3/4 moist colour; few very coarse prominent yellowish red concentrated mottles; weak fine sub angular blocky structure; Consistence: hard, slightly sticky, slightly plastic; gradual irregular boundary
O3	>750	Moist state: dark reddish brown 5YR3/4 moist colour; few very coarse prominent yellowish red depleted mottles; weak fine sub angular blocky structure; Consistence: very hard slightly sticky, slightly plastic; gradual irregular boundary

Profile Name:	C3T1P3W50 (P-25)	Soil form:	Fibric Haplohemists
Latitude + Longitude:	S 28°53.823 E 028°47.523	Surface rockiness:	none
Surface stoniness:	none	Occurrence of flooding:	Yes
Altitude:	3172 m	Water erosion:	Yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	600 mm
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	09/12/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-130	Moist state: black N 3/ moist colour; few fine faint concentrated olive mottles; weak very fine sub angular blocky structure; Consistence: soft, non-sticky, non-plastic; common fine roots; clear wavy boundary
O1	130-400	Moist state: black N 3/ moist colour; few fine faint depleted olive mottles; weak fine sub angular blocky structure; Consistence: hard, non-sticky, non-plastic; few fine roots; clear wavy boundary
O2	400-600	Moist state: greenish black 10Y 2,5/1 moist colour; weak fine sub angular blocky structure; Consistence: hard, non-sticky, non-plastic; clear wavy boundary
O3	>600	Moist state: black N 3/ moist colour; weak fine sub angular blocky structure; Consistence: hard, non-sticky, non-plastic; gradual irregular boundary

Profile Name:	C3T1P4W100 (P-26)	Soil form:	Fluvaquentic Cryofibrists
Latitude + Longitude:	S 28°53.813 E 028°47.415	Surface rockiness:	Yes
Surface stoniness:	Yes	Occurrence of flooding:	Yes
Altitude:	3173 m	Water erosion:	Yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	09/12/15
Parent Material Solum:	Origin single, soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-90	Moist state: very dark gray N 3/ moist colour; few fine faint yellowish red concentrated mottles; weak very fine angular blocky structure; Consistence: loose, non-sticky, non-plastic; few very fine roots; clear smooth boundary.
A1	90-170	Moist state: dark greenish gray 10Y 3/1 moist colour; few fine faint yellowish red concentrated mottles; weak very fine angular blocky structure; Consistence: loose, non-sticky, non-plastic; many coarse roots; clear smooth boundary.
A2	170-320	Moist state: black 7.5YR2.5/1 moist colour; few fine faint concentrated yellowish red mottles; weak fine angular blocky structure; Consistence: soft, non-sticky, non-plastic; few very fine roots; clear smooth boundary.
A3	320-520	Moist state: very dark gray 7.5YR3/1 moist colour; few fine distinct concentrated yellowish red mottles; weak fine angular blocky structure; Consistence: soft, non-sticky, non-plastic; few very fine roots; gradual wavy boundary.
B	520-700	Moist state: very dark gray 7.5YR3/1 moist colour; few fine distinct depleted yellowish red mottles; weak fine granular blocky structure; Consistence: slightly hard, non-sticky, non-plastic; few very fine roots; gradual wavy boundary.
B	>700	Moist state: black 2.5Y2.5/1 moist colour; few fine faint depleted yellowish red mottles; weak fine granular blocky structure; slightly hard, non-sticky, non-plastic; few very fine roots; gradual wavy boundary.

Profile Name:	C3T2P1E100 (P-27)	Soil form:	Fibric Haplohemists
Latitude + Longitude:	S 28°53.812 E 028°47.617	Surface rockiness:	Yes
Surface stoniness:	Yes	Occurrence of flooding:	Yes
Altitude:	3060 m	Water erosion:	Yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	East	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	09/12/15
Parent Material Solum:	soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Sand stone and basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-120	Moist state: black 10 YR 2/1 moist colour; weak very fine sub angular blocky structure; Consistence: soft, non-sticky, non-plastic; many very fine roots; few medium pores; gradual smooth boundary.
O1	120-300	Moist state: black 10 YR 2/1 moist colour; weak fine sub angular blocky structure; Consistence: slightly hard, non-sticky, non-plastic; few very fine roots; few medium pores; gradual smooth boundary.
O2	300-400	Moist state: very dark brown 10 YR 2/2 moist colour; weak medium sub angular blocky structure; Consistence: slightly hard, slightly sticky, slightly plastic; gradual smooth boundary.
O3	>400	Moist state: dark yellowish brown 10 YR 3/4 moist colour; few medium distinct concentrated yellowish red mottles; weak medium sub angular blocky structure; Consistence: moderately hard, slightly sticky, slightly plastic; gradual smooth boundary.

Profile Name: C3T2P2E50 (P-28)
Latitude + Longitude: S 28°53.797 E 028°47.586
Surface stoniness: Yes
Altitude: 3060 m
Terrain Unit: Bottom slope
Slope Shape: Concave
Aspect: East
Micro-relief: none
Parent Material Solum: soil rock
Underlying Material: Sand stone and basalt

Soil form: Fibric Haplohemists
Surface rockiness: None
Occurrence of flooding: Yes
Water erosion: yes
Vegetation/Land use: Grassveld/grazing
Water table: None
Described by: Rasekoele M.G
Date described: 09/12/15
Alteration of underlying material: Kaolinised

Horizon	Depth (mm)	Description
O1	0-50	Moist state: very dark grayish brown 10YR3/2 moist colour; weak very fine sub angular blocky structure; Consistence: soft, non-sticky, non-plastic; few medium roots; few medium pores; clear smooth boundary.
O1	50-100	Moist state: very dark grayish brown 10YR3/2 moist colour; weak very fine sub angular blocky structure; Consistence: soft, non-sticky, non-plastic; few medium roots; few medium pores; clear smooth boundary.
O1	100-170	Moist state: very dark grayish brown 10YR3/2 moist colour; few medium distinct concentrated yellowish red mottles; weak fine sub angular blocky structure; Consistence: soft, non-sticky, non-plastic; few medium roots; few medium pores; clear smooth boundary.
O2	170-300	Moist state: black 10YR2/1 moist colour; few medium distinct depleted yellowish red mottles; weak fine sub angular blocky structure; Consistence: slightly hard, non-sticky, non-plastic; few medium roots; few medium pores; diffuse irregular boundary.
O2	300-490	Moist state: black 10YR2/1 moist colour; few medium distinct concentrated yellowish red mottles; weak medium sub angular blocky structure; Consistence: moderately hard, slightly sticky, slightly plastic; diffuse irregular boundary.
O3	490-650	Moist state: dark brown 10YR3/3 moist colour; few medium distinct depleted yellowish red mottles; weak medium sub angular blocky structure; Consistence: hard, slightly sticky, slightly plastic; diffuse irregular boundary.
O3	>650	Moist state: very dark gray 10YR3/1 moist colour; few medium distinct concentrated yellowish red mottles; weak medium sub angular blocky structure; Consistence: hard, slightly sticky, slightly plastic; diffuse irregular boundary.

Profile Name:	C3T2P3W50 (P-29)	Soil form:	Fibric Haplohemists
Latitude + Longitude:	S 28°53.779 E 028°47.554	Surface rockiness:	None
Surface stoniness:	None	Occurrence of flooding:	Yes
Altitude:	3060 m	Water erosion:	Yes
Terrain Unit:	Bottom slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	340 mm
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	09/12/15
Parent Material Solum:	soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Sand stone and basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-150	Moist state: very dark gray 10YR3/1 moist colour; few medium prominent yellowish red concentrated mottles; weak very fine sub angular blocky structure; Consistence: loose, non-sticky, non-plastic; common fine roots; few medium pores; gradual smooth boundary.
O1	150-340	Moist state: very dark gray 10YR3/1 moist colour; weak fine sub angular blocky structure; Consistence: soft, non-sticky, non-plastic; few medium roots; few fine pores; gradual irregular boundary.
O2	>340	Moist state: black N 2.5/ moist colour; weak fine sub angular blocky structure; Consistence: slightly hard, non-sticky, non-plastic; few fine roots; few medium pores; clear irregular boundary.

Profile Name:	C3T2P4W100 (P-30)	Soil form:	Fibric Haplohemists
Latitude + Longitude:	S 28°53.765 E 028°47.528	Surface rockiness:	None
Surface stoniness:	None	Occurrence of flooding:	Yes
Altitude:	3167 m	Water erosion:	Yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	600 mm
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	09/12/15
Parent Material Solum:	soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Sand stone and basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-80	Moist state: very dark gray 10YR3/1 moist colour; few fine distinct concentrated yellowish red mottles; weak very fine sub angular blocky structure; Consistence: loose, non-sticky, non-plastic; common fine roots; few medium pores; clear smooth boundary.
O2	80-350	Moist state: very dark gray 10YR3/1 moist colour; few fine faint depleted yellowish red mottles; weak fine sub angular blocky structure; Consistence: moderately hard, non-sticky, non-plastic; few fine roots; few medium pores; abrupt wavy boundary.
O3	>350	Moist state: very dark gray 10YR3/1 moist colour; weak fine sub angular blocky structure; Consistence: moderately hard, non-sticky, non-plastic; few fine roots; few medium pores; diffuse irregular boundary.

Profile Name:	C3T3P1E100 (P-31)	Soil form:	Fibric Haplohemists
Latitude + Longitude:	S 28°53.647 E 028°47.602	Surface rockiness:	None
Surface stoniness:	None	Occurrence of flooding:	Yes
Altitude:	3055 m	Water erosion:	none
Terrain Unit:	Bottom slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	East	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	15/01/16
Parent Material Solum:	soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Sand stone and basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-130	Moist state: black 7.5YR2.5/1 moist colour; weak very fine sub angular blocky structure; Consistence: loose, non-sticky, non-plastic; common very fine roots; few medium pores; gradual wavy boundary.
O1	130-370	Moist state: black 5YR2.5/1 moist colour; weak very fine granular structure; Consistence: soft, non-sticky, non-plastic; common very fine roots; few medium pores; gradual wavy boundary.
O2	370-450	Moist state: very dark gray 5YR3/1 moist colour; moderately fine granular structure; Consistence: soft, non-sticky, non-plastic; gradual wavy boundary.
O2	450-600	Moist state: dark reddish brown 5YR2.5/2 moist colour; moderately fine sub angular blocky structure; Consistence: slightly hard, non-sticky, non-plastic; gradual wavy boundary.
O3	>600	Moist state: dark reddish brown 5YR3/2 moist colour; moderately fine sub angular blocky structure; Consistence: slightly hard, non-sticky, non-plastic; gradual wavy boundary.

Profile Name:	C3T3P2E50 (P-32)	Soil form:	Fibric Haplohemists
Latitude + Longitude:	S 28°53.641 E 028°47.556	Surface rockiness:	None
Surface stoniness:	None	Occurrence of flooding:	Seasonal
Altitude:	3147 m	Water erosion:	Yes
Terrain Unit:	Bottom slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	
Aspect:	East	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	15/01/16
Parent Material Solum:	soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Sand stone and basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-150	Moist state: black 10YR2/1 moist colour; common fine distinct concentrated yellowish red 5YR 5/8 mottles; weak very fine sub angular blocky structure; Consistence: loose, non-sticky, non-plastic; common very fine roots; many fine pores; clear smooth boundary.
O1	150-280	Moist state: black 7.5YR2.5/1 moist colour; few fine faint concentrated yellowish red 5YR 5/8; weak fine sub angular blocky structure; Consistence: soft, slightly sticky, slightly plastic; common very fine roots; common fine pores; clear smooth boundary.
O2	280-450	Moist state: black N 2.5/ moist colour; weak fine sub angular blocky structure; Consistence: soft, moderately sticky moderately plastic; common very fine roots; common fine pores; gradual wavy boundary.
O2	450-600	Moist state: very dark gray N 3/ moist colour; weak fine sub angular blocky structure; Consistence: soft, moderately sticky moderately plastic; common very fine pores; gradual wavy boundary.
O3	>600	Moist state: dark greenish gray 10Y3/1 moist colour; common coarse prominent concentrated greenish black 5G 2.5/1 weak fine sub angular blocky structure; Consistence: soft, slightly sticky, slightly plastic; common very fine pores; gradual wavy boundary.

Profile Name:	C3T3P3W50 (P-33)	Soil form:	Fibric Haplohemists
Latitude + Longitude:	S 28°53.639 E 028°47.525	Surface rockiness:	None
Surface stoniness:	None	Occurrence of flooding:	Yes
Altitude:	3162	Water erosion:	Yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	15/01/16
Parent Material Solum:	soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Sand stone and basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O1	0-120	Moist state: black 5YR2.5/1 moist colour; weak very fine sub angular blocky structure; Consistence: loose, non-sticky, non-plastic; common fine roots; many fine pores; abrupt smooth boundary.
O1	120-200	Moist state: black 5YR2.5/1 moist colour; weak very fine sub angular blocky structure; Consistence: loose, slightly sticky, slightly plastic; common fine roots; many fine pores; abrupt smooth boundary.
O2	200-350	Moist state: very dark brown 7.5YR2.5/2 moist colour; common medium distinct concentrated bluish gray 5PB 6/1 mottles; moderately fine sub angular blocky structure; Consistence: slightly hard, moderately sticky, moderately plastic; clear wavy boundary.
O2	350-600	Moist state: very dark brown 7.5YR2.5/3 moist colour; common medium distinct depleted light bluish gray 10B 7/1 mottles; moderately fine sub angular blocky structure; Consistence: slightly hard, moderately sticky, moderately plastic; clear wavy boundary.
O3	>600	Moist state: dark brown 7.5YR3/3 moist colour; common medium distinct depleted light bluish gray 10B 7/1 mottles; moderately fine sub angular blocky structure; Consistence: slightly hard, moderately sticky, moderately plastic; clear wavy boundary.

Profile Name:	C3T3P4W100 (P-34)	Soil form:	Histic humaquepts
Latitude + Longitude:	S 28°53.632 E 028°47.495	Surface rockiness:	Yes
Surface stoniness:	Yes	Occurrence of flooding:	None
Altitude:	3165 m	Water erosion:	Yes
Terrain Unit:	Foot slope	Vegetation/Land use:	Grassveld/ grazing
Slope Shape:	Concave	Water table:	None
Aspect:	West	Described by:	Rasekoele M.G
Micro-relief:	none	Date described:	15/01/16
Parent Material Solum:	soil rock	Weathering of underlying material:	Advanced physical, strong chemical
Underlying Material:	Sand stone and basalt	Alteration of underlying material:	kaolinised

Horizon	Depth (mm)	Description
O	0-170	Moist state: black10YR2/1 moist colour; weak very fine sub angular blocky structure; Consistence: loose, non-sticky, non-plastic; many very fine roots; many fine pores; diffuse irregular boundary.
O2	170-520	Moist state: very dark brown10YR2/2 moist colour; weak very fine sub angular blocky structure; Consistence: soft, non-sticky, non-plastic; common very fine roots; many fine pores; diffuse irregular boundary.
O3	520-750	Moist state: dark yellowish brown10YR3/4 moist colour; moderately fine granular structure; Consistence: slightly hard, non-sticky, non-plastic; diffuse irregular boundary.