INFLUENCE OF REGIONAL ENVIRONMENTAL FACTORS ON THE DISTRIBUTION, CHARACTERISTICS AND FUNCTIONING OF HYDROGEOMORPHIC WETLAND TYPES ON THE MAPUTALAND COASTAL PLAIN, KWAZULU-NATAL, SOUTH AFRICA

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

INTRODUCTION

Wetlands are globally recognised as one of the support systems of humankind, providing a wide range of goods and services. Wetlands are threatened by population expansion and the increasing need for natural resources, especially where impoverished communities encroach on the resources for their daily survival. The Maputaland Coastal Plain (MCP) located in the Umkhanyakude District, north-eastern KwaZulu-Natal province in South Africa is such an area. Not only does the MCP host a large portion of South Africa’s wetlands but it is also known for the high incidence of poverty and disease.

The MCP stretches from the town of Mtunzini in the south to Kosi Bay in the north (at the South African border with Mozambique) and continues north towards the town of Cabo Santa Maria. Not only are the wetlands on the MCP important for the maintenance of the rich biodiversity of the area, but they are equally important for the local communities as a key resource in subsistence agriculture. The Tonga people that live in the area depend on the wetlands as a natural resource for water, vegetation for building and making crafts, for fishing and for cultivating crops on the organic soils in the wetlands. Traditional ways to access the water resource are extraction from wells, lakes, streams and springs. However, environmental concerns such as agriculture, forestry and water supply schemes within the catchments, in addition to prolonged periods of drought, have led to reduced availability of groundwater. Therefore, the wetlands of the area have become vulnerable ecosystems and consequently there is a need to determine spatial and temporal changes in the distribution and function of these wetlands and understand the controlling processes.

AIM AND OBJECTIVES

The aim of Water Research Commission project K5/1923 is to understand the regional environmental factors that control the distribution, characteristics and function of different wetland types on the Maputaland Coastal Plain in north-eastern KwaZulu-Natal, including interactions with the underlying Maputaland Coastal Aquifer.

The primary focus of the study was based on the three main themes of mapping, classifying and characterising the different wetland types and the main objectives were:

1. To map the distribution of wetlands in wet and dry years and to map land-use changes in recent decades;
2. To classify wetlands using the hydrogeomorphic classification;
3. To characterise the relationships between rainfall, topography and water table depth;
4. To define the relationship between soil organic carbon and hydroperiod in the different wetness zones.

REPORT LAYOUT

Chapter 1: Introduction
Provides the background, problem statement and research approach.

Chapter 2: Description of the study area
The study area is described and includes a literature review on the landscape, abiotic and biotic characteristic of the area as well as a discussion on wetland classification and land-cover mapping.

Chapter 3: Land-cover mapping
Deals with land-cover mapping, permanent and temporary wetlands and open water. Classification was classified based on vegetation and open water spectral signatures in wet and dry years by using Landsat TM and ETM imagery and ancillary data. The reason for this approach was to create a wetness map using wet and dry years to show the location of temporary and permanent wetland and open water areas. For the purposes of this study, only general wetland areas (e.g. swamp forest and sedge/moist grassland wetlands (including reeds)) were mapped spatially with the use of time series Landsat TM and ETM imagery.

Chapter 4: Hydrogeomorphic classification
The classification of wetland types is based on the Classification System for Wetlands and other Aquatic Ecosystems in South Africa. This hydrogeomorphic classification approach was evaluated in terms of the relationship between hydrogeomorphic wetland units and environmental factors and considers how well the hydrogeomorphic classification could be applied on the MCP. The following questions are tested: 1) whether wetlands are dependent on landscape setting and 2) whether wetlands belonging to the same hydrogeomorphic unit share common properties and function the same.

Chapter 5: Soil organic carbon and hydroperiod
Characteristics of wetland types are investigated. A geomorphic classification approach was used in combination with one specifically developed for the study area, based on biophysical characteristics and functional attributes (landscape setting, water table, vegetation and soil). The wetland definition of the National Water Act of 1998 is used as a point of reference. A conceptual model on how wetlands work in order to illustrate how landscape and aquifer properties affect the potential extent and distribution of wetlands is used.

Chapter 6: Characterising landscape processes
The purpose of this chapter is to consider the role of landscape processes in the character of the Maputaland Coastal Plain wetlands thereby linking the findings of previous chapters on the extent and distribution of wetlands and the hydrogeomorphic wetland types with regional environmental factors and processes that control the different wetland systems.

Chapter 7, 8, 9: These chapters respectively deal with the conclusion, references and the capacity building and technology transfer of the project.

FINDINGS AND CONCLUSION

This study increased knowledge of the different wetland types and gave valuable insights into holistic environmental processes, thus aiding in the development of practical solutions for managing the effects of climate variability, land-use planning and development and implementation of informed rehabilitation strategies. The recognition of the environmental problems associated with the mismanagement of wetlands should lead to improved management by all stakeholders with the aim to re-establish natural wetland functioning and to re-initiate peat-forming processes.

The capability of using Landsat remote sensing imagery with ancillary datasets to establish wetland extent and permanence was demonstrated, as well as land-use activities (plantations, cultivation and urban classes) and change, bearing in mind the spatial limitations of Landsat (e.g. wetlands and croplands <1 ha and cultivated fields in swamp forests will be difficult to map). The ambiguity between classes: cultivation and grassland; temporal wetland and grassland; and bare soil and cultivation were highlighted. These classes are closely related they could not be classified without the support from ancillary datasets such as vegetation maps.

An important outcome of this part of the study showed that wetland loss is a significant problem for the local communities of the Maputaland Coastal Plain that depend on these wetlands as a natural resource and illustrates the need for improved management by all stakeholders. The permanent and temporary wetland map and land-use impact assessment on wetlands can be used to emphasise wetland functions (eco-services) and vulnerability. It can guide land-use practices that have a direct and indirect effect on them.

A wetland classification for the MCP with its extreme precipitation events and wet and dry seasons remains a challenge. The hydrogeomorphic classification brings into prominence the important underlying features of all wetlands, i.e. land (geomorphology) and water (hydrology). The hydrogeomorphic classification was applied in the northeastern part of the study area based on wetland position in the landscape. Local environmental determinants (water table, rainfall and elevation) were examined to show the link between these and the distribution of hydrogeomorphic units. The results in the relationship between rainfall, elevation and depth to water table show an increase in the variety of hydrogeomorphic wetland units in wetter lowland areas compared to drier upland areas. In this study area it was found that wetland occurrence is not dependent on rainfall or elevation but rather depth to water table based on localised topographical features supporting hydrological processes.

An accuracy assessment and comparison was done as part of this study. The semi-automated approach of this to map hydrogeomorphic unit on the MCP was 81% accurate, while the NFEPA wetland ecosystem type was 40% accurate compared to groundtruthed sites. Both classifications stressed that incomplete and inaccurate input layers (e.g. wetlands layer and river layer) and limited groundtruthed points with substantiated groundwater monitoring data are the major limitation in an automatic approach for hydrogeomorphic wetland classification.

The risk in using the hydrogeomorphic unit map (level 4) created in the study is that the classification is based on the fundamental factors landscape setting and permanence of water but not on aspects such as: 1) the origin of the landscape setting (e.g. interdunal or fluvial-like floodplains); 2) the importance of the landscape setting (recharge or discharge area); 3) the description of the water source (e.g. water table rise, ponding of rainwater, seepage of groundwater discharge or runoff or through-flow/interflow); or 4) if the wetland is permanent, seasonally or intermittently inundated. All this additional detailed information can only be added to the hierarchical manner in which the hydrogeomorphic classification is applied, when and if the information becomes available. Using the broad hydrogeomorphic classification with limited criterion for future land-use planning and assessments is problematic in that it permits a direct judgement of a single wetland's value.

This study highlights that the hydrological data of a wetland (i.e. to show interaction with the regional water table, either recharge or discharge function) are much needed for biodiversity management or sustainable aquifer development. However, this study gives a better understanding of the wetland types found on the MCP and how well the hydrogeomorphic classification could be applied. The methods and findings contribute to further refining of the wetland classification work in South Africa and can be applied on similar sandy coastal plains.

The delineation of wetland wetness zones as defined by the period of inundation (hydroperiod) is of importance in wetland management. Results in this study found that soil organic carbon (SOC) is a good indicator of hydroperiod and can be used to delineate and classify permanent, seasonal and temporal wetlands on sandy coastal aquifers. The vegetation indicators in combination with the SOC content provide the best options to define different wetland systems and individual wetness zones.

It was previously suggested that the wetland distribution on the Maputaland Coastal Plain follows an east-west pattern and mirrors the rainfall pattern to a large extent. However, this research confirms that the patterns and wetland form and function are predominately shaped by the hydrogeomorphic setting and not the rainfall distribution, although some wetland types such as peatlands do occur in areas where the rainfall exceeds 600 mm/year and at elevations between sea level and 50 m above mean sea level. Groundwater is an important driver in wetland distribution on the MCP and it was therefore assumed that its wetlands are aquifer dependent, but the results indicate that some wetlands are perched systems and not dependent on the aquifer. Groundwater is the principal source of water for rivers, lakes and permanent wetlands. Furthermore, the temporary upland depressions are also unlikely to be derived from an external groundwater source, although locally perched conditions or deeper low permeability sediments (e.g. Kosi Bay Formation) can retain groundwater in a way that sustains wetland processes. Wetlands formed by groundwater discharge rely more heavily on shallow aquifer contributions.

Recommendations

- Significant investment is needed to fund research in this area, particularly given the scarcity of wetland ecosystem management response data.
- Appropriate groundwater monitoring programmes, e.g. the South African Environmental Observation Network (SAEON), need to be implemented on the entire MCP.
- Socio-economic aspects impacting on wetlands and water security (which were not part of this study) should be studied and alternative land-use practices investigated.
- Future research focus areas:
    - Improvements to the remote sensing method used in this study can be applied to similar coastal areas, such as the MCP in Mozambique, supporting future research (e.g. Landsat imagery with supporting ancillary data such as maps for wetland vegetation, cultivation and urban classes from high resolution spectral and spatial resolution imagery).
    - A ground and surface monitoring network should be installed in the different wetland zones on the northern transect to monitor wetland ecosystem responses to land management change.

This study clearly demonstrates that landscape processes contribute to the dynamic nature and character of wetlands on the Maputaland Coastal Plain and control the extent and distribution of wetlands as well as the different types. In investigating the regional environmental factors that control the distribution, characteristics and function of different wetland types the main objectives of the projects were achieved: The distribution of wetlands in wet and dry years was defined and mapped as well as land-use changes in recent decades and the impact on wetlands; soil organic carbon as a method to measure hydroperiod in the different wetness zones was determined; and wetlands were classified using different hydrogeomorphic approaches. Finally the relationships between landscape processes and wetland type, distribution and extent were established.

PHOTOS: Althea Grundling

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GLOSSARY

Abiotic: the non-living (*bios* = Greek word for life). This includes rock, soil, water and climate conditions (Colvin *et al*., 2007).
Aeolian: Aeolian deposits are made of wind-blown material (driven or caused by the movement of wind) (Colvin *et al.*, 2007).
Aerobic: having molecular oxygen (O_2) present (Kotze, 2000).
Anaerobic: not having molecular oxygen (O_2) present (Kotze, 2000).
Aquifer: a permeable deposit which yields useful quantities of water when tapped by a well. A geological formation that has permeable substance, i.e. structures or textures that hold water or permit appreciable water movement through the substance (National Water Act, 1998).
Aquitarde/aquiclude: a geological formation that is poorly permeable. It is capable of slowly absorbing water from and releasing it to an aquifer, but is not an aquifer because groundwater flow is hindered (groundwater transmissivity is not rapid enough) (Colvin *et a*l., 2007).
Baseflow: baseflow is made up of several components, such as groundwater discharge, bank storage and lateral unsaturated flow. Typically, baseflow is not subject to wide fluctuation and is indicative of aquifer characteristics within the basin (Kelbe and Germishuyse, 2010).
Biotic: pertaining to all living organisms (*bios* = Greek word for life).
Bog: a peatland that is influenced solely by water falling directly onto it, e.g. precipitation (Ewart-Smith *et al*., 2006; Grundling, 2007).
Champagne soil form: contains organic carbon of 10% at 0-200 mm and is for long periods saturated with water (Soil Classification Working Group, 1991).
Channel: a linear landform that, when inundated, usually carries flowing water (Ewart-Smith *et al*., 2006).
Classification: land-use/land-cover classification or mapping is based on statistical pattern recognition techniques applied to multispectral remote sensing data (Jensen, 2005). In this report the word *classification* is used to describe the different classification systems to group wetland types whilst the word *mapping* is used to describe remote sensing classification.
Confined Aquifer: groundwater is confined between impermeable (confining) layers, so the aquifer is under pressure (Kelbe and Germishuyse, 2010).
Depression: a basin-shaped area increasing in depth from the perimeter to a central area of greatest depth (Ewart-Smith *et al*., 2006).
Discharge: refers to groundwater that moves upwards across the water table and discharges directly to the surface or unsaturated zone.
Drainage: the source and movement of water entering or passing through a wetland (Ewart-Smith *et al*., 2006).
Effective recharge: the total recharge minus losses that occur subsequent to infiltration to the groundwater.
Estuarine system: a partially enclosed ecosystem, permanently or periodically connected to the ocean and influenced by tidal fluctuations. The ocean water is at least occasionally diluted by freshwater derived from sub-surface or surface drainage.

Fens: peat-forming systems influenced by water derived from outside their immediate limits. Wetlands that commonly receive groundwater discharge (Winter, 1999).

Floodplains: these can be defined as valley-bottom areas with a well-defined meandering river system characterised by alluvial transport and deposition of sediment (Ewart-Smith *et al*., 2006).

Forested wetlands: wetlands dominated by woody vegetation >6 m in height (Ewart-Smith *et al*., 2006). This includes swamp forests.

Geohydrology: Vegter (2001) define geohydrology (also hydrogeology) as the field dealing with subsurface water (i.e. water in both the saturated and unsaturated zones).

Geomorphic setting: refers to the topographic location of the wetland and its consequent water sources: precipitation, surface flow and groundwater (Brinson, 1993). Relates to landscape shape or surface configuration/structure (Ewart-Smith *et al*., 2006).

Groundwater: water in the saturated zone that flows into boreholes/wells or debouches as springs (Vegter, 2001).

Hydraulic conductivity: the rate of water flowing through a unit (cross-section of soil or rock) under a hydraulic gradient (Vegter, 2001).

Hydrodynamics: refers to the direction of flow and strength of water movement within the wetland (Brinson, 1993).

Hydrogeomorphic: relates to a classification system, one based on the shape of the land (landform setting) and the patterns of surface and sub-surface water flow (Ewart-Smith *et al*., 2006).

Hydroperiod: degree, duration, frequency and seasonality of inundation (Ewart-Smith *et al*., 2006).

Inland wetland system: an ecosystem that is permanently or periodically inundated or saturated and has no existing connection to the ocean, and is therefore characterised by the complete absence of marine exchange and/or tidal influence (Ewart-Smith *et al*., 2006).

Isolated subsystem: an inland system that is hydrologically isolated in terms of surface flows (Ewart-Smith *et al*., 2006).

Lacustrine wetlands: these are associated with lakes (permanently inundated, usually large wetlands with water zones too deep to support rooted plants).

Lake: a permanently inundated, usually large wetland with a deepwater zone too deep to support rooted plants (Ewart-Smith *et al*., 2006).

Landform: the “container” of a wetland, which delimits its shape, size and depth (Ewart-Smith *et al*., 2006).

Littoral: covered by water no more than 2 m deep (Ewart-Smith *et al*., 2006).

Major aquifer region: a high yielding aquifer system of good water quality, while a sole source aquifer can be defined as an aquifer used to supply 50% or more of the urban domestic water for a given area and for which there is no reasonably available alternative source of water (Parsons and Conrad, 1998).

Marsh: a general term used to describe low-growing wetland vegetation (Ewart-Smith *et al*., 2006).

Mire: a term used to indicate living peatlands that actively accumulate peat (IPS/IMCG, 2010).

National Land Cover (NLC) 2000: 1:50 000 scale national land-cover based on satellite imagery from 2000 and 2001.

Non-isolated subsystem: an inland system with an observable hydrological connection to a surface drainage network.

Non-permanent wetlands: in this report the term refers to seasonal and temporary zone of wetness (DWAF, 2005).

Palustrine wetlands: include inland systems that could be permanently or periodically inundated and have no existing connection to the ocean with complete absence of marine exchange and/or tidal influence.

Pan: a wetland contained in a topographic depression that has a closed drainage system, is shallow (<2 m deep when fully inundated), has a flat bottom, is usually circular to oval in shape (sometimes kidney-shaped or lobed) and usually seasonally dry (Ewart-Smith *et al*., 2006).

Peat: defined as a sedimentary (*in situ*) accumulated material that comprises at least 30% (dry mass) of dead organic matter (IPS/IMCG, 2010). A dark brown or black organic soil layer, composed of partly decomposed plant matter and formed under permanently saturated conditions (Ewart-Smith *et al*., 2006).

Peatlands*:* wetlands that have accumulated a minimum layer of 30 cm of peat (National Wetlands Working Group, 1997; Joosten and Clark, 2002). Peatlands can be divided into fens, bogs and several swamp types (including swamp forest based on the origin of water supply).

Permanent inundated: surface water (open water) is present throughout the year (Ewart-Smith *et al*., 2006).

Permanent wetland: a wetland or the inner zone of a wetland that is permanently saturated (DWAF, 2005).

Recharge: the volume of infiltrated water that crosses the water table and becomes part of the groundwater flow system (Anderson and Woessner, 1992).

Remote sensing: the science of gathering data on an object or area from a considerable distance, as with radar or infrared photography, to observe the earth or a heavenly body (Jensen, 2005).

Runoff: surface runoff occurs when water is unable to infiltrate and when the ground surface is sloping. Surface runoff rate depends on surface slope and roughness, soil moisture content at the surface, as well as on the rates at which additional water is supplied by rainfall and extracted by infiltration or evaporation.

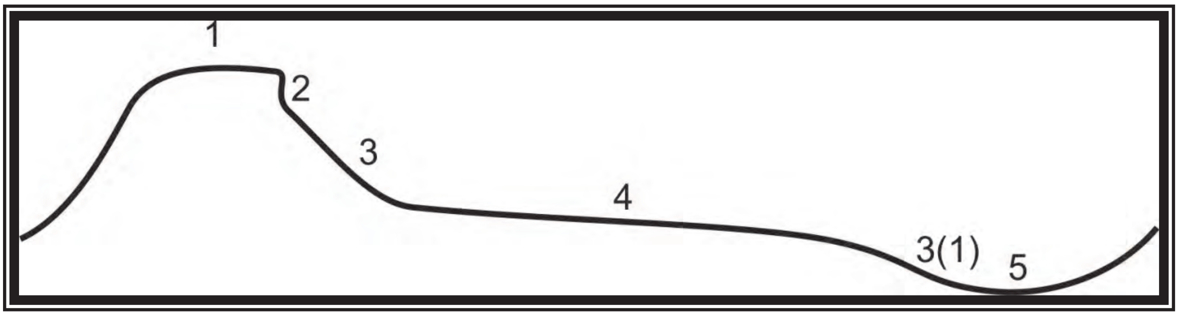
Saturated: as relating to wetland sediments, waterlogged, usually resulting in hydric soils that support vegetation adapted to aquatic conditions (Ewart-Smith *et al*., 2006).

Seasonal zone of wetness: the zone of a wetland that lies between the temporary and permanent zones and is characterised by saturation for 3-10 months of the year, within 50 cm of the surface (DWAF, 2005).

Seep: concave or convex area that is permanently or periodically saturated, usually on a slope, where the groundwater or inflow meets the surface (Ewart-Smith *et al*., 2006).

Sole source aquifer: an aquifer used to supply 50% or more of the urban domestic water for a given area and for which there is no reasonably available alternative source of water (Parsons and Conrad, 1998).

Spring: an outflow of groundwater at the surface (Ewart-Smith *et al*., 2006).
Storage coefficient: the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head. Storage coefficient is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storage coefficient is equivalent to the specific yield.
Swamps: refers to permanently inundated wetlands that support tall emergent vegetation and can include trees.
Temporarily inundated: surface water (open water) is present for less than 3 months of the year.
Temporary zone of wetness: wetland area characterised by saturation within 50 cm of the soil surface for less than 3 months of the year, e.g. the outer zone of a wetland (DWAF, 2005).
Terrain units**:** Terrain unit 1 represents a crest, 2 a scarp, 3 a midslope, 3(1) a secondary midslope, 4 a footslope and 5 a valley-bottom **(**Van den Berg *et al.*, 2009).



Unconfined aquifer: an aquifer in which there are no less permeable confining beds between the saturated zone and the groundwater surface.
Valley-bottom: a low-lying, gently-sloped area that receives water from an upstream channel and/or from adjacent hillslopes, not subjected to periodic over-bank flooding by a river channel (Ewart-Smith *et al*., 2006).
Vlei: a colloquial South African term for a wetland.
Wetland: land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil (National Water Act, 1998).
Wetland classification: refers to the process of typing wetlands according to their biophysical characteristics and the way in which they function (Ewart-Smith *et al*., 2006).
Wetland spectral signatures: pure pixels (remote sensor data) of wetland vegetation indicative of hydric conditions have their own spectral signature that varies or can be similar to other vegetation classes (Jensen, 2005).

ABBREVIATIONS

ARC-ISCW – Agricultural Research Council – Institute for Soil, Climate and Water
AWL – Advance Wetland Layer
DEM – Digital Elevation Model
DWAF – Department of Water Affairs and Forestry (currently Department of Water Affairs)
EC – Electrical Conductivity
KZN – KwaZulu-Natal province
LOI – Loss on Ignition
MCA – Maputaland Coastal Aquifer
MCP – Maputaland Coastal Plain
NAIPS – National Alien Invasive Plant Survey
NFEPA – National Freshwater Ecosystem Priority Areas
NWI – National Wetland Inventory
SAC – Satellite Application Centre
SAEON – South African Environmental Observation Network
SANBI – South African National Biodiversity Institute
SOC – Soil Organic Carbon
SRTM – Shuttle Radar Topography Mission
W-B – Walkley-Black method
WRC – Water Research Commission

CHAPTER 1: INTRODUCTION

PHOTO: Althea Grundling

1 INTRODUCTION

1.1 BACKGROUND

Wetlands are globally recognised as one of the support systems of humankind, providing a wide range of goods and services (Mitsch and Gosselink, 2000). Wetlands are threatened by population expansion and the increasing need for natural resources, especially where impoverished communities encroach on the resources for their daily survival (Maltby and Barker, 2009). The Maputaland Coastal Plain (MCP) located in the Umkhanyakude District, north-eastern KwaZulu-Natal province in South Africa (Figure 1.1) is such an area (Morgenthal *et al*., 2005; Smith and Leader-Williams, 2006). Not only does the MCP host a large portion of South Africa's wetlands but it is also known for the high incidence of poverty and disease (e.g. HIV/AIDS) (Benatar, 2004; Gillespie *et al*., 2007). The Tonga people that live in the area depend on the wetlands as a natural resource for water, vegetation for building and making crafts, for fishing, and for cultivating crops on the organic soils in the wetlands (Louw, 1984; Taylor, 1988). Traditional ways to access the water resource are extraction from wells, lakes, streams and springs (Grundling *et al*., 1998).

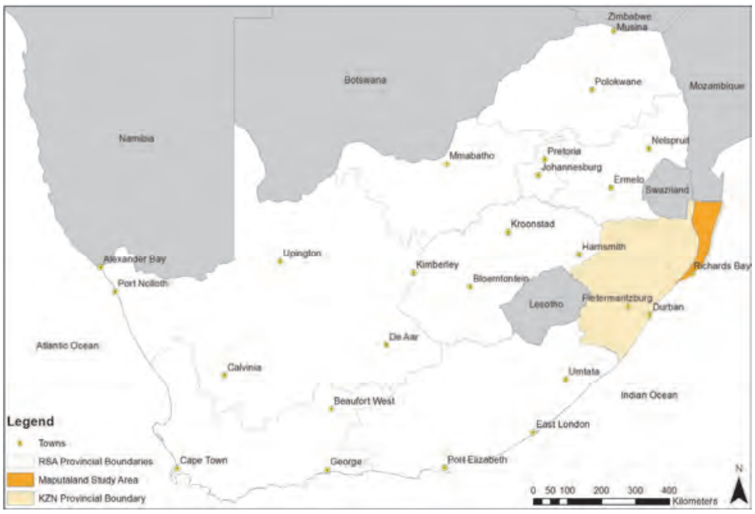
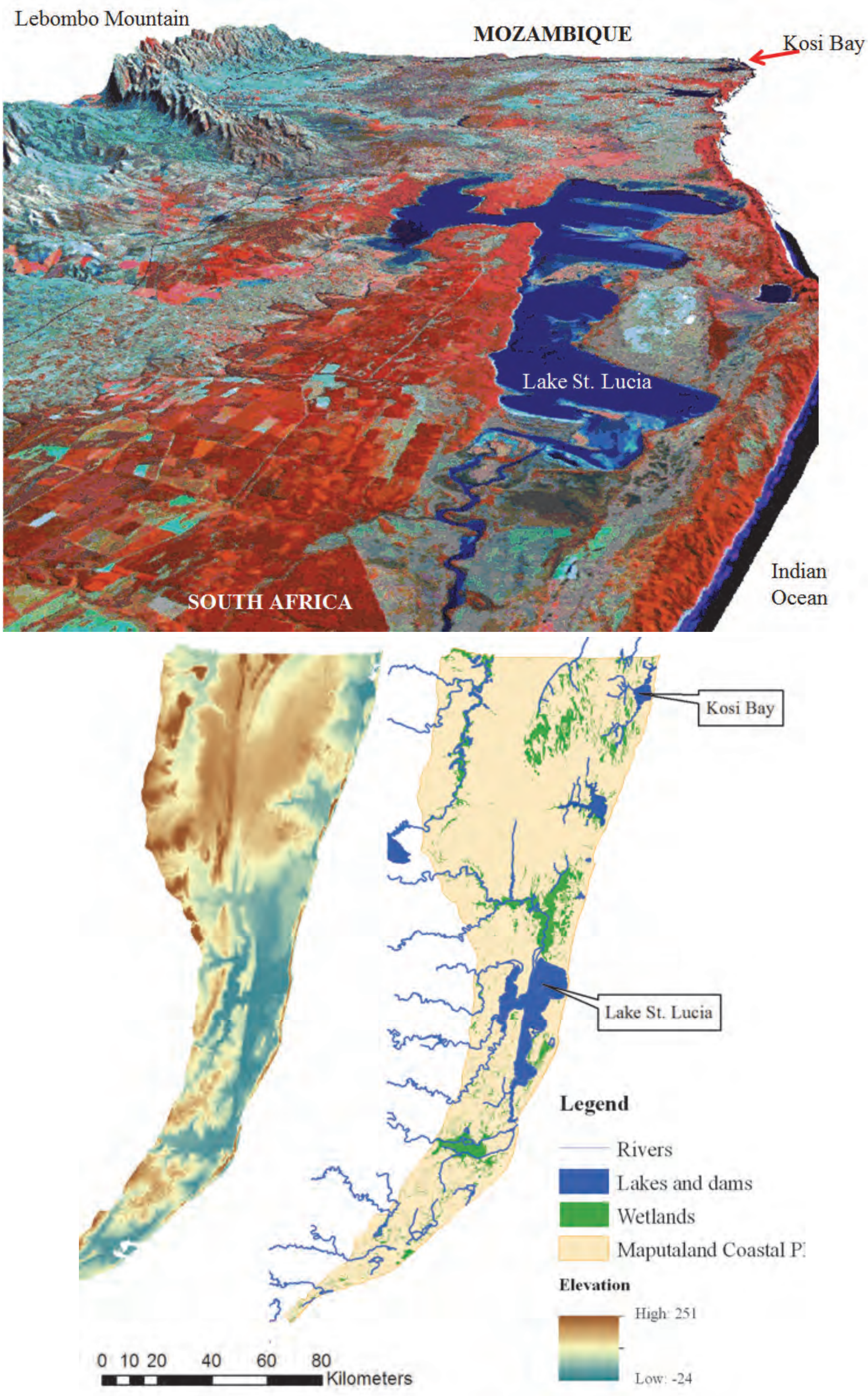


Figure 1.1: The Maputaland Coastal Plain located in north-eastern KwaZulu-Natal, South Africa.

The MCP stretches from the town of Mtunzini in the south to Kosi Bay in the north (at the South African border with Mozambique) and continues north towards the town of Cabo Santa Maria (Momade *et al*., 2004). The linear north-south Lebombo Mountains range consists of the basalts and rhyolites of the Jurassic Jozini Formation that forms the MCP border in the west, while the barrier dune complex of the Maputaland Group forms the border between the Indian Ocean and the MCP in the east. The MCP is located between the Lebombo Mountains and the barrier dunes and is 70 km wide in places (Figure 1.2). Erosion and sedimentation processes form part of the Quaternary marine transgression and regression episodes (Hobday, 1979; MacDevette, 1989) and are responsible for the characteristic of north-south-orientated sandy dune ridges of the MCP. Taylor (1991) distinguishes five major landscape units in the MCP, namely: the gentle undulating terrain at the base of the Lebombo Mountains; sandy ridges of relic coastal dunes; coastal lake systems; coastal dunes and river-related systems (Figure 1.2). Botha and Porat (2007) described the significant Tshongwe-Sihangwane composite sand mega-ridge where the buried aeolian sand landscape (Kosi Bay Formation) is exposed. The MCP consists of many different types of surface water bodies, such as rivers, floodplains, estuaries, swamps, pans and coastal lakes. Several large rivers including the Pongola, uMhlatuze, iMfolozi and uMkhuze meander through the landscape (Botha and Porat, 2007), of which the iMfolozi and uMkhuze rivers are the largest with vast associated delta swamps (Briggs, 2006) (Figure 1.2). The area hosts 50% of South Africa's wetlands and 75% of its known peatlands (Marneweck *et al*., 2001; Grundling and Grobler, 2005) and is characterised by cover sands with high, north-south orientated dune cordons on the coastal plain (Whitmore *et al*., 2003). A variety of wetlands ranging from peatlands, swamp forests, saline reed swamps, salt marshes, submerged macrophyte beds, mangroves and riverine woodlands (Taylor, 1991) occur in the MCP. Colvin *et al*. (2007) suggests that many ecosystems of this region are aquifer dependent and that hydrological systems support ecological patterns and processes. Izidine *et al*. (2003) emphasised the botanical richness of the area with its high occurrence of endemic species (Maputaland Centre of Plant Endemism), and the important role that soil water plays in these sensitive water-linked ecosystems.

Not only are the wetlands on the MCP important for the maintenance of the rich biodiversity of the area (Taylor *et al*., 2006; Rivers-Moore *et al*., 2007), but they are equally important for the local communities as a key resource in subsistence agriculture (Taylor, 1988; Sliva, 2004). However, environmental concerns such as agriculture, forestry and water supply schemes within the catchments in addition to prolonged periods of drought have led to reduced availability of groundwater (Rawlins and Kelbe, 1998). Therefore, the wetlands of the area have become vulnerable ecosystems and consequently there is a need to determine spatial and temporal changes in the distribution and function of these wetlands and understand the controlling processes.



Data Source:
3D Image: False colour 2005 Landsat winter image draped over 20 m contour DEM (Grundling and Beukes, 2011)
Rivers: River line layer **(**NGI, 2012b) and SPOT 2010 imagery used to digitise the prominent channels (SANSA, 2013)
Lakes and dams: Inland wetland layer **(**NGI, 2012a)
Wetlands: National Freshwater Ecosystem Priority Area (NFEPA) wetland types (Nel *et al.*, 2011)
Elevation: Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (Farr and Kobrick, 2000)

Figure 1.2: Landscapes, rivers and wetlands of the Maputaland Coastal Plain.

Grundling *et al*. (1998) and Marneweck *et al*. (2001) suggest that there could be a strong relationship between the spatial distribution of wetlands and landscape factors, such as geology, hydrology, rainfall distribution and soil type. However, these landscape factors have not yet been used to quantitatively explain the wetland type and distribution on a regional scale. A number of vegetation and land-cover datasets do exist for the study area (e.g. Mucina and Rutherford, 2006; Scott-Shaw and Escott, 2011; Ezemvelo KZN Wildlife, 2011) and wetland layers (e.g. the recently classified wetland units of the KZN wetland layer 2011 (beta v.3) (Scott-Shaw and Escott, 2011) and the National Freshwater Ecosystem Priority Areas (NFEPA) wetland type layer (Nel *et al*., 2011; Driver *et al*., 2011)). However, no accuracy assessment has been done on the two wetland type datasets. Driver *et al*. (2011) stated that the Freshwater Ecosystem Priority Area Maps should ideally be groundtruthed by a wetland specialist for local level planning. This is of concern as the MCP not only hosts a significant portion of South Africa's wetlands but also a complex array of wetland types.

1.2 PROBLEM STATEMENT

Wetlands on the MCP are adapted to the prevailing weather and climate conditions (MacDevette, 1989) but are threatened because of changing land-use (MacDevette, 1989; Morgenthal *et al*., 2005; Smith and Leader-Williams, 2006). Agriculture, forestry and water supply schemes within catchments and prolonged periods of drought have resulted in land degradation and groundwater depletion (Rawlins and Kelbe, 1998). To be able to manage these systems and implement conservation practices requires that wetlands be mapped, described and classified more effectively according to biophysical characteristics and functional attributes (Ewart-Smith *et al*., 2006; Mucina and Rutherford, 2006). Mapping and classification techniques using satellite remote sensing images such as Landsat Thematic Mapper (TM) to cover extensive areas such as the MCP can be ambiguous because vegetation units can have similar spectral signatures (e.g. swamp, dune and sand forests (Walsh, 2004)), the spatial resolution and severity of fire scars can prevent the classification of smaller pans (Været and Sokolic, 2008).

Classifying a wetland type depends on the wetland's structure and functioning characteristics, i.e. the process of typing wetlands according to their biophysical characteristics and the way in which they function (Ewart-Smith *et al*., 2006). The hydrogeomorphic classification developed by Brinson (1993) as a basis to assign wetland functioning through the consideration of the geomorphic setting, water source and hydrodynamics has been adopted as the basis for the Classification System for Wetlands and other Aquatic Ecosystems in South Africa (SANBI, 2009b; Ollis *et al.*, 2013). However, an underlying assumption of the hydrogeomorphic wetland classification concept is that aquatic ecosystems function slightly differently in different landscape settings and that wetlands belonging to the same hydrogeomorphic unit share common features in terms of environmental drivers and processes. Although widely applied in South Africa this underlying assumption has yet to be tested. Therefore, Ollis *et al.* (2013) stressed that there is an urgent need to test and refine the Classification System for Wetlands and other Aquatic Ecosystems in South Africa by incorporating knowledge supported by research on how wetlands and other inland aquatic ecosystems function.

The wetland types on the MCP range from seasonal, semi-permanent and permanently wet interdune valley-bottoms and seepage wetlands, to pans and floodplains in different hydrogeomorphic settings (SANBI, 2009b) and hydrological regimes, supporting a variety of flora and fauna (Grundling *et al.*, 1998; DLP, 1992, 1992; Kelbe and Rawlins, 1992; Matthews *et al*., 2001; Grundling *et al*., 2000; Været, 2002; Goge, 2003; Venter, 2003; Taylor *et al*., 2006; Van Rooyen, 2006). The contribution of the underlying geology with different hydrological and hydraulic characteristics needs to be investigated in order to understand the distribution of different wetland types on the MCP and their contribution to biodiversity and ecological services. In this study the distribution of rainfall and the contribution of the underlying geology to groundwater exchanges will be investigated on a sub-regional scale to understand the functioning of wetlands on the MCP.

It is necessary to develop criteria and thresholds to distinguish between different wetland types and wetness zones in a wetland and to understand the processes that drive these systems on the MCP. Wetlands on sandy aquifers in general, and specifically those of the MCP, are difficult to delineate because morphological signs of wetness (i.e. the presence of chroma mottles in the soil profile to a depth of 50 cm) are not always detectable (DWAF, 2005).

Hydroperiod (the degree, duration and level/extent of inundation and/or saturation) results in specific structural and functional attributes for different wetland types. The edge of a wetland can be delineated if the wetland has a clear boundary, e.g. swamp forest, usually without quantitative data on the hydroperiod, and such data are not needed to classify a wetland up to the level of the hydrogeomorphic unit. However, soil organic carbon associated with hydroperiod can help with the delineation for the rest of the wetlands on predominantly deep sandy soils that have species not exclusive to the type of wetland.

An understanding of environmental factors and processes is required before human-induced changes can be evaluated. Factors controlling the distribution of different wetland types, and the environmental features contributing to their functioning, will support the management of these systems. Therefore, the following research questions need to be addressed:

- *How are the wetlands distributed and impacted on the MCP?*
- *What types of wetlands are found on the MCP?*
- *What regional environmental factors control this distribution?*
- *How can MCP wetland types be managed?*

1.3 TERMS OF REFERENCE

The Water Research Commission (WRC) funded project (K5/1923) commenced in April 2009 and was completed in November 2012. The objectives stated in the original WRC project proposal were:

1. To investigate the regional environmental factors and processes that control the different wetland systems.
2. To identify the hydrogeomorphic wetland units on the Zululand Coastal Plain.
3. To test and refine soil organic carbon content as an indicator of hydroperiod in order to delineate and classify permanent, seasonal and temporary wetlands on sandy coastal aquifers.
4. To determine the relationship between the spatial distribution of wetlands and depth to groundwater and/or groundwater fluctuation.
5. To address shortages found in practice regarding wetland classification for the Zululand Coastal Plain.
6. To aid in accurate wetland classification and delineation for the Zululand Coastal Plain.
7. To make recommendations for land-use practices, especially afforestation and subsistence agriculture under a changing climate, on the water and soil dynamics of the wetland systems.

1.4 MOTIVATION

The aim of WRC project K5/1923 is to understand the regional environmental factors that control the distribution, characteristics and function of different wetland types on the Maputaland Coastal Plain in north-eastern KwaZulu-Natal, including interactions with the underlying Maputaland Coastal Aquifer. The primary focus of the study was based on the three main themes of mapping, classifying and characterising the different wetland types. The main objectives were: to map the distribution of wetlands in wet and dry years and to map land-use changes in recent decades; to classify wetlands using the hydrogeomorphic classification; to characterise the relationships between rainfall, topography and water table depth; and to define the relationship between soil organic carbon and hydroperiod in the different wetness zones.

1.4.1 Objectives and Report Structure

The original objectives for the study (listed in section 1.3) were refined to form ten specific objectives based on the three main themes of the project (mapping, classifying and characterising the different wetland types) in order to address the research questions and to simplify the final report (Table 1.1).

Table 1.1: Objectives for each chapter based on the three main themes of the project

WRC OBJECTIVES	SPECIFIC OBJECTIVES
CHAPTER 3: Land-Cover Mapping	
To make recommendations for land-use practices, especially afforestation and subsistence agriculture under a changing climate, on the water and soil dynamics of the wetland systems.	1.1 To use Landsat TM and ETM imagery along with ancillary data to determine the distribution and extent of wetlands on the MCP. 1.2 To identify and map “permanent” and “temporary” (inland) wetlands and open water based on their spatial extent and distribution during wet and dry years. 1.3 To determine wetland loss from land-use changes due to cultivation, plantations and urbanisation between 1992 and 2008.
CHAPTER 4: Hydromorphic Classification	
To identify the hydrogeomorphic wetland units on the Zululand Coastal Plain. To address shortages found in practice regarding wetland classification for the Zululand Coastal Plain. To aid in accurate wetland classification and delineation for the Zululand Coastal Plain. To determine the relationship between the spatial distribution of wetlands and depth to groundwater and/or groundwater fluctuation.	2.1 To identify the different hydrogeomorphic wetland types and determine if wetlands that belong to the same hydrogeomorphic unit share common features in terms of environmental drivers and processes. 2.2 To investigate their relationship with environmental factors such as water table, rainfall and elevation. 2.3 To apply the hydrogeomorphic wetland classification in the study area. 2.4 To compare verification sites with the National Freshwater Ecosystem Priority Areas (NFEPA) project wetland type layer.
CHAPTER 5: Soil Organic Carbon and Hydroperiod	
To test and refine in order to delineate and classify permanent, seasonal and temporal wetlands on sandy coastal aquifers.	4.1 To determine soil organic carbon content and hydroperiod in different wetness zones.
CHAPTER 6: Characterising Landscape Processes	
To investigate the regional environmental factors and processes that controls the different wetland systems.	3.1 To classify wetlands types within the study area on the basis of their structure and function. 3.2 To characterise the landscape processes shaping the dynamics and distribution of the wetland types.

1.5 RESEARCH APPROACH

The study focused on climatic, geomorphological and hydrological processes to improve the scale-based understanding of wetland process within the landscape. It also focused on palustrine wetlands (i.e. inland systems with no connection to the ocean) including peatlands. Not all the wetlands that occur on the coastal aquifer contain peat and one therefore needs to distinguish between permanent and temporary wetland (non-permanent saturated) mineral soil. For the purpose of this study, only general wetland areas were mapped spatially with the use of time series Landsat TM imagery.

1.5.1 Different Scales

The MCP is situated in north-eastern KwaZulu-Natal, South Africa (Figure 1.3). The triangular shape of the study area covers 943 000 ha and stretches from the Mozambique border in the north to the town of Mtunzini in the south. It is bordered by the Indian Ocean in the east and the Lebombo Mountains in the west.

Two study sites on the MCP were chosen that represent two different scales (sub-regional scale – northern study area (250 000 ha) and local scale – southern study area (62 000 ha); Figure 1.3). They also represent different rainfall distribution, vegetation and land-use activities on the MCP. The mean annual precipitation (rainfall) for the Indian Ocean Coastal Belt is 985 mm (Mucina and Rutherford, 2006). However, the rainfall is not evenly distributed across the coastal plain. Taylor *et al.* (2006) reported that there is a rainfall gradient from east (1 200 mm/y) to west (600 mm/y). Rainfall also decreases from south to north, e.g. mean annual rainfall at St. Lucia (south) is 1 000 mm while Kosi Bay near the Mozambique border in the north only receives 750 mm (iSimangaliso Wetland Park, 2008b). MacDevette (1989) identified two major successional gradients in vegetation, namely north to south and east to west. The north to south gradient is characterised by reduction in plant species number whilst the east to west gradient represents different plant species composition. Matthews *et al*. (2001) reported on the relationship between east to west gradient in plant species composition and Grundling *et al.* (1998) reported that wetland variety and distribution on the MCP also follow this east-west pattern.

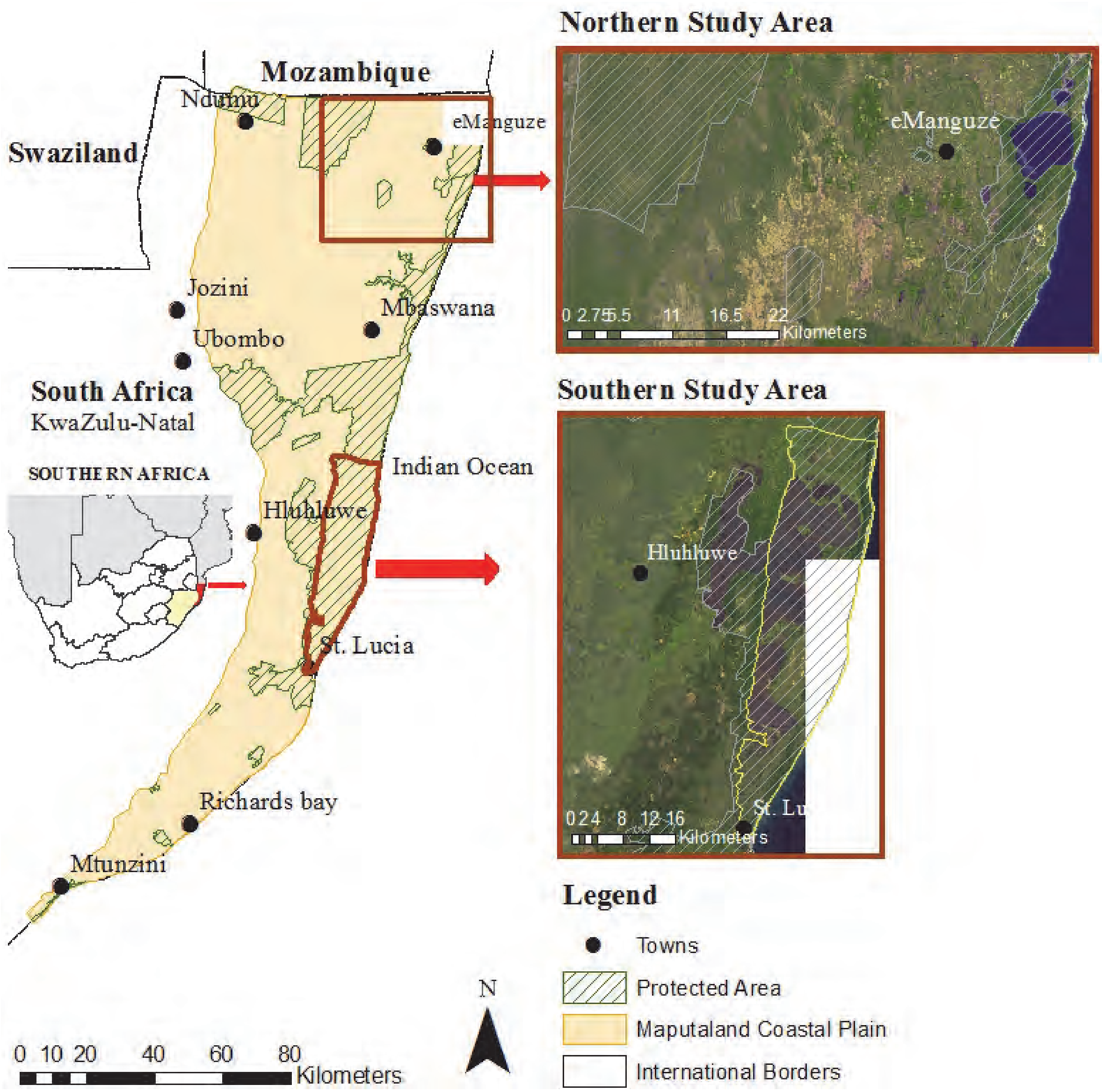


Figure 1.3: Two study areas on the Maputaland Coastal Plain.

The northern study area is a combination of 79% unspecified or subsistence agricultural land in the Tembe Tribal area (iSimangaliso Wetland Park, 2008a), while the remaining 21% is conservation area that includes the iSimangaliso Wetland Park in the east and the Tembe Elephant Park in the west. The southern study area is located in the iSimangaliso Wetland Park. Although it represents 100% conservation area there have been impacts of forestry on the Eastern Shores of Lake St. Lucia. Været *et al*. (2008) reported that the plantations on the Eastern Shores were eradicated from the late 1990s and completed in 2006, followed by an intensive burning programme.

More detailed investigations were done on the northern and southern study areas. The dataset for the shorter, smaller southern transect is very comprehensive, with detailed elevation, vegetation, soil, and hydroperiod data for each zone in each wetland. The dataset for the longer, more extensive northern transect, however, only has broad scale hydroperiod and elevation data for the various wetlands, and not the associated zones. The southern transect will therefore focus on the relationship between the various parameters in the wetland zones, while the northern transect will focus on broad scale processes in the different wetland systems and types.

The transect selection was based on the following criteria:

- level of existing knowledge and availability of data (e.g. existing wetland studies, as well as accessible groundwater, rainfall and soil information);
- variety of different wetland types; and
- accessibility and safety.

1.5.2 Other Important Sources of Information

The project deliverables are listed under Reports and Publications in Chapter 9. These reports served as building blocks towards the final report product.

CHAPTER 2: DESCRIPTION OF THE STUDY AREA

PHOTO: Althea Grundling

2 DESCRIPTION OF THE STUDY AREA: LITERATURE REVIEW

The Maputaland Coastal Plain (MCP) is the southern part of the East African Coastal Plain and stretches from the Umlalazi River in the south, near the town of Mtunzini (Kelbe *et al*., 2001), northwards to the Mozambique border along the Indian Ocean to the east and the Lebombo Mountains range to the west (see Figure 1.2). The MCP (694 410.82 ha in extent) includes the iSimangaliso Wetland Park (previously called the Greater St. Lucia Wetland Park) which is a World Heritage Site. The MCP area from Mtubatuba (St Lucia) in the south to Kosi Bay in the north falls within the Umkhanyakude District Municipality area (KwaZulu-Natal Top Business, 2009). Land-uses include conservation areas, commercial farming, small-scale farming and forestry (Morgenthal *et al*., 2004). The literature review deals with the MCP as a whole.

2.1 LANDSCAPE

The undulating dune topography of the MCP is in general 45-75 m above mean sea level (m.a.s.l.), except for the high dune cordons along the sea edge which are 100-180 m in height. The dunes are orientated north-south and occur in sub-parallel cordons with a distinct east-west series of dune ridges (Botha and Porat, 2007) (Figure 2.1).

PHOTOS: Ian Kotzé

Figure 2.1: Cordon dunes on the left and dune ridges (right) with dune forest vegetation.

2.2 GEOLOGY

The break-up of Gondwanaland (135 million years ago) opened up the Mozambique Channel or rift (Ellery *et al*., 2009b), causing an ocean crust to develop beneath the Indian Ocean (McCarthy and Rubidge, 2005). The interior part of the country underwent episodes of uplift (20 million and 5 million years ago) that resulted in sediments that eroded from the interior part of the country and deposited on the continental shelf (McCarthy and Rubidge, 2005), forming the present day surface geology of the MCP.

The MCP consists of Jurassic rhyolites and basalts (volcanic rocks) from the Lebombo Mountains (in the west) and underlines the coastal plain (Botha and Porat, 2007). In the Mid- to Late-Cretaceous period, terrestrial and recent marine sediments (of the Zululand Group) were deposited on top of the volcanic rocks (Van Wyk and Smith, 2001). The older Zululand Group includes the Makatini, Mzinene and St. Lucia Formations. The younger Maputaland Group consists of the Uloa and Port Durnford Formations (beach conglomerate, coquina and sub-tidal sands) (Johnson *et al*., 2006). All, except for the Makatini Formation, consist of sedimentary deposits formed by marine and/or fluvial environments presently or historically (Briggs, 2006). Most of the coastal plain consists of geologically recent fine-grained aeolian, infertile sands (Van Wyk and Smith, 2001), mainly yellowish and argillaceous redistributed sands of the Berea and Muzi Formations (Mucina and Rutherford, 2006). The Kosi Bay Formation (aeolian sands) underlies the Late Pleistocene dunes. The term aeolian describes the process of wind erosion, transportation and deposition of particles (e.g. sand dunes) (Colvin *et al*., 2007). The rubified palaeosol in the Kosi Bay Formation marks the existence of a buried aeolian sand landscape (Cooper and Kensley, 1991). Along the coastline, the Middle to Late Pleistocene coastal lake organic-rich mud (Port Durnford Formation) and the overlying Kosi Bay Formation aeolian sands are uncovered (Botha and Porat, 2007).

The youngest aeolian activity (Holocene) signifies sand mobilisation resulting in the accumulation of the coastal dune cordon barrier of at least five transverse ridges of ascending parabolic dunes forming the Sibayi Formation (Botha and Porat, 2007). According to Botha and Porat (2007) the strandline complex (dune cordon systems) with its base at ~50 m.a.s.l. and dune ridges rising to 175 m.a.s.l. is made up of sandy deposits that represent the previous sea levels of various ages of which the oldest is the Ndumu dune cordon (25 million years old) to the west. The dunes that cover the Port Durnford Formation are 70 000 years old in the area between Richards Bay and Umlalazi (Mucina and Rutherford, 2006). The Isipingo Formation is made up of calcified dunes and beach deposits (Figure 2.2) while the hummocky dune systems comprise the KwaMbonambi Formation. The Indian Ocean seaboards of South Africa were much cooler and drier around 118 000 years ago (Van Zinderen Bakker, 1982; Adams, 2012) and the Agulhas Current was also much shallower and weaker (Mucina and Rutherford, 2006).

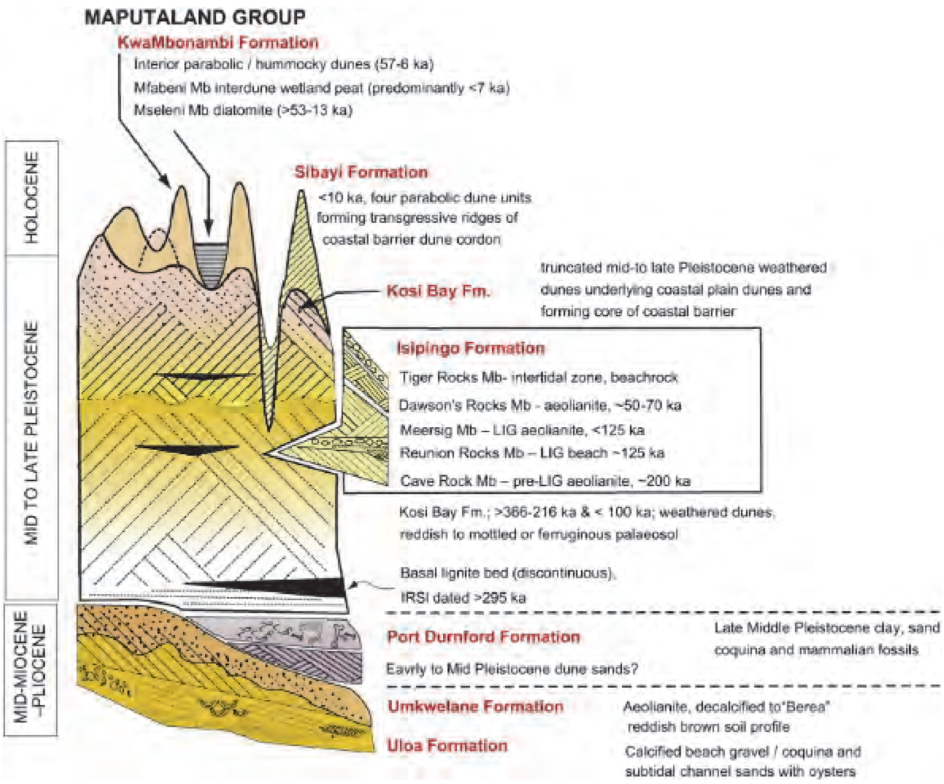


Figure 2.2: Idealised composite section representing the lithostratigraphic units of the Maputaland Group (Botha and Porat, 2008).

2.3 HYDROLOGY

2.3.1 Climate

The climate in southern Africa underwent dramatic changes (known as the Pleistocene marine regressions) of alternative dry/cold and wet/warm climates, each approximately 1 000 000 years (Mucina and Rutherford, 2006). Several global and macro-regional factors are also responsible for the tropical/subtropical character of the MCP, e.g. hot, wet summers (tropical) with high humidity and mild, slightly drier winters (subtropical) (Taylor, 1991; Mucina and Rutherford, 2006). These factors include the unusual movement of the Intertropical Convergence Zone towards the south during the summer months as well as the warming influence of the Agulhas Current close to the eastern coast (Mucina and Rutherford, 2006; Været, 2008). Tropical cyclones can cause major climatic and hydrological forcing (e.g. ‘Domoina’ cyclone in 1984). The cyclones originate over the Indian Ocean and approach the MCP from the north-east. Mucina and Rutherford (2006) reported that 60% of the MCP rainfall occurs during the summer months (November to March) and 40% during the winter months (April to October). The mean annual precipitation is 963 mm and the mean annual temperature is 21^{o}C (Mucina and Rutherford, 2006). Taylor *et al.* (2006) reported that there is a rainfall gradient from east (1200 mm/y) to west (600 mm/y). The evaporation rate is highest in the winter and early spring (Van Wyk, 1994; Van Wyk and Smith, 2001). Annual evaporation on the eastern shores of Lake St. Lucia is 900 mm for the Mfabeni mire and 478 mm for the coastal dunes (Clulow *et al.*, 2012).

2.3.2 Hydroperiod

Ollis *et al.* (2013) defined hydroperiod as the frequency and persistence of saturation and/or inundation within an aquatic ecosystem. The degree of saturation in wetlands is generally controlled by the level of the water table (above or below the soil surface) which fluctuates with time and the capillary fringe of varying thickness existing above the water table (Richardson and Vepraskas, 2001). According to Brady and Weil (2007), the temporal pattern of these water table changes is known as the hydroperiod of the soil. Generally, it is not valid to equate the measurement of groundwater levels (i.e. depth to water table) with the hydroperiod. Such a relationship may hold true for wetlands that are known to be aquifer dependent ecosystems but the hydroperiod is not only influenced by groundwater and the position of the water table. Some wetlands are only fed by rainfall and surface water flow, with their hydroperiod determined by the nature of these inflows and no relationship at all to groundwater and the level of the water table (Ollis *et al.*, 2013). For example, 'perched' systems are not connected to the underlying aquifer but they do have a water table (albeit perhaps transient). They may not be part of the regional aquifer system yet are still a product of the system. The hydroperiod of a wetland may vary from daily (e.g. a coastal marsh where tides rise and fall) to seasonal or even longer (e.g. ephemeral pans). Most inland wetland hydroperiods are seasonal, with high water tables occurring during the rainy season. No monitoring has been done in terms of water table levels in wetlands for the study area. This type of data can be gathered from staff gauges, shallow monitoring wells, and semi-continuously recording dataloggers using piezometers (Barton *et al.*, 2008) or dipwells (Araya, undated).

2.4 SOIL

DWAF (2005) reported that the delineation of wetlands on sandy coastal aquifers is problematic. The reason why delineating wetlands on the MCP is difficult can be attributed to the undetectable morphological signs of wetness in the sandy soil profile to a depth of 50 cm (DWAF, 2005). DWAF (2005) recommends the use of soil organic carbon (SOC) content as a pedological criterion in the identification of permanent, seasonal and temporary zones of wetness, e.g. for the temporary zone of wetness in the following soil forms: >7% SOC in Fernwood soil forms and >4% SOC in other wetland soil forms such as Longlands, while SOC in permanent and/or seasonal zone of wetness is excessively high (>10%) and topsoils are typically peaty, commonly known as the Champagne soil form (Soil Survey Staff, 1999). It was also noted by DWAF (2005) that >10% SOC in the topsoil of other soil forms (e.g. Fernwood and Longlands) may also occur. Champagne soil forms are characterised by >10% SOC in the profile that is at least 200 mm thick.

2.4.1 Soil Organic Carbon

Anaerobic conditions (not having molecular oxygen (O_2) present) are typically found in wetlands (Kotze, 2000). Under these conditions the decomposition of organic matter in wetlands can accumulate very efficiently. The decomposition rate is strongly influenced by water table depth (Hilbert *et al.*, 2000) and water table fluctuation (Belyea and Clymo, 2001). Therefore, the accumulation of organic matter in the soil serves as a carbon sink, making wetlands one of the most effective ecosystems for storing soil carbon (Richardson and

Vepraskas, 2001; Whittington and Price, 2006; Adhikari *et al*., 2009). Mitsch and Gosselink (2000) reported that organic soils can be further classified by their percentage carbon content:

- Organic soil material: ≥10% organic C
- Mucky mineral soil material: 5-10% organic C
- Mineral soil material: <5% organic C

An increase in soil water results in an increase in SOC (Brady and Weil, 2007). Carbon pools are therefore expected to be greater in the permanent wetland zones than in the seasonal/temporary zones (Bernal and Mitsch, 2008). During dry periods a considerable portion of the carbon that would have been retained in the saturated soil gets oxidised. Carbon fluxes and pools also vary in different wetlands types (Adhikari *et al*., 2009). For example, 8% of South Africa's land surface is covered by wetlands (SANBI, 2010b) but less than 10% of these are peatlands (Grundling, 2011). Peatland is a special type of wetland where peat accumulates due to permanent inundated conditions. Peat can be defined as a sedimentary (*in situ*) accumulated material that comprises at least 30% (dry mass) of dead organic matter (IPS/IMCG, 2010). An important attribute of peat is its ability to hold and retain water (Richardson and Vepraskas, 2001). The Third Research Note (Grundling *et al*., 2010) provides background information on three carbon analysis methods, namely: loss on ignition (LOI = Total C), dry combustion or Dumas (Total C) and rapid oxidation [Soil Organic Carbon (SOC) – Walkley-Black (W-B)].

2.5 VEGETATION

The MCP lies in what is considered the Maputaland Centre of Endemism with an extremely rich biodiversity (Van Wyk and Smith, 2001). The Maputaland Centre of Endemism is located at the southern end of the African tropics, where many plant (and animal) species reach the southernmost limit of their range. Two biomes occur in the MCP: the Savanna biome and the Indian Ocean Coastal Belt biome, and two bioregions: the Lowveld (SVI) bioregion and the Indian Ocean Coastal Belt (CB) bioregion (Mucina and Rutherford, 2006).

The strong east-west rainfall gradient documented by Taylor *et al.* (2006) (1 200 mm/y in east and 600 mm/y in west) results in various ecological zones (Matthews *et al*., 2001). The vegetation consists of various forest types (e.g. coastal dune forest, sand forest, swamp forest), thickets, as well as primary and secondary grasslands. Vegetation types include freshwater wetlands that range from temporal to semi-permanent wet areas, such as hygrophilous grasslands (e.g. seasonally wet grasslands of the Palm Veld), swamp systems (e.g. Muzi swamp) and floodplains (e.g. Pongola floodplain (Grundling *et al*., 1998; Grundling, 2001).

Regional vegetation studies include various studies describing the ecology of Maputaland (Moll, 1977, 1980; Van Wyk, 1994; Van Wyk and Smith, 2001; Morgenthal *et al*., 2005; Mucina and Rutherford, 2006). Descriptive vegetation studies have indicated that plant species distribution patterns respond predominantly to a wetness gradient (Conlong, 1986; Van Wyk, 1991a, 1991b; Goge, 2003) and long-term changes in plant species composition correlated with rainfall patterns (Van Wyk, 1991b). Detailed work has been done mostly in the larger game reserves such as Ndumo Game Reserve, Mkhuzi Game Reserve, Tembe

Elephant Park (Matthews *et al*., 2001), Sileza Nature Reserve (Matthews *et al*., 1999) and the iSimangaliso Wetland Park (Goge, 2003; Venter, 2003; Walsh, 2004; Van Rooyen, 2006). Lubbe (1996) did a comprehensive and detailed classification of coastal and inland communities from the Mozambique border to Sodwana Bay (Matthews, 2007).

Grundling *et al.* (1998) described wetland vegetation on peatlands but very few detailed surveys have been done on the wetlands discussed in this study. Some wetlands are dominated by reeds, sedges and waterlogged meadows dominated by grass. The wetland vegetation in the area is mapped according to various vegetation units such as Swamp Forests and Subtropical Freshwater Wetlands vegetation (Mucina and Rutherford, 2006). According to Matthews (2007) and Van Wyk (1991b) the main ecological driving factors on the MCP are the interrelated effects of water table, soil type and topography, with fire and vegetation dynamics as secondary drivers. Kotze and Marneweck (1999) used obligate wetland (OW) species and facultative wetland (FW) species to classify permanently, seasonally and temporarily wet areas (Table 2.1).

Table 2.1: Obligate and facultative plant classification (Kotze and Marneweck (1999), adapted from U.S. Fish and Wildlife Service Indicator Categories (Reed, 1988))

SPECIES	**OCCURRENCE**
Obligate wetland (OW) species	Almost always grow in wetlands (> 99% of occurrences)
Facultative wetland (FW) species	Usually grow in wetlands (67-99% of occurrences) but occasionally are found in non-wetland areas
Facultative (F) species	Equally likely to grow in wetlands and non-wetland areas (34-66% of occurrences)
Facultative dryland (FD) species	Usually grow in non-wetland areas but sometimes grow in wetlands (1-34% of occurrences)

2.6 WETLANDS

Wetland variety and distribution on the MCP follow this east-west pattern recognised by a distinct east-west series of dune ridges (Botha and Porat, 2007), rainfall gradient (Taylor *et al.*, 2006) and vegetation zones (Matthews *et al*., 2001). The MCP consists of many different types of surface water bodies such as rivers, floodplains, estuaries, swamps, pans and coastal lakes (Botha and Porat, 2007) and is characterised by cover sands with high, north-south orientated dune cordons on the coastal plain (Whitmore *et al*., 2003). A variety of wetlands ranging from peatlands, swamp forests, saline reed swamps, salt marshes, submerged macrophyte beds, mangroves and riverine woodlands (Taylor, 1991) occur in the MCP. Sixty-six percent of the recorded peatlands in South Africa occur on the MCP (Marneweck *et al.*, 2001; Grundling and Grobler, 2005).

2.7 WETLAND CLASSIFICATION

Mitsch and Gosselink (2000) stated that most wetland classification approaches consider differences and changes in soils, vegetation and hydrological behaviour as the most appropriate criteria to distinguish wetland types. Wetlands receive water by three main inputs, namely rainfall, surface water and/or groundwater depending on their hydrogeomorphic setting (Ellery *et al*., 2009a; Ellery *et al*., 2009b) (Table 2.2). The Classification System for Wetlands and other Aquatic Ecosystems in South Africa adapted the hydrogeomorphic classification system (SANBI, 2009b; Ollis *et al.*, 2013). Wetlands can thus be classified according to their water source, geomorphic setting and hydrodynamics in hydrogeomorphic units (Brinson, 1993). *Geomorphic setting* refers to the location of the wetland with respect to the surrounding and underlying topography and lithology which control its water sources, including precipitation, surface flow and groundwater. *Hydrodynamics* refers to the direction of flow and strength of water movement within the wetland (Brinson, 1993). The hydrogeomorphic approach attempts to group aquatic ecosystems in a way that explains how they function (Ollis *et al.*, 2013). However, the assumption of the hydrogeomorphic approach is: 1) that aquatic ecosystems function slightly differently in different landscape settings, e.g. valley floor, slope, plain or bench; and 2) that wetlands belonging to the same hydrogeomorphic unit, e.g. depression of channelled valley-bottom, share common features in terms of environmental drivers and processes. These assumptions have yet to be tested by research on how wetlands and other inland aquatic ecosystems function.

Preliminary studies done by Amis *et al.* (2009) suggested that the National Wetland Classification System (SANBI, 2009b) can possibly be applied to the National Wetland Map in an automated manner (at least to level 3: landscape setting) in order to generate a national wetland type map. The wetland type map of the National Freshwater Ecosystem Priority Areas (NFEPA) initiative (Nel *et al.*, 2011; Driver *et al.*, 2011) described wetlands according to the regional setting (level 2), landscape setting (level 3) and hydrogeomorphic unit (level 4) (Van Deventer, 2010) using the hydrogeomorphic classification approach (Mbona *et al.*, 2010; Ollis *et al.*, 2013). GIS techniques and existing data were used in an automated approach to classify wetland types. However, Nel *et al.* (2011) recommend further investigation into the automation of the classification system, based on a thorough review of the availability of information required to distinguish one wetland type from another.

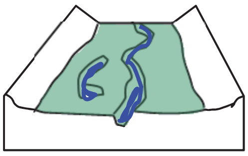
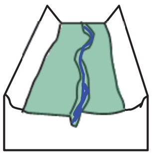
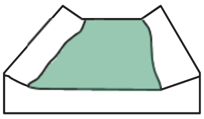
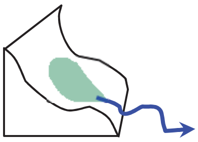
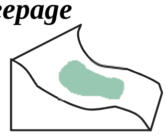
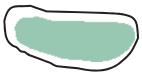
Wetland classification forms a major component of the study and several different classifications are presented on a sub-regional scale to address the different wetland types found in the study area. In each chapter a different approach was adopted:

- In Chapter 3, which deals with land-cover mapping, permanent and temporary wetlands and open water were classified based on vegetation and open water spectral signatures in wet and dry years by using Landsat TM and ETM imagery and ancillary data. The reason for this approach was to create a wetness map using wet and dry years to show the location of temporary and permanent wetland and open water areas. For the purpose of this study, only general wetland areas (e.g. swamp forest and sedge/moist grassland wetlands (including reeds)) were mapped spatially with the use of time series Landsat TM and ETM imagery.

- In Chapter 4, which deals with classifying wetland types, the Classification System for Wetlands and other Aquatic Ecosystems in South Africa (SANBI, 2009b; Ollis *et al.*, 2013) that adapted the hydrogeomorphic classification system was applied on a sub-regional scale. This hydrogeomorphic classification approach was evaluated in terms of the relationship between hydrogeomorphic wetland units and environmental factors and considers how well the hydrogeomorphic classification could be applied on the MCP. The following questions are tested: 1) whether wetlands are dependent on landscape setting, and 2) whether wetlands belonging to the same hydrogeomorphic unit share common properties and function the same.

- In Chapter 5, which deals with characterising wetland types, a similar geomorphic classification approach to that of Semeniuk and Semeniuk (1995) was used in combination with one specifically developed for the study area, based on biophysical characteristics and functional attributes (landscape setting, water table, vegetation and soil). The wetland definition of the National Water Act of 1998 is used as a point of reference. A conceptual model on how wetlands work in order to illustrate how landscape and aquifer properties affect the potential extent and distribution of wetlands is used.

Table 2.2: Wetland hydrogeomorphic (HGM) types typically supporting inland wetlands in South Africa (modified from Ellery *et al.*, 2009a; Kotze *et al.*, 2005; Kotze, 1999)

Hydrogeomorphic type	**Description**	**Source of water maintaining the wetland**[1]	
		Surface	**Sub-surface**
Floodplain 	Valley-bottom areas with a well defined stream channel, gently sloped and characterised by floodplain features such as oxbow depressions and natural levees and the alluvial (by water) transport and deposition of sediment, usually leading to a net accumulation of sediment. Water inputs from main channel (when channel banks overspill) and from adjacent slopes.	***	*
Valley-bottom channelled 	Valley-bottom areas with a well defined stream channel but lacking characteristic floodplain features. May be gently sloped and characterised by the net accumulation of alluvial deposits or may have steeper slopes and be characterised by the net loss of sediment. Water inputs from main channel (when channel banks overspill) and from adjacent slopes.	***	*/ ***
Valley-bottom unchannelled 	Valley-bottom areas with no clearly defined stream channel usually gently sloped and characterised by alluvial sediment deposition, generally leading to a net accumulation of sediment. Water inputs mainly from channel entering the wetland and also from adjacent slopes.	***	*/ ***
Hillslope seepage linked to a stream 	Slopes on hillsides, which are characterised by the colluvial (transported by gravity) movement of materials. Water inputs mainly from sub-surface flow and outflow is usually via a well defined channel connecting the area directly to a stream channel.	*	***
Isolated Hillslope seepage 	Slopes on hillsides, which are characterised by the colluvial (transported by gravity) movement of materials. Water inputs mainly from subsurface flow and outflow are either very limited or through diffuse sub-surface and/or surface flow but with no direct surface water connection to a stream channel.	*	***
Depression (includes Pans) 	A basin shaped area with a closed elevation contour that allows for the accumulation of surface water (i.e. is inward draining). It may also receive sub-surface water. An outlet is usually absent, and therefore this type is usually isolated from the stream channel network.	*/ ***	*/ ***

[1] Precipitation is an important water source and evapotranspiration an important output in all of the above settings

Water source: * Contribution usually small
*** Contribution usually important
*/ *** Contribution may be small or important depending on the local circumstances
 Wetland

2.8 LAND-COVER AND LAND-USE MAPPING

Wetlands can be mapped using remotely sensed imagery based on vegetation characteristics, soils and frequency of flooding (Jensen, 2005). Asner and Heidebrecht (2002) documented the successful application of remote sensing techniques to achieve a better understanding of vegetation cover and condition. Vegetation mapping is one of the most important and extensively used tools to simplify spatial complexity of vegetation cover by incorporating new approaches of remote sensing and spatial environmental correlation through GIS (Mucina and Rutherford, 2006). Remote sensing techniques using Landsat TM imagery may provide a first step in determining spatial and temporal changes to determine permanent and temporary wetlands (Ewart-Smith *et al*., 2006). However, mistakes in remote sensing classification can easily be made on a large scale. Both the South African National Land Cover (NLC) 2000 (NLC2000 Management Committee, 2005) and VegMap 2006 (Mucina and Rutherford, 2006) are limited in showing the spatial extent and distribution of all the wetlands and do not indicate whether the wetlands are permanent or temporarily "wet" (i.e. soil saturated with water). In this chapter the term 'temporary' is used for all non-permanent wetlands that include temporary and seasonal zones of wetness described by DWAF (2005).

2.8.1 Spectral Signature Recognition

Remote sensing has become one of the most important tools in the field of pattern analysis (Benediktsson and Sveinsson, 1997). Remote sensing analysis translates spectral classes into information classes (Jensen, 2005) (e.g. spectral classes for water, vegetation, or concrete and vegetation mix into information classes such as lake, forest or residential). The bands in the visible and shortwave infrared spectral range (blue, green, red and near infrared (~15-20 nm) spectral resolution) are used for mapping vegetation, soil and water in wetland studies (Jensen, 2005). To recognise patterns the extracted features should discriminate between classes (Benediktsson and Sveinsson, 1997; Griffiths and Lee, 2000; Griffith *et al*., 2000). Statistical pattern recognition techniques applied to multispectral remote sensor data is one of the most often used methods of information extraction (Jensen, 2005; Wilson, 2001). This method helps to group pixel information of individual pixels into meaningful land-cover, land-use or vegetation classes based on similar spectral signatures. The actual multispectral classification can be performed using unsupervised and supervised feature extraction methods (Benediktsson and Sveinsson, 1997). The unsupervised classification used in remote sensing mapping allows the computer to group pixels with similar spectral characteristics into unique clusters according to statistical determined criteria. Unsupervised classification is generally used when no ground reference information is available. On the other hand, the analyst carefully defines the classification scheme, ideally supported with ground reference sites to run a supervised classification during the remote sensing mapping procedure.

Landscape classes need to represent land-cover (e.g. water, soil, crops, forest, wetlands) and land-use (e.g. agriculture, forestry, urban areas, infrastructure), which can be used to determine wetland types and land-use stressors impacting them. Change brought about through environmental stressors (e.g. drought) or anthropogenic stressors (e.g. forestry, agriculture) can be determined if one has compatible datasets in terms of information content and data format for different years (GeoTerraImage, 2006) (e.g. satellite imagery acquired from the same sensor for the same area of interest at the same time of the year for different years). Changes in the hydrological regime at landscape level are likely to be manifested in vegetation responses to this change (Taylor *et al*., 2006). For example, drought or human activities such as draining for agriculture will influence the size, extent, texture, pattern and "greenness" and "wetness" of wetlands. The "greenness" refers to the active growth of vegetation (amount of green) and "wetness" refers to the soil moisture in wetlands (NLC2000 Management Committee, 2005). This change can be measured by the percentage area of wetland vegetation replaced by terrestrial vegetation or crops. On the other hand, a wet year associated with an increase in rain, flooding and a rise in the groundwater level might increase the wetland area.

2.8.2 Layered Modeling Approach

Remote sensing and the use of ancillary data may be analysed to extract thematic information in characterising wetland extent and distribution (Jensen, 2005). A layered modeling approach can improve ecosystem characterisation and prediction by using additional primary and derived datasets that possess various levels of measurement (Treitz and Howarth, 2000). Additional sources with attribute information can be used (Ewart-Smith *et al*., 2006) such as aquatic ecosystem features (e.g. wetland layer from 1:50 000 topographical maps), geology (lithostratigraphic units), and vegetation types. A Digital Elevation Model (DEM) can be used to calculate gradient or slope, position in the landscape and depressions or sinks (Webster, 2007). Webster (2007) used terrain-based analysis to generate topographic characteristics such as dune ridges, valleys, midslopes, footslopes, upperslopes and flat surfaces from a DEM. Temporal datasets such as rainfall and spectral signatures from wet and dry years can help to characterise permanent and temporary wetland types. Examples of vegetation and land-cover datasets that followed a layered modelling approach include VegMap 2006 (Mucina and Rutherford, 2006), the KwaZulu-Natal (KZN) wetland layer (beta version) (Scott-Shaw and Escott, 2011) and the National Freshwater Ecosystem Priority Areas (NFEPA) wetland type layer (Nel *et al*., 2011; Driver *et al*., 2011).

The mapping procedure adopted in the VegMap 2006 project recognised environmental factors such as climate, water dynamics, salinity, soil patterns and geology at various scales for mapping vegetation (Mucina and Rutherford, 2006). Proxy data (soil maps, geology maps and modeled climatic surfaces) were used to create physio-geographical units to help map vegetation units. Furthermore, a top-down approach in conceptualising mapping units and a bottom-up approach in building a hierarchy of mapping units (biomes, bioregions) were also applied.

The mapping procedure adopted in the NFEPA project (Nel *et al.,* 2011; Driver *et al.,* 2011) followed an automated wetland typing method, by classifying the National Wetland Inventory (NWM v.3) wetland layer into the National Wetland Classification System (SANBI, 2009b) by using a HGM approach which describes the functional character of the wetlands. On the other hand the KZN wetland layer (Scott-Shaw and Escott, 2011) initially used biogeographical 'zones' based on geological classes, climatological and altitudinal range limits as described in VegMap (Mucina and Rutherford, 2006) to delineate the major wetland groups. Once defined, the classification was further refined based on either features located within these 'zones' such as proximity to river networks (alluvial vs. pan) or according to previous classifications or expert knowledge, e.g. coastal lowland – subtropical freshwater – short grass/sedge; reed; swamp forest wetlands.

In both the NFEPA and KZN projects, landform coverages were determined by using the Jenness Topographic Position Index software. The NFEPA team used ArcMap version and the 20 m DEM with buffer distances using mean valley widths while the KZN team used the add-on to ArcView 3.x and elevation data from the Shuttle Radar Topographic Mission System (SRTM) 90 m DEM.

2.8.3 Limitations in Wetland Mapping

Using spectral signatures to map wetlands (classifying using imagery) is not always an ideal approach because of similar spectral response or overlapping spectral signatures of different land-cover classes to that of wetlands classes. NLC2000 used the “greenness” and “wetness” (2 or 3 information bands) calculated with the Tassel Cap transformation method to map and model wetlands, assuming that all wetlands are either green (i.e. vegetated) or have open water (i.e. are inundated) (NLC2000 Management Committee, 2005). The Tassel Cap transformation enables one to optimise data for vegetation studies. “Greenness” is strongly related to the amount of green vegetation in the image while “wetness” relates to the canopy and soil moisture.

In the grassland biome, wetland features are relatively easy to detect using spectral signatures of “wetness” and “greenness” and can have a mapping accuracy level between 70 and 90%, but the accuracy rate is less in the savannah biome (NLC2000 Management Committee, 2005). Wetlands are not always characterised by one of these two features: “wetness” and “greenness”. The high chlorophyll activity of shrubland and bushland classes might also have a similar spectral response to that of wetlands, especially riparian areas along streams. Spectral signatures can also overlap between wetlands and agricultural crops (Ozesmi and Bauer, 2002) and between swamp forests and other forest types on the MCP (Walsh, 2004). Biotic features such as vegetation growth forms can also influence the ability of the modelling and mapping techniques, e.g. swamp forest wetlands are excluded from the NLC2000 Advance Wetland Layer (AWL) because the land-cover class of “forest” is not included as an input layer in the modelling process to determine areas where wetlands could occur. Also, if temporary wetlands (pans or depressions) were dry during the development of the NLC2000 map, they could not be detected as water bodies or wetlands, and might have been classified as “natural bare rock or soil” (Ewart-Smith *et al.*, 2006). Other factors that limit the use of spectral signatures include fire scars, cloud cover and spatial resolution (Ozesmi and Bauer, 2002; NLC2000 Management Committee, 2005).

CHAPTER 3: LAND-COVER MAPPING

PHOTO: Althea Grundling

3 LAND-COVER MAPPING

3.1 INTRODUCTION

The distribution and inter-annual variability of MCP wetlands are poorly documented, but the variability of their wetted extent provides an opportunity to assess their relative permanence, hence part of their form and function. This, along with the extent of ecological change resulting from land-use change and environmental degradation, is unknown. Monitoring wetland dynamics is required to inform and support management and decision-making related to natural resource utilisation including access to groundwater resources by local communities, outbreak of water-borne diseases like malaria and cholera, and determination of land-use zoning and planning for sustainable resource use. Therefore, this chapter addresses the research question: *How are the wetlands distributed and impacted on the MCP?*

3.2 SPECIFIC OBJECTIVES

1) To use Landsat TM and ETM imagery along with ancillary data to determine the distribution and extent of wetlands on the MCP.
2) To identify and map “permanent” and “temporary” (inland) wetlands and open water based on their spatial extent and distribution during wet and dry years.
3) To determine wetland loss from land-use changes due to cultivation, plantations and urbanisation between 1992 and 2008.

3.3 METHODS

3.3.1 Study Area

The MCP is situated in north-eastern KwaZulu-Natal, South Africa (see Figure 1.3). This mapping chapter will mainly focus on the sub-regional scale (northern study area) with reference to land-cover mapping for the entire MCP and the smaller southern study area (see section 1.5.1).

3.3.2 Rainfall Data

To address the spatial-temporal variability of precipitation events (rainfall), related not only to summer/winter and wet/dry periods but also to extreme weather events, long-term (40-year) rainfall data was acquired from the Agricultural Research Council-Institute for Soil, Climate and Water (ARC-ISCW) climate database (ARC-ISCW, 2009). Additional 23-year total monthly rainfall data for the northern and southern study areas was acquired from the ARC-ISCW (2011) for the period January 1989 to December 2011. Rainfall surfaces were interpolated from ARC-ISCW automatic weather station data and the dekadal (10-day) FEWSNet Rainfall Estimate using the Satellite Enhanced Data Interpolation method (Hoefsloot, 1995). This involved the following steps: 1) extracting values from the Rainfall Estimate and calculating the ratio of weather station and Rainfall Estimate values; 2) using inverse distance weighting to form a regularly spaced grid of the ratios; and 3) multiplying the grid with the Rainfall Estimate grid to obtain the final interpolated rainfall surface. The rainfall data were grouped monthly and annually to determine dry and wet years to facilitate satellite imagery selection. Box-and-whisker plots were placed in hydro-calendar months over the 23 years (Figure 3.1). The long-term rainfall (1989-2012) indicates high summer rainfall from October to March and lower winter rainfall (April to September) (Figure 3.1). Rainfall records indicate that less than average rainfall was received from 2002 to 2012 for the northern and southern study areas (Figure 3.2). The average annual rainfall (586 mm from 2002-2012) for the northern study area was far below the long-term average rainfall of 753 mm (measured over the past 23 years) (Figure 3.2A). Likewise, the average annual rainfall (2002-2012) for the southern study area is 142 mm, far below the long-term average rainfall of 982 mm (measured over the past 23 years) (ARC-ISCW, 2011) (Figure 3.2B). Therefore, Landsat TM imagery was acquired for both 1992 and 2008 (dry years), and Landsat ETM imagery for 2000 (wet year). The latter selection was made because 2000 was the only distinctly wet year in the period of record (Figure 3.2A).

3.3.3 Wetland and Land-Use Mapping

3.3.3.1 Software

All remote sensing analysis was performed using ERDAS 2011 (ERDAS, 2012) and MIPS image processing software. GIS analysis was done using ArcGIS and ArcMap 10 software by ESRI (ESRI, 2012) while MS Excel and Access were used for statistical analysis in wetland and land-use extent calculations. SAS software (SAS, 1999) was used for the rainfall box-and-whisker plots.

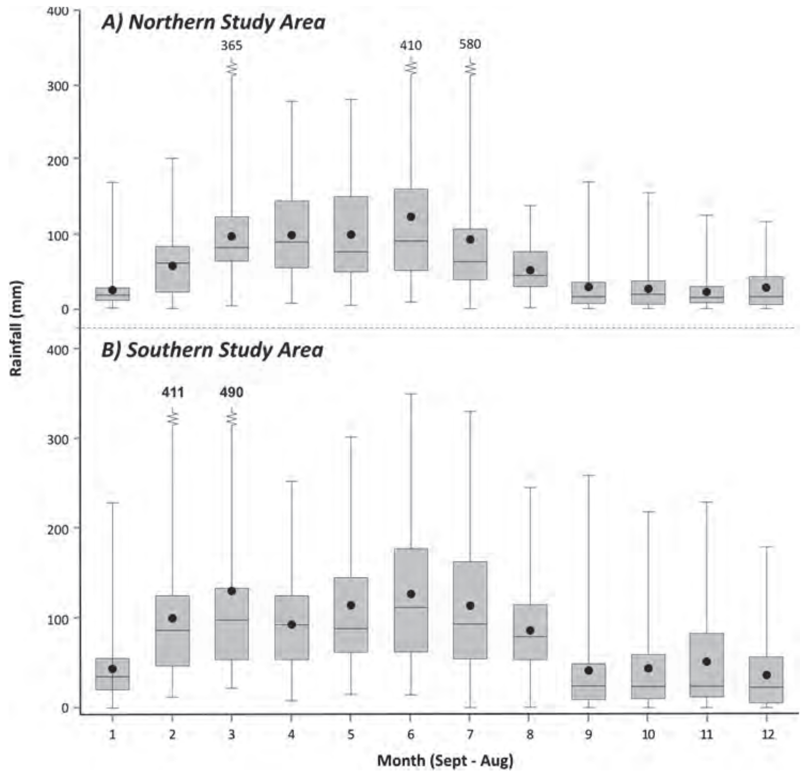


Figure 3.1: Average, minimum and maximum (box-and-whisker plots) rainfall over 23 years (Jan 1989 - March 2012) arranged according to the hydro-calendar (Sept-Aug) in A) northern study area and B) southern study area (ARC-ISCW, 2011). The box is the range in which the rainfall values fall (bottom of box, median (dot), top of box) and the whiskers are the minimum value and maximum values recorded.

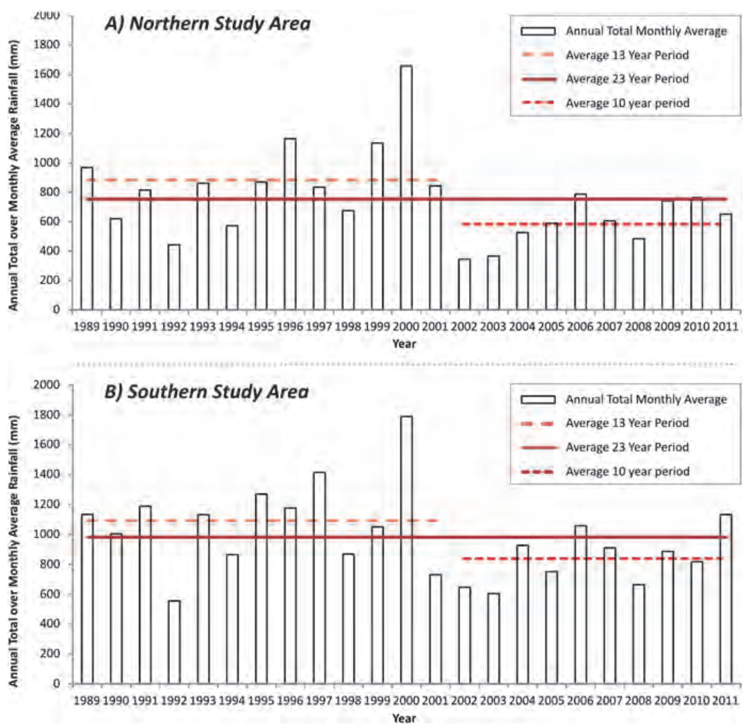


Figure 3.2: The yearly average rainfall measured over the last 23 years in A) northern study area and B) southern study area (ARC-ISCW, 2011).

3.3.3.2 Data Preparation

The moderate resolution Landsat Thematic Mapper (TM) and Landsat Enhanced Thematic Mapper (ETM) data (30 m x 30 m pixel) were used to map the extent of wetlands in dry and wet years. The three assessment years (1992, 2000 and 2008) were selected from the Landsat imagery archive (USGS Global Visualization Viewer, 2010) and acquired through the former Satellite Application Centre. The decision to choose Landsat 1992 (dry year), 2000 (wet year) and 2008 (dry year) imagery was primarily made on the basis of: 1) representation of wet/dry rainfall conditions; 2) availability of images with limited cloud or cloudless conditions; and 3) the images acquired were for the driest month of the requisite year (winter) (July 1992 and September 2000 and 2008). The 1992, 2000 and 2008 Landsat images were orthorectified using the 90 m x 90 m Shuttle Radar Topography Mission (SRTM) DEM (CGIAR-CSI, 2008) and 2002 Global Land Cover network Landsat images as base maps. The orthorectification was done in the original UTM (Universal Transverse Mercator; Datum World Geodetic System 84) projection after which it was re-projected to the Geographic (Datum World Geodetic System 84) projection. Towns, roads, borders (Land Surveyor General, 1980, 1985) and conservation areas (SANBI, 2009a) were sourced, and the study area boundary defined.

3.3.3.3 Data Processing

Landsat images for three different years (1992, 2000 and 2008) were processed by using both un-supervised classification and vegetation indices using pixel-based classifiers in ERDAS Imagine software. The land-cover maps created for the study follow the classification scheme proposed for the Standard Land-Cover Classification for South Africa (Thompson, 1996). The South African National Land-Cover 2000 Project reported that the ERDAS ISODATA clustering classification method (ERDAS, 1999; Thompson *et al.*, 2002) using all the available Landsat TM spectral bands works best for wetlands and for other land-cover classes applied in the National Land-Cover 2000 initiative (Van den Berg *et al.*, 2008). Therefore, an interactive self-organised clustering procedure (ISODATA) classification with 200 classes was created. The 200 classes were interpreted and merged into 14 preliminary land-cover classes before the initial field reconnaissance to create the first draft map. A field reconnaissance trip (21-25 February 2011) was used to select training sites representative of the different classes to be mapped. Only broad wetland, vegetation and land-cover classes were mapped. At each of the 378 observation sites, descriptive information was recorded, geographical positions were determined by means of a Global Positioning System (GPS) and a colour photograph taken at some of the points. The field data were processed and a spatial layer created containing all relevant information for each specific point. Since most of the land in the study area was in conservation areas or in very remote areas, access was limited and data were therefore collected mainly along major, secondary and tertiary roads, depending on the visibility from the roadside edge. The land-cover classification map was created and classification improved using the knowledge gathered during the field reconnaissance to evaluate the first draft classification; and interpretation and refinement based on the information from selected classes from existing ancillary datasets (Table 3.1). The ancillary datasets were only used as guidelines, together with known verification sites, to create areas of interest to classify the different land-cover classes. All the datasets were cut to cover the full extent of the study area. The final classification scheme used for this study

(Table 3.2) is similar to that proposed by Thompson (1996) and GeoTerraImage (2006), with modifications of the wetlands (sedge/moist grasslands) and swamp forest classes; their classification did not distinguish swamp forest from other forest classes, and was not recognised as a wetland class. Two statistical filters were applied to the classifications. In these filters, the middle pixel of the moving window is replaced by the predefined value (mean, median or maximum) of all the pixels within the window (ERDAS Field Guide, 2008). Firstly, a 3 x 3 maximum filter was applied, to assist in the connection of isolated pixels which formed part of linear features such as rivers or inter-dune wetlands. Secondly a 3 x 3 median filter was applied to filter out very small areas which otherwise create a salt and pepper effect.

Table 3.1: Ancillary datasets used to assist in the land-cover classification interpretation

Datasets	**Reference**	**Purpose**
Vegetation map of South Africa, Lesotho and Swaziland	SANBI (2005)	To familiarise with the distribution of subtropical freshwater wetlands and swamp forests on the coastal lowlands
Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM)	CGIAR-CSI (2008)	To determine the elevation (height above sea level)
KwaZulu-Natal (KZN) Province soil and terrain unit map	Van den Berg *et al.* (2009)	To use the valley bottom and foot slope terrain units which are closely associated with wetlands occurrences
National Wetland Inventory (NWI) version 3 National Freshwater Ecosystem Priority Area (NFEPA) wetland types	Nel *et al.* (2011)	To familiarise with the distribution of different wetland types
KZN Wetland layer	Scott-Shaw and Escott (2011)	To re-classify the forest classes (dune, sand, swamp and riverine classes)
KZN Land-Cover 2008	Ezemvelo KZN Wildlife (2011)	To familiarise with the distribution of the wetland class

Table 3.2: Selected land-cover classes (adapted from: Thompson, 1996; GeoTerraImage, 2006)

Class No.	Class Name	Definitions (summarised)
1	Open water	All areas of open water
2	Wetlands (Sedge/moist grassland)	All permanent, temporary fresh water and brackish wetland areas with sedge and/or moist grasslands (i.e. excludes swamp forests)
3	Urban	All urban and built-up areas, irrespective of associated populated residential, commercial or industrial use that includes some mines and quarry areas
4	Grassland	Open grassland with shrubs smaller than 50 cm high (<10% canopy closure)
7	Cultivation	Identifiable areas of commercial, scattered or clustered, small-scale, dryland or wetland cultivation associated with rural dwelling
8	Plantations	All areas of timber plantations and temporary clear-felled stands awaiting re-planting within timber plantations
14	Swamp forest wetlands	Indigenous, dense, tall trees associated with a water source (i.e. river or stream) that grow in permanent wet areas associated with footslope and valley-bottom terrain units (landscape position where wetlands are more likely to occur) with >70% canopy closure

3.3.3.4 Data Analysis

The wetland maps created from the 1992 (dry), 2000 (wet) and 2008 (dry) imagery were used to map the temporal character of the wetlands and open water, based on previously established definitions that include the following:

1) **Permanent wetlands:** areas that are permanently saturated (DWAF, 2005) with soil that is inundated or waterlogged throughout the year, in most years (Thompson *et al.*, 2002). The vegetation is lush green and varies from tall trees (>70% canopy closure) associated with swamp forests, to reed and sedge wetlands and discontinuous permanent wet patches in depressions within the sedge/moist grasslands.

2) **Temporary wetlands:** seasonal wetlands characterised by saturation for 3-10 months of the year, within 50 cm of the surface (DWAF, 2005). This class also includes the temporary areas where the soil close to the surface (i.e. top 50 cm) is wet for periods >2 weeks during the wet season in most years (seldom flooded or saturated at the surface for longer than a month). They can remain dry for more than a year (Thompson *et al.*, 2002). The vegetation cover of temporary wet areas can include moist grasslands with the presence of sedge species (Pretorius, 2011).

In accordance with these previously established wetland definitions, for open water the following are added:

3) **Permanent open water:** inland areas with open surface water such as lakes that exist in all years except the most extreme dry conditions.

4) **Temporary open water:** areas where open surface water occurs only seasonally or in extremely wet years. For the temporal analysis, two steps were used to describe the extent and wetness type (permanent or temporary) of wetlands and open water in the MCP. Firstly, an area comparison was made between the three years by overlaying the wetland and open water layers representing the different years (Figure 3.3). A script was used (Table 3.3) to calculate the sum value for the three years with each pixel value equal to 1. If the total value for the three years was 3, it was considered to be a permanent wetland or permanent open water area. If the total value for the three years was 2 or 1, it was considered to be a temporary wetland or temporary open water area. The second step made use of a simple script in ERDAS to allocate class number to create a "wetness" map that distinguishes permanent and temporary wetlands and open water.

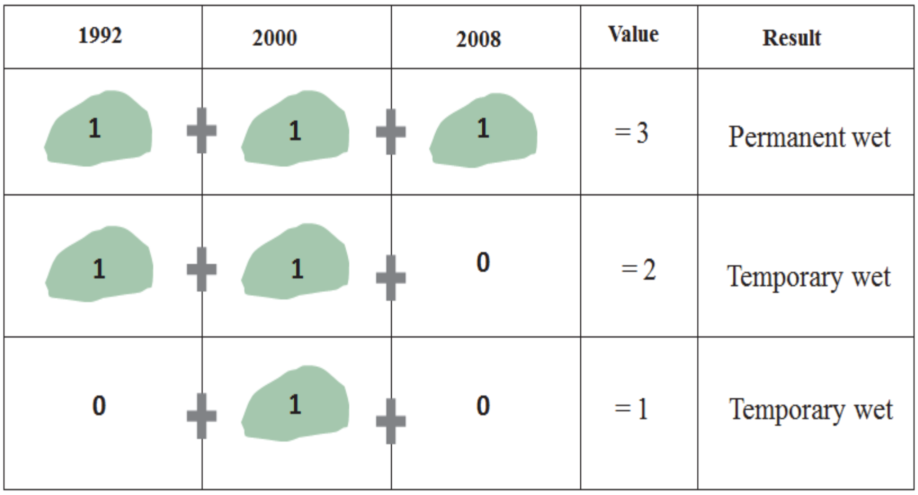


Figure 3.3: Area comparison to determine permanent and non-permanent water and wetlands.

Table 3.3: ERDAS script to allocate class number for new map

Wetland Class	**Script**
Open water	If (raster 1992 = water) and (raster 2000 = water) and (raster 2008 = water) then class 4 (water)
Temporary water Inundated wetland	If (raster 1992 = water) or (raster 2000 = water) or (raster 2008 = water) then class 3 (non-permanent water)
Permanent wetland Saturated and inundated	If (raster 1992 = wetland) and (raster 2000 = wetland) and (raster 2008 = wetland) then class 2 (permanent wetland)
Temporary wetland	If (raster 1992 = wetland) or (raster 2000 = wetland) or (raster 2008 = wetland) then class 1 (non-permanent wetland)

For land-cover change analysis, all three datasets were used to describe the extent of wetlands and land-use classes during the three different years (1992, 2000 and 2008). Comparative tables were completed, summarising the area and percentages of the following land-cover classes over the three assessment years. Comparison between the three mapping years (1992, 2000 and 2008) was used to quantify the change within the landscape classes from one year to the next. Finally the wetness map (permanent and temporary wetland and open water product using all three years) was compared with the 2008 land-use map to quantify the wetlands that were impacted by land-use.

3.3.3.5 Accuracy Assessment

The accuracy assessment analyses were done using two methods:

3.3.3.5.1 Error Matrix

The land-cover accuracy statistics were calculated using an error matrix (confusion matrix), usually represented in terms of overall, user's and producer's accuracy to compare the land-cover classes derived from satellite image classification with referenced sample points acquired in the same year (Stehman and Czaplewski, 1998; Shao and Wu, 2008). The accuracy assessment data were collected from two independent datasets, the National Alien Invasive Plant Survey (NAIPS) database (Kotze *et al.*, 2010) and Google Earth satellite data (Google Inc., 2011). The NAIPS database points were produced using a stratification process that includes the use of NDVI and terrain unit classes, land-cover classes and bioregion information (Figure 3.4). The survey was performed in 2008 using a fixed-wing aircraft. A digital photo was taken at each point. Each point was assigned a land-cover code using an interpretation of the photo and high resolution Google Earth satellite images. The dominant land-cover class in a 100 m x 100 m area was used for the accuracy assessment database. All classification accuracies were calculated on the final filtered version of the 2008 Landsat TM classification dataset for the entire Maputaland Coastal Plain that includes the smaller study area. A total of 1753 reference points were used to calculate the overall mapping accuracy. Accuracy results included overall land-cover classification accuracy as well as omission and commission error percentages for the full 2008 classification. No field verification data or high resolution satellite images were available for the 1992 and 2000 assessment years.

3.3.3.5.2 Land Cover Change Analysis

The land-cover change analysis used the Two-date Sequence Logic Review modelling procedure (Schoeman *et al.*, 2010) to ensure compilation of comparable and standardised land-cover class allocations, prior to any year-on-year change analyses. A uniform grid (100 m x 100 m cells) over the study area was used to compare the three assessment years using MS Access 2008 software. The 100 m x 100 m cell size was selected to correspond with the minimum mapping unit associated with the Landsat datasets. The land-cover class allocated to each cell represented the spatially dominant feature within that cell, as determined from the original land-cover mapping datasets for the three years. The database calculated changes in land-cover class between the different assessment years that are likely to occur and those that are not likely to occur based on a probability list with 132 probabilities. For example, if the pixel in the first and second assessment year was water, this is not likely to be a mapping error; but if it is water in the first assessment and woodland in the second assessment, then this is likely to be a mapping error. The changes are in percentage values, indicating the percentage of the original cells that have changed to another class.

Figure 3.4: The NAIPS database points on the MCP used in the accuracy assessment analysis.

3.4 RESULTS

3.4.1 Land-Cover Mapping for the Entire MCP

KwaZulu-Natal Province (9 436 132 ha) has the highest (4%) distribution of wetlands and wetland types in South Africa (SANBI, 2010). The Landsat TM image was acquired in September 2008. The land-cover classes mapped for the entire MCP (Figure 3.5 and Table 3.4) indicate that wetland distribution was 7.70% and swamp forest was 1.03%. Different types of surface water bodies such as rivers, floodplains, estuaries, pans and coastal lakes occur on the MCP. The total open water area mapped was 4.72%. Main land-use on the MCP was cultivation (16.11%), followed by plantations (12.13%), while urban covers only 1.63%. Protected areas like the iSimangaliso Wetland Park, the Tembe Elephant Park and the Ndumo Game Reserve are located in the MCP, while large areas are rural and undeveloped.

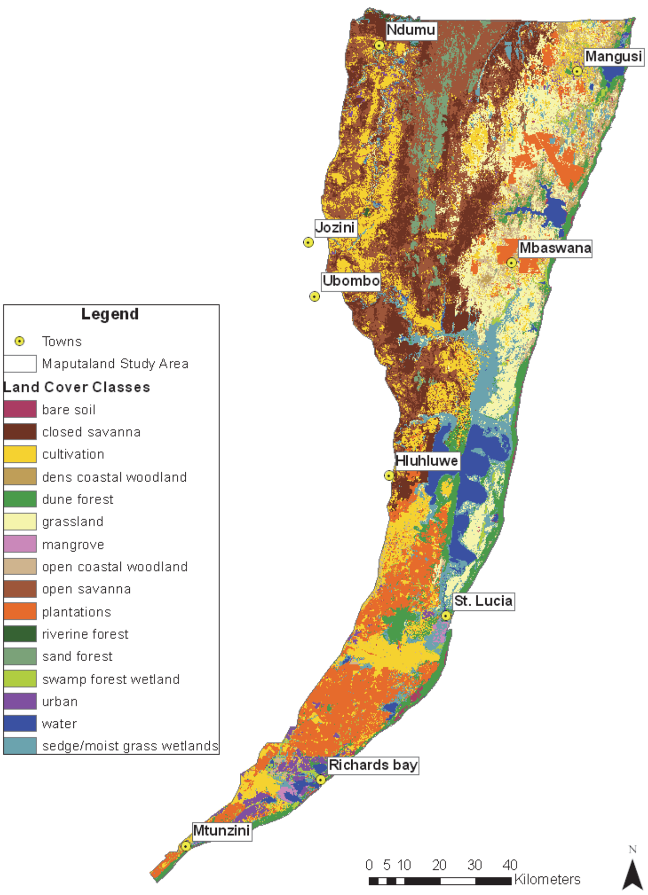


Figure 3.5: Mapped areas for the MCP from Landsat (September 2008).

Table 3.4: Mapped areas for the MCP

	2008			2008	
Classes	**ha**	**%**	**Classes**	**ha**	**%**
water	42 362.19	4.72	clouds and shadow	0	0.00
wetlands	69 122.79	7.70	mangrove	2 338.47	0.26
urban	14 645.88	1.63	sand forest	22 956.39	2.56
grassland	100 463.40	11.19	riverine forest	1 696.14	0.19
closed savanna	102 029.00	11.37	swamp forest	9 277.29	1.03
open savanna	171 109.70	19.07	dune forest	57 633.75	6.42
cultivation	144 592.40	16.11	dense coastal woodland	17 432.64	1.94
plantations	108 852.40	12.13	open coastal woodland	27 219.24	3.03
bare soil	5 671.53	0.63			
TOTAL				**897 403.20**	

3.4.2 Northern Study Area

3.4.2.1 Permanent and Temporary Wetlands and Open Water

The nature of the aquifer, topography and rainfall distribution (hydrogeomorphic setting) is related to the wetland distribution and temporal character. The topography (Figure 3.6A) reflects the regional geological template that slopes towards the east, and is superimposed by more recent dune formations. The upland is an area of higher ground (≥50 m.a.s.l.) separating lower-lying areas west and east (<50 m.a.s.l.). The criterion of 50 m.a.s.l was used as it is recorded in literature that peatlands, which formed under permanent wet conditions, occur below that altitude (Grundling, 2001). There is also a precipitation (rainfall) gradient: rainfall decreases from east (>820 mm) to west (680 mm) (ARC-ISCW, 2009) (Figure 3.6B).

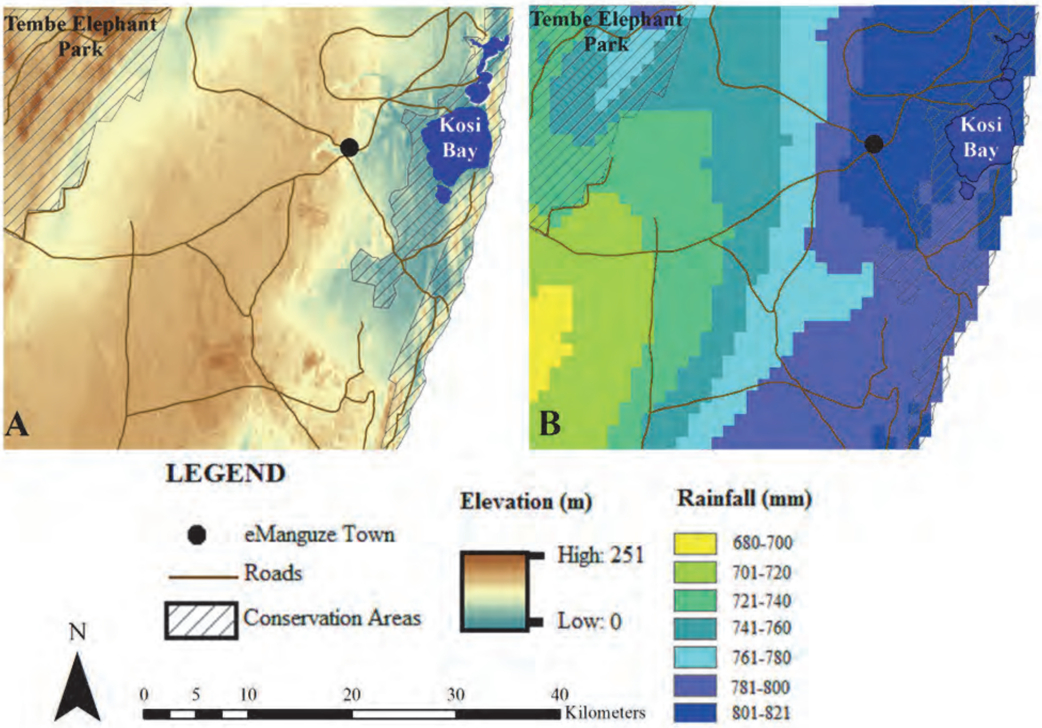


Figure 3.6: Elevation (A) and long-term rainfall distribution (B) of the study area.

A wetness map showing temporary and permanent wetlands and open water was created by overlaying the occurrence of swamp forest and sedge/moist grassland and open water classes for each year (1992, 2000 and 2008 shown in Figure 3.7A-C). Wetlands cover ~18% of the total study area. For 2000 (wettest year) this includes sedge/moist grassland (~16%) and swamp forest (~2%); open water comprises ~3% of the total study area including the Kosi Bay lake system (Table 3.5). The permanent wetlands (swamp forest, reed/sedge wetlands and a mosaic of discontinuous permanent wet patches in depressions within the sedge/moist grasslands wetlands) comprise 15% of the total wetland and open water area, while temporary wetlands (sedge/moist grasslands) cover 72% of the total wetland and open water area (Figure 3.7D). The sedge/moist grassland wetlands on the uplands (50-82 m.a.s.l.) are flooded during large rainfall events (e.g. the floods in 2000). These wetlands can be temporarily inundated with open water during very wet years for a short period (Figure 3.7 D).

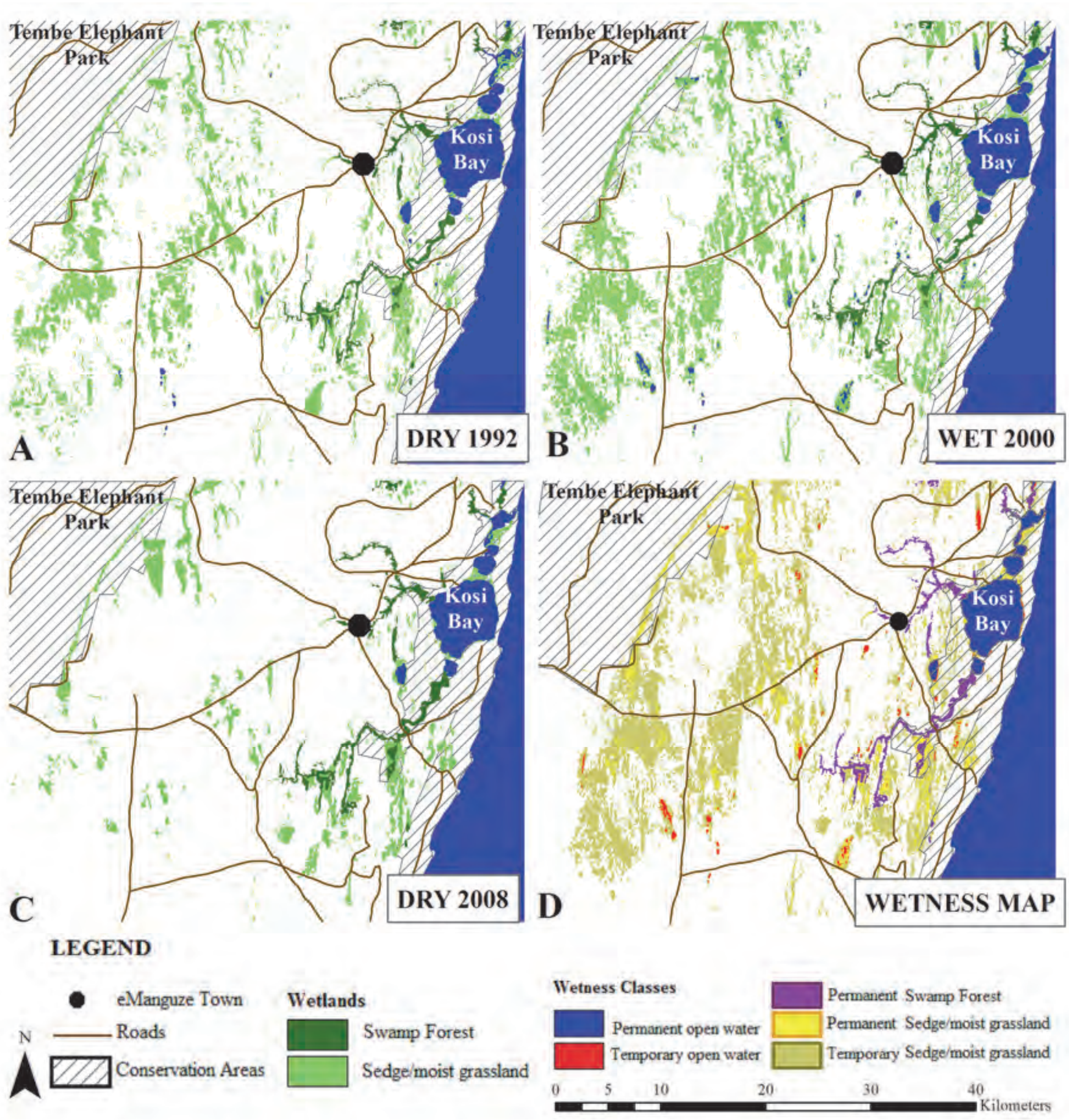


Figure 3.7: Wetland distribution in dry years (A and C), wet year (B) and wetness map with permanent and temporary wetlands and open water areas (D).

Table 3.5: Selected land-cover class areas for 1992, 2000 and 2008 expressed as a percentage and in hectares (ha)

Land-cover Class	Northern Study Area					
	1992		2000		2008	
	%	ha	%	ha	%	ha
Open water	2.48	4201	2.84	4781	2.34	3951
Wetlands (Sedge/moist grassland)	11.14	18845	15.97	26908	4.96	8373
Wetlands (Swamp forest)	1.39	2352	1.58	2655	1.63	2751
Grassland	19.03	32202	16.98	28619	23.76	40089
Cultivation	17.16	29028	15.14	25523	11.12	18764
Plantations	6.96	11782	9.60	16176	8.85	14929
Urban	0.07	119	0.10	163	0.87	1472

3.4.2.2 Land-Cover Change Analysis: Wetland Loss and Land-Use Change

Figure 3.8 indicates the open water, grasslands, urban, cultivation and plantations classes for both dry years (1992 and 2008). These are only five of the eighteen land-cover classes mapped for the MCP. Table 3.5 summarises the results for open water, sedge/moist grass wetlands, swamp forests, grasslands, urban, cultivation and plantations classes mapped for all three years. Comparing the percentage area for all the land-cover classes for the entire study area in both the dry years (1992 and 2008), open water, swamp forest, plantations and urban areas all changed by less than 2.64% (Table 3.5). However, the plantation area (south) (Figure 3.8) had bare soil and clear-felled stands (areas awaiting re-planting in September 2008) that were not calculated in the plantation class for 2008. Accurate mapping of swamp forest were problematic, and the results in Table 3.5 shows that swamp forest cover slightly increased. However, swamp forest loss has been reported due to the slash-burn and draining of these systems for cultivation purposes (Grobler *et al.*, 2004; Sliva, 2004). There was a slight increase in the urban and plantation classes (Table 3.5). In contrast, sedge/moist grassland wetlands, grasslands and cultivation areas changed considerably between dry years and between wet and dry years. The wetland (sedge/moist grassland) areas decreased from 11% in 1992 to 5% in 2008 (Table 3.5). The results for the wet year (2000) (Figure 4B) indicate a larger wetland extent (16%) (Table 3.5). Some of the areas that appear to be grassland in the dry years are actually wetland, based on the wet year image (2000). Grassland areas in dry years range from 19% (1992) to 24% (2008) (Table 3.5). Cultivation areas in 1992 were more (17%) than in 2000 (15%) and 2008 (11%) (Table 3.5). The cultivation, plantation and urban distribution pattern changed significantly from 1992 to 2008 (Figure 3.8A and B). Cultivated and urban areas became more prominent near the town of eManguze and the main road network instead of being dispersed throughout the landscape, while plantations spread across the study area (Figure 3.8B).

Results from comparing the known permanent and temporary wetlands and open water areas (Figure 3.7D) with 2008 land-cover classes (Figure 3.8B) indicate that temporary sedge/moist grassland wetlands have been replaced by 883 ha of plantation. Urban development affected 96 ha of temporary and 31 ha of permanent sedge/moist grassland wetlands. Although cultivation areas were the lowest in 2008 (compared with 1992 and 2000) (Table 3.5), the importance of wetland utilisation for cultivation practices should not be overlooked as

4212 ha temporary sedge/most grasslands wetlands, 19 ha permanent wetlands and 37 ha temporary open water areas changed to cultivated area.

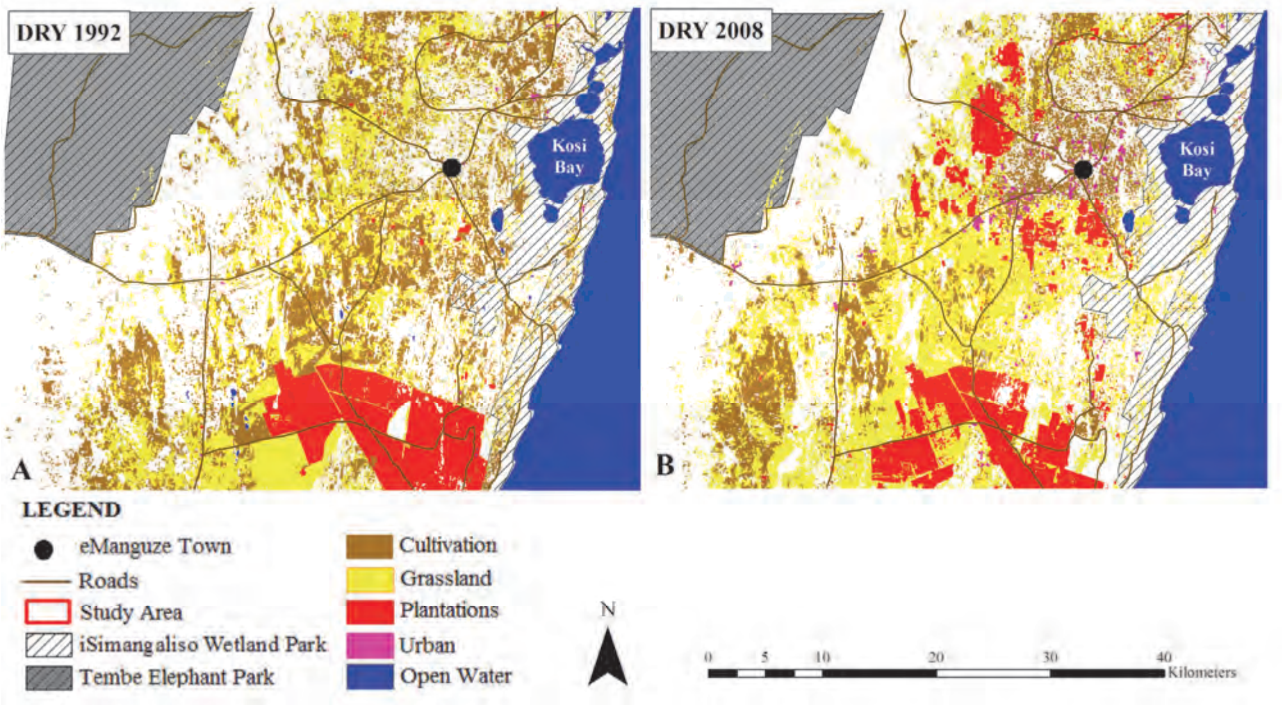


Figure 3.8: Comparing land-cover classification maps for the dry years 1992 (A) and 2008 (B).

3.4.3 Southern Study Area

3.4.3.1 Permanent and Temporary Wetlands and Open Water

Comparison of wetland (swamp forest and sedge/moist grassland) and open water classes was made between the three different years (1992, 2000 and 2008) by overlaying the layers and calculating an index of change. If the pixel value was wetland or open water in both years it was considered permanent but if the pixel value was only classified wetland or open water in 2 or 1 of the years, it was considered to be a temporary wetland or temporary open water area. The permanent wetlands including swamp forests and sedge/moist grassland, the temporary sedge/moist grassland wetlands as well as the permanent and temporary open water areas are shown in Figure 3.9B. Table 3.6 lists the percentage cover for the water and wetland areas for the southern study area. In the southern study area the permanent wetlands cover 19.57%. The large permanent open water areas include Lake St. Lucia (20 255 ha) and Lake Bangazi (268 ha). The temporary wetlands (sedge and moist grasslands) cover 24.41% while temporary open water is 10.16%.

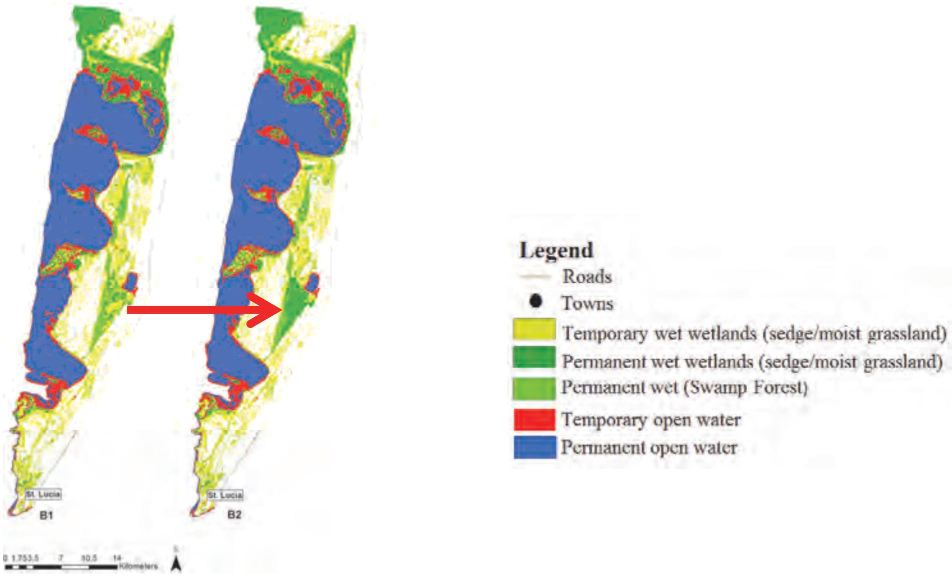


Figure 3.9: Wetland and water analysis maps for the southern study area. The Mfabeni sedge fen (red arrow) indicates a dry area mapped within it in B1 which has been corrected in B2, highlighting limitations in mapping.

Table 3.6: Wetland and water area calculations for the southern study area

	Southern Study Area		
Class	**Count**	**ha**	**%**
Temporary wetlands	121360	10922.4	24.41
Permanent wetlands	97314	8758.26	19.57
Temporary open water	50493	4544.37	10.16
Permanent open water	228038	20523.42	45.86
		44748.45	**100.00**

3.4.3.2 Land-Cover Change Analysis: Wetland Loss and Land-Use Change

The removal of plantations can clearly be seen in Figure 3.10 and Table 3.7 (5.70% in 1992, 3.43% in 2000 and 0% in 2008). No cultivation is practised in the conservation area.

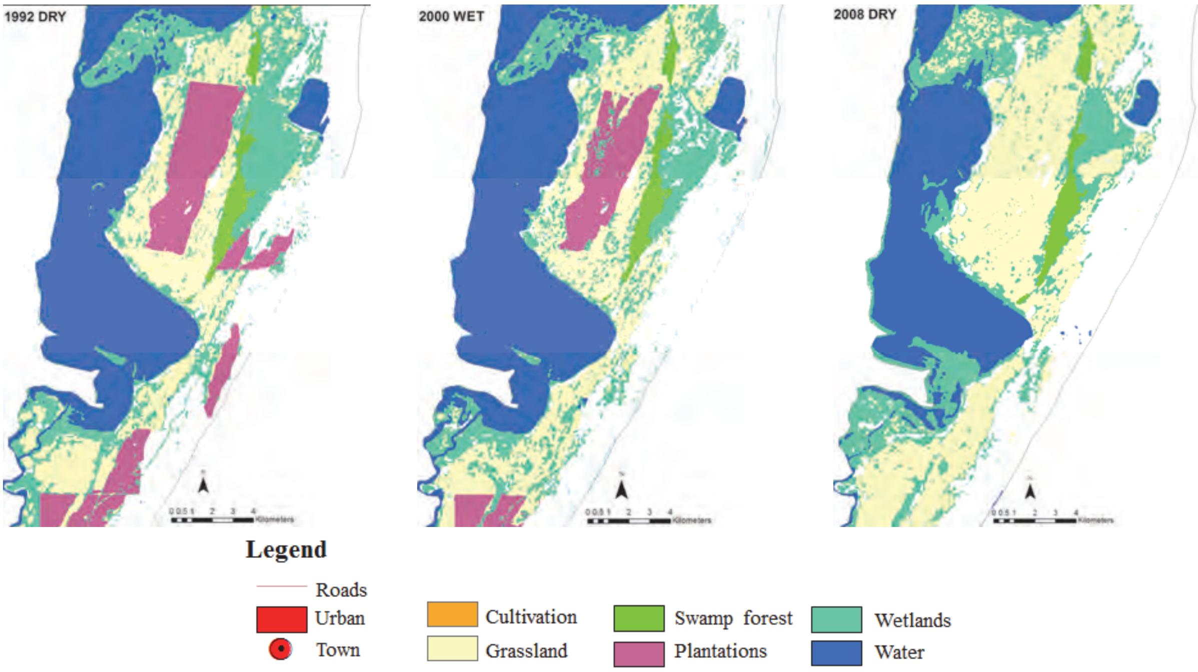


Figure 3.10: Southern study area maps for different years showing only seven selected classes (zoomed in area).

Table 3.7: Area calculations for all the classes mapped on the southern study area

	1992 ha	**%**	**2000 ha**	**%**	**2008 ha**	**%**
water	24 187.32	38.65	24 791.22	39.85	20 208.15	33.22
wetlands	14 639.31	23.39	13 552.29	21.78	15 467.49	25.43
urban	53.73	0.09	64.26	0.10	111.96	0.18
grassland	9 073.62	14.50	9 968.04	16.02	12 643.38	20.79
closed savanna	0	0.00	0	0.00	1.08	0.00
open savanna	0	0.00	0	0.00	5.94	0.01
cultivation	0	0.00	0	0.00	21.51	0.04
plantations	3 568.05	5.70	2 132.19	3.43	1.35	0.00
bare soil	1 237.23	1.98	725.85	1.17	983.79	1.62
clouds and shadow	0.09	0.00	0.63	0.00	0	0.00
mangrove	38.07	0.06	36.27	0.06	0	0.00
sand forest	0	0.00	0	0.00	0	0.00
riverine forest	0	0.00	0	0.00	0	0.00
swamp forest	932.22	1.49	999.27	1.61	1 065.60	1.75
dune forest	8 659.44	13.84	9 694.17	15.58	10 084.86	16.58
dense coastal woodland	0	0.00	0	0.00	23.04	0.04
open coastal woodland	193.86	0.31	245.43	0.39	211.14	0.35
TOTAL	**62 582.94**		**62 209.62**		**60 829.29**	

3.5 DISCUSSION

3.5.1 Northern Study Area

3.5.1.1 Permanent and Temporary Wetlands and Open Water Areas

The distribution of permanent and temporary wetlands and open water are related to the hydrological and geomorphological processes on the MCP. The upland (50-82 m.a.s.l.) has a greater proportion of temporary sedge/moist grassland wetlands whilst lowland areas (1-50 m.a.s.l.), where precipitation is also higher, host most of the permanent wetlands, including swamp forest, as well as some temporary wetlands and most of the permanent open water (Figure 3.7D). Groundwater recharge takes place when there is sufficient rainfall, while groundwater discharge occurs in low-lying areas, facilitated by the underlying regional geology that slopes towards the east. Consequently, the permanent open water areas (Kosi Bay lakes system and Lake Shengeza) which represent 2-3% of the study area, and all of the swamp forest are congruent with the high water table in the coastal region. Swamp forests covered only ~2% of the study area and are restricted to incised valley bottoms associated with drainage lines intercepting the regional water table that ensure permanently wet conditions. The sedge/moist grassland wetlands that occur primarily on the uplands cover ~5% of the study area and are associated with interdune depressions and upland depressions as well as some valley bottoms. The sedge/moist grassland wetlands on the uplands are flooded during large rainfall events (e.g. the floods in 2000). In locations where the depression intercepts the water table throughout the year it is permanently wet, but where the base is elevated relative to the water table, the wetlands are only wet during high rainfall events. The temporary sedge/moist grasslands on the upland are vital recharge areas that contribute to the regional groundwater resource, and hence may be undervalued habitat.

3.5.1.2 Land-Cover Change Analysis: Wetland Loss and Land-Use Change

The change in spatial land-use distribution from 1992 to 2008 exhibited a slight increase in urban (+1 353 ha) and plantation (+3 147 ha) areas and a decrease in cultivation practices (by 10 264 ha). The increase in tourism and entrepreneurial activities near the town of eManguze, close to the Mozambique border, may explain the slight increase and definite change in spatial distribution of urban, plantation and cultivation land-use classes. The 11% temporary sedge/moist grassland wetlands loss by 2008 can be directly linked to land-use change (by 883 ha plantation, 96 ha urban development and 4 212 ha cultivation) that replaced these wetlands and the drop in water table resulting in the temporary wetlands that appear as grassland. The indirect impact of water abstraction (Schapers, 2012) and evapotranspiration by plantations on wetland function and distribution is unknown and is therefore a major research need.

3.5.2 Southern Study Area

Figure 3.10 indicates a 2.4% increase in wetland (sedge/moist grassland) extent, comparing the two dry years (1992 and 2008). Similar spectral signatures of sedge/moist grasslands (Figure 3.11) made it difficult to map because of the limited contrast between aquatic and terrestrial areas, e.g. the grassland area mapped in the Mfabeni mire in 2008 (Figure 3.9B1 and B2) highlights limitations in the mapping due to similar spectral signatures (Figure 3.11).

Another explanation could be that 2008 was a dry year and the area mapped as grassland has a higher elevation due to a sand lens (Figure 3.9B1). This area becomes drier than the rest of the Mfabeni mire. Similar spectral signatures for swamp, dune and riverine forest had to be refined further.

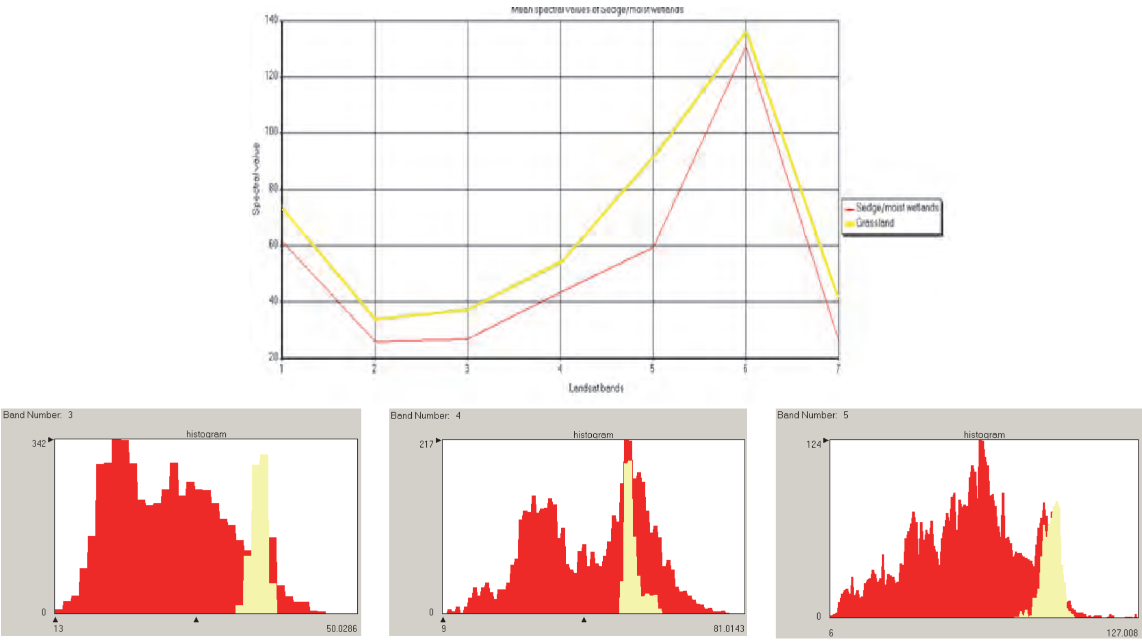


Figure 3.11: Similar spectral signatures of sedge/moist grassland and grassland in bands 3, 4 and 5.

3.5.3 Accuracy Assessment

Accuracy assessment was performed using an error matrix (Table 3.8). Using the known verified points for the land-cover classes from an independent validated dataset (Kotze *et al.*, 2010) against the classification data for each land-cover class (represent the pixels classified as a specific land-cover class) one can calculate the accuracy for each land-cover class as well as the overall mapping accuracy for the dataset. The overall land-cover/wetland mapping accuracy for the entire Maputaland Coastal Plain dataset (not the smaller study area), derived from single date 2008 Landsat TM satellite imagery, was 80% (Table 3.8).

Table 3.8: Error matrix with verified points for land-cover classes (rows) vs. the classified cases for each land-cover class (columns)

		Classification data										
		Water	Wetland	Urban	Grassland	Cultivation	Plantation	Bare Soil	Swamp Forest	Woodland/ Savanna/ Forest	Total	Producer's Accuracy (%)
Verified points	**Water**	**16**	1		0	1	0	0	1	0	19	84
	Wetland	1	**114**		17	4	0	0	2	12	150	76
	Urban			**0**							0	
	Grassland	0	13	2	**351**	73	7	3	3	73	525	67
	Cultivation	0	2	3	5	**92**	3	0		18	123	75
	Plantation	0	2		1	4	**45**	1		5	58	78
	Bare Soil	0	0		0	0	0	**12**		0	12	100
	Swamp Forest								**2**		2	100
	Woodland/ Savanna/Forest	0	11		28	20	12	0	21	**782**	874	89
	Total	17	143	5	402	194	67	16	29	890	1763	
	User's Accuracy (%)	94	80	0	87	47	67	75	7	88		
											Overall Accuracy (%)	**80**

High mapping confidence (75-100%) was obtained for land-cover classes: water, wetlands (sedge/moist grasslands), cultivation, plantation and bare soil. The urban and swamp forest classes gave unsatisfactory results because the number of independent points representing these areas were few and both classes represent small areas on the MCP. The grassland class obtained 67% due to the overlap with cultivation practices and temporary wetlands. The woodland, savanna and other forest classes (e.g. dune forest, sand forest) were grouped because these classes were difficult to map due to the similar spectral signatures and they were not of concern for the study. The 80% mapping accuracy for the 2008 Maputaland dataset compares well with the NLC2000 land-cover dataset (average accuracy 48.5%) that also used Landsat imagery and a similar mapping procedure (Van den Berg *et al.*, 2008). The same mapping technique was used for both 1992 and 2000 but no independent dataset with verified points exists for these years to calculate the mapping accuracy.

The Two-date Sequence Logic Review analysis was used to determine errors in change detection that resulted from the original land-cover mapping misclassifications. The database calculated changes in land-cover class between the different assessment years in percentage values, indicating the percentage of the original cells that have changed to another class. The highest percentage errors occurred between cultivated and grassland classes (33-41%), between wetland and grassland classes (34%) and between bare soil and cultivation classes (26%). Ozesmi and Bauer (2002) indicated that the overlap in spectral signatures between wetlands and other land-cover classes such as agricultural crops and upland forests can result in errors. The cultivation class mainly represents areas outside the swamp forests in open grassland areas and in sedge/moist grassland wetlands because cultivation activities inside the swamp forests are covered (hidden) by the tree canopy, or in some instances the gardens are too small for a single pixel to be mapped as cultivation. The higher cultivation (17%) in 1992 could be because grassland areas were classed as cultivation due to the low grass cover in a dry year, similar to dry cultivated lands. Mapping of swamp forest and sedge/moist grassland wetland types indicates that Landsat classification did well in mapping the latter but the swamp forest wetland type proved to be more difficult. The resolution of the Landsat imagery (30 m) is not optimal to map swamp forests because of their relatively narrow linear form and similar spectral signatures compared to dune forests and sand forests (Walsh, 2004), but can be used for larger sedge/moist grassland wetlands. Swamp forests could not be classified without support from ancillary datasets, e.g. vegetation maps. Care must be given in the interpretation of swamp forest extent for the different years; it seems as if this wetland type increased, but field visits and other work indicated swamp forest loss due to cultivation practices.

The advantages of using Landsat data are: 1) the images are free; 2) an archive of historic data is available for large areas of the world; 3) Landsat TM and Landsat ETM has 7 multispectral bands, with good spectral information; 4) limited image processing time is needed; and 5) it is effective in monitoring the wetland dynamics between wet and dry years and land-use change on a regional scale. SPOT imagery, in contrast, is not so readily available and has limited spectral bands.

Availability of the images for specific years can affect the classification accuracy, e.g. 1992 was the driest year early in the study period, while 2008 was chosen to represent dry conditions in the latter part of the study, although 2002 and 2003 were even drier years; however, those images were unavailable. Moreover, 2008 followed a sequence of dry years so lag effects from prior wet years were less likely. The implication of assessing the spatial patterns based on imagery from a dry year (e.g. 1992) in a relatively wet period (Figure 3.2) is that one would be likely to overestimate the coverage of permanent wetlands, while in extremely wet years (e.g. 2000), temporary wetlands would be overestimated. During the very wet years wetlands can be temporarily inundated with open water for a short period. The spatial scale of the sensor is the most important factor in separation of temporary open water classes with temporary wetlands in this type of wetland environment. Ramsey and Laine (1997) reported that classifications derived from Landsat TM images provided good class separation when one class dominated more extensive areas (>1 ha), but not when mixtures of water and wetland vegetation were of the same order as the Landsat TM sensor spatial resolution (30 m). Using data over several more years, instead of only three, and images for each wet and dry season, might prove to be more successful in mapping the temporal stages and extents of wetlands and open water. The seasonality and annual rainfall of the study area need to be considered. Rainfall variability over the study area, as well as during the season, induces change in the growth and composition of vegetation and can lead to changes in the spectral signature of the land surface. The accessibility of the study areas to gather verification points for the classification were limited due to deep sandy soils, overgrown dirt roads and access entering conservation areas. This also has an implication on the accuracy of the classification.

3.6 CONCLUSION

This study has demonstrated the capability of using Landsat remote sensing imagery with ancillary datasets to establish wetland extent and permanence, as well as land-use activities (plantations, cultivation and urban classes) and change, bearing in mind the spatial limitations of Landsat (e.g. wetlands and croplands <1 ha and cultivated fields in swamp forests will be difficult to map). The ambiguity between classes: cultivation and grassland; temporal wetland and grassland; and bare soil and cultivation need to be highlighted. These classes are closely related and driven by seasons and wet and dry periods; this is evident in the study area where abandoned gardens on temporary wetlands have become covered by grassland because of drier conditions. Similar spectral signatures of swamp forests with other forest types (dune and sand forests), as well as their relatively narrow linear form, pose a problem to accurately mapping swamp forests; they could not be classified without the support from ancillary datasets such as vegetation maps. Urban areas, characterised by open bare soil, house structures and small croplands made class separation difficult. The combination of Landsat imagery with ancillary data shows that land-use activities and drought have reduced wetland extent and distribution by 11%. Wetlands loss is a significant problem for the local communities that depend on them as a natural resource and illustrates the need for improved management by all stakeholders. The permanent and temporary wetland map and land-use impact assessment on wetlands can help to underline the wetland function and vulnerability and guide land-use practices that have a direct and indirect effect on them. Improvements to this method (e.g. Landsat imagery with supporting ancillary data such as maps for wetland vegetation, cultivation and urban classes from high resolution spectral and spatial resolution imagery) can be applied to similar coastal areas, such as the MCP in Mozambique, supporting future research.

CHAPTER 4: HYDROGEOMORPHIC CLASSIFICATION

PHOTO: Althea Grundling

4 HYDROGEOMORPHIC CLASSIFICATION

4.1 INTRODUCTION

The hydrogeomorphic classification developed by Brinson (1993) to assign wetland functioning through the consideration of geomorphic setting, water source and hydrodynamics has been adopted as the basis for the Classification System for Wetlands and other Aquatic Ecosystems in South Africa (SANBI, 2009b; Ollis *et al.*, 2013). However, an underlying assumption of the hydrogeomorphic wetland classification concept is that aquatic ecosystems function slightly differently in different landscape settings and that wetlands belonging to the same hydrogeomorphic unit share common features in terms of environmental drivers and processes. Although widely applied in South Africa this underlying assumption has yet to be tested. Other hydrogeomorphic typing initiatives include the wetland ecosystem type map, product of the National Freshwater Ecosystem Priority Areas (NFEPA) (Nel *et al.*, 2011; Driver *et al.*, 2011) which describes wetlands according to levels 2, 3 and 4 (Van Deventer, 2010) using the hydrogeomorphic classification approach (Mbona *et al.*, 2010). GIS techniques and existing data were used in an automated approach to classify the wetland ecosystem types. However, Nel *et al.* (2011) recommended further investigation into the automation of the classification system, based on a thorough review of the availability of information required to distinguish one wetland type from another. Ollis *et al.* (2013) stressed that there is an urgent need to test and refine the Classification System for Wetlands and other Aquatic Ecosystems in South Africa by incorporating knowledge supported by research on how wetlands and other inland aquatic ecosystems function. In this chapter the hydrogeomorphic classification is applied to answer the research questions: *What types of wetlands are found on the MCP and what regional environmental factors control this distribution, i.e. do wetlands belonging to the same hydrogeomorphic unit share common features in terms of environmental drivers and processes?*

4.2 SPECIFIC OBJECTIVES

1) To identify the different hydrogeomorphic wetland types and determine if wetlands that belong to the same hydrogeomorphic unit share common features in terms of environmental drivers and processes.
2) To investigate their relationship with environmental factors such as water table, rainfall, and elevation.
3) To apply the hydrogeomorphic wetland classification in the study area.
4) To compare verification sites with the National Freshwater Ecosystem Priority Areas (NFEPA) project wetland type layer.

4.3 METHODS

4.3.1 Northern Study Area

This chapter will mainly focus on the northern study area (sub-regional scale) (see Figure 1.3 in section 1.5.1). The MCP is characterised by the relatively flat, low relief, undulating dune landscape of the coastal plain bordering the Lebombo Mountains in the west and the Indian Ocean in the east (Figure 4.1.B) (Scott-Shaw and Escott, 2011). The study area (~250 000 ha) was used as a study site because it hosts a diverse set of wetlands and supporting baseline data are available to assist in the hydrogeomorphic classification process.

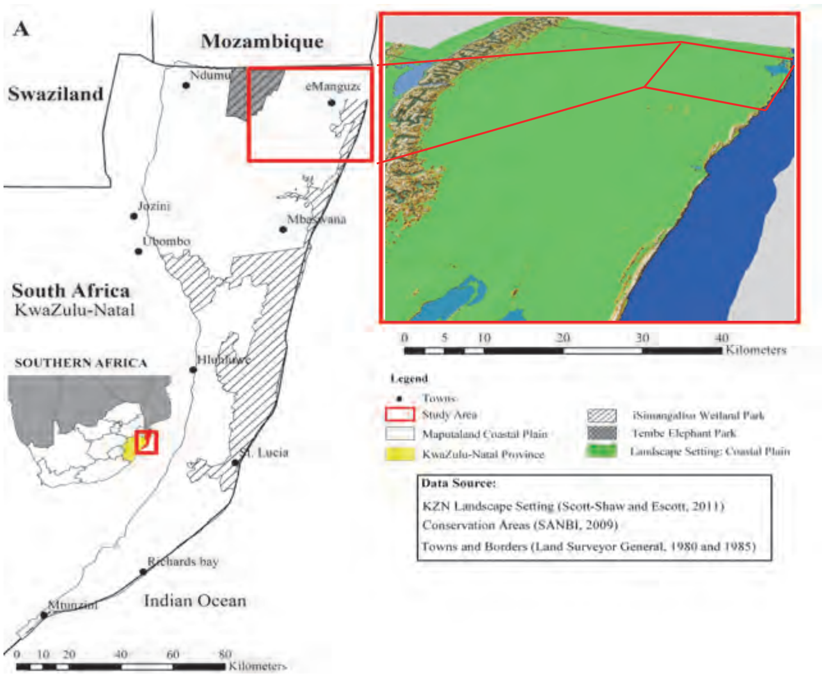


Figure 4.1: Landscape setting of the study area with conservation areas (SANBI, 2009a).

4.3.2 Hydrogeomorphic Classification System

The Classification System for Wetlands and other Aquatic Ecosystems in South Africa adapted the hydrogeomorphic classification system (Ollis *et al.*, 2013; SANBI, 2009b). This system has a six-tiered structure with four spatially-nested primary levels, applied in a hierarchical manner to distinguish between different wetland types according to their abiotic features that drive their functionality (Table 4.1). The higher levels 1, 2 and 3 provide the broad regional and landscape setting, while the lower levels provide more detailed descriptions of the particular hydrogeomorphic unit according to biotic features. Level 1 differentiates between marine, estuarine and inland wetlands; level 2 describes the regional setting based on the Department of Water Affairs ecoregions (Kleynhans *et al.*, 2005) and level 3 has different landscape units/settings (i.e. slopes, benches, valley floors and plains) (Ollis *et al.*, 2013). Hierarchical implies that each level must split into smaller units applied in a set order. The entire hydrogeomorphic unit is classified and considered as a unit at level 4 of the classification system, while the lower levels (levels 5 and 6) described the wetland unit according to its hydroperiod and structural characteristics (Ollis *et al.*, 2013).

Table 4.1: Structure of the Classification System for inland wetland systems (Ollis *et al.*, 2013, p. 6)

Ecosystem Context		**Functional Unit**		**Characteristics**
Level 2 Regional Setting	**Level 3 Landscape Unit/Setting**	**Level 4 Hydrogeomorphic (HYDROGEOMORPHIC) Unit**	**Level 5 Hydrological Regime**	**Level 6 Descriptors**
DWA Ecoregions or NFEPA Wet Veg Groups or Other spatial framework	Valley Floor Slope Plain Bench	River Floodplain Channelled Valley-bottom Unchanneled Valley-bottom Depression Seep Wetland Flat	Perenniality Period and depth of inundation Period of saturation	Natural vs. Artificial Salinity pH Substratum type Vegetation cover type Geology

4.3.3 Water Table Monitoring Sites

Figure 4.2 shows the 59 *in situ* sites that were established in the study area to measure groundwater level (see section 5.3.5). Of the 59 observation points, 42 sites included wetlands, two included lakes and 15 were non-wetland terrestrial sites. Monthly readings were taken in the period September 2008 to December 2009, June 2010 and February 2011 with the use of a Solinst waterlevel meter.

4.3.4 Rainfall

Total monthly rainfall data for the study area was acquired from the ARC-ISCW (2011) for the period January 1989 to December 2011 (see section 3.3.2).

4.3.5 Elevation and Hydrogeomorphic Setting

An elevation map (Figure 4.2A) highlighting lowland and upland areas was derived from a 90 m DEM that was created using the elevation data from the Shuttle Radar Topographic Mission System (SRTM) (CGIAR-CSI, 2008) (Figure 4.2B). The upland is an area of higher ground (≥50 m.a.s.l.) separating lower-lying areas west and east. SRTM data were used to generate a digital topographic map of the Earth's land surface with data points spaced every 3 arc seconds for Global coverage of latitude and longitude (approximately 90 m) (Figure 4.3B). The SRTM data meet the absolute horizontal and vertical accuracies of 20 m (circular error at 90% confidence) and 16 m (linear error at 90% confidence), respectively, as specified for the mission. However, the *absolute vertical accuracy* (this is m.a.s.l.) is significantly better than the 16 m and is closer to +/- 10 m for the world. The *relative vertical accuracy* is much higher, up to 1 m. Most importantly, the SRTM data is the best available dataset for relatively flat landscape areas such as the coastal plain, even more accurate than the 20 m or even 5 m contours for the area. The limitation with this dataset is the amalgamation of high vegetation (e.g. swamp forest and plantations) canopies. A land surveyor was contracted in June 2010 to measure the elevation at each groundwater monitoring site (accuracy 3-6 mm). This data was compared to the 90 m and interpolated 30 m SRTM data (Van den Berg *et al.*, 2009) and the results indicated an average difference of 3 m higher and 1 m lower for areas without high tree cover (this is the accuracy in good conditions) and an average of 6 m for sites in or near swamp forests and plantations. The SRTM data are the best available for large areas at 1:50 000 scale that can be applied in meaningful modeling (with some corrections and interpolation) at larger scales (e.g. the SRTM data coupled with Landsat imagery is useful to calculate flow paths (Weepener *et al.*, 2012)).

4.3.6 Relationship with Environmental Factors

The relationships between water table depth, total monthly rainfall and elevation for each of the 59 monitoring sites were statistically determined. Statistical analysis using XLSTAT was used to run the Principal Component Analysis (SAS, 1999). Estimations were done for the missing readings for some months (e.g. if the monitoring site was dry or slumped) with Nearest Neighbourhood calculations.

4.3.7 Landscape Units

Although the study area is situated on a coastal plain, distinct landscape units do occur (see Chapter 6). The landscape units identified in the study area were upland (bench), lowland (plain) and valley floors (incised valleys part of the drainage network), based on the level 3 categories of the NWCS, namely slopes, benches, valley floor and plains (SANBI, 2009b) (Figure 4.2).

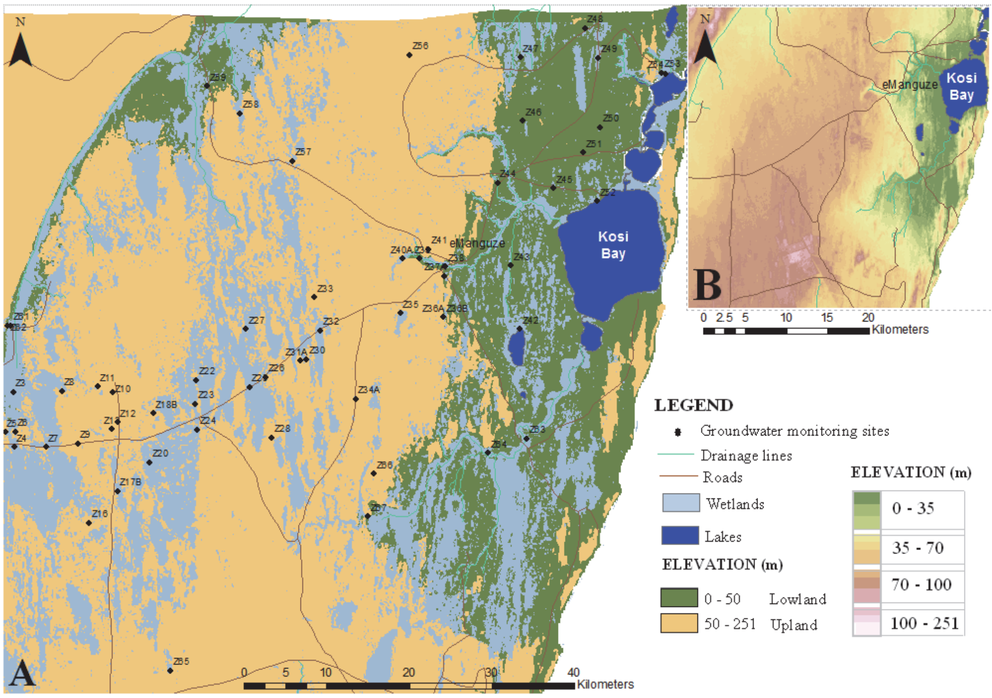


Figure 4.2: Elevation of the study area, wetland distribution and groundwater monitoring sites on upland and lowland areas.

4.3.8 Hydrogeomorphic Units

4.3.8.1 Identify Hydrogeomorphic Units

Using the site location for the 42 water table monitoring sites (41 wetlands and Lake Shengeza), see section 4.3.3), inspection of these sites was done in the field and using the Google Earth elevation profile tool (Dolliver, 2012) and compared with the terrain unit map (Van den Berg *et al.*, 2009).

4.3.8.2 Apply the Hydrogeomorphic Wetland Classification

Smaller topographical features such as swales and small depressions are just as important locally and these needed to be considered in creating the hydrogeomorphic unit map. Therefore, not only the upland and lowland classes based on the SRTM DEM, but also the percentage slope (Weepener *et al.*, 2012) and the terrain unit map (Van den Berg *et al.*, 2009) were used in the hydrogeomorphic unit classification. Van den Berg *et al.* (2009) used curvature morphology to define terrain units (Figure 4.3). This technique to define the smaller topography features is used extensively in soil mapping as topography consists of slopes having distinctive morphologic elements with different hydraulic characteristics (Richardson and Vepraskas, 2001). The terrain units (Figure 4.3A) could be used to indicate areas likely to support wetlands since wetlands form where there are subtle elevation changes, i.e. toeslope (terrain unit 5). Firstly, the concave and convex areas were mapped from the SRTM by adapting algorithms from Evans (1979) and Schmidt *et al.* (2003). The terrain analysis then interactively scaled the surface using slope into crests, convex midslopes, concave midslopes, footslopes and toeslopes by lumping concave and convex classes (Figure 4.3A). Terrain units were mapped at a scale of 1:100 000 using the 90 m SRTM data.

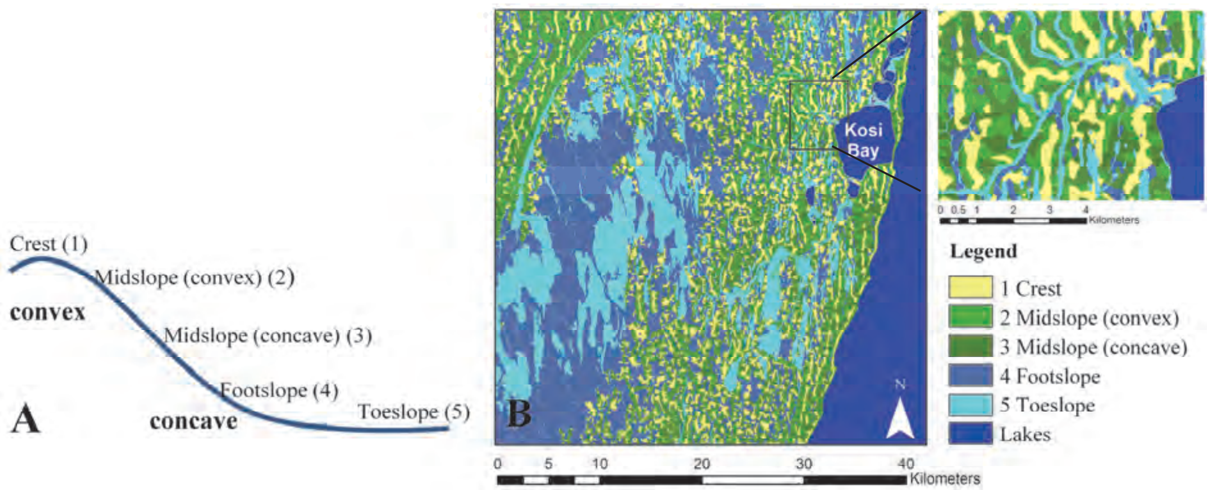


Figure 4.3: A) Profile of terrain units found in this study area: 1 represents a crest, 2 a midslope (convex), 3 a midslope (concave), 4 a footslope and 5 a toeslope; B) Map of the study area indicating the various terrain units (Van den Berg *et al.*, 2009). Only terrain units 4 and 5 were considered to support wetland areas.

Given the flat, undulating dune landscape with deep sandy soils of the study area, Figure 4.3B shows smaller topographical features according to slope changes and surface profile shapes (concave and convex) used to define the terrain units or settings. These changes are expressed in smaller topographical features of local importance on the uplands (e.g. large drier flat-bottomed or small wetter depressions), while in the lowlands differences are more accentuated (e.g. dune crests and incised valley bottoms with round-bottom interdune depressions (basins)).

In order to apply the hydrogeomorphic wetland classification for inland hydrogeomorphic wetland units (level 4 in Table 4.1), a semi-automated approach with the use of ancillary datasets (Table 4.2) was used. The input layers used as criteria for the hydrogeomorphic wetlands classification comprise:

A) The wetness map indicating permanent and temporary wetlands and open water (product of the change analysis in Chapter 3) (Grundling *et al.*, 2013).

B) The terrain unit map (footslope and toeslope terrain units) derived from the SRTM DEM (Van den Berg *et al.*, 2009).

C) The slope, drainage pattern and flow direction derived from the improved SRTM DEM (Weepener *et al.*, 2012) which were used to calculate the modal slope values for each wetland polygon, using the value that appears most often for all cells in the slope grid for the wetland polygon and indicate upland ($\geq$50 m.a.s.l.) and lowland (<50 m.a.s.l.) areas.

D) SPOT 5 2010 imagery used as a backdrop to digitise distinct channels coupled to the 1:50 000 channel layer (NGI, 2012b).

E) The National Geo-spatial Information on inland water features specifically pans <5 ha (NGI, 2012a).

Table 4.2: Ancillary datasets used to assist in the hydrogeomorphic unit classification and evaluation

Dataset	Reference	Purpose
Wetness layer (permanent and temporary wetlands and open water areas) (Chapter 2)	Grundling *et al.* (2013)	To use as a baseline dataset for the distribution of subtropical freshwater wetlands and swamp forests on the coastal lowlands
Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM)	Farr and Kobrick (2000)	To determine the elevation (height above sea level), slope, and catchments for the study area
KwaZulu-Natal (KZN) soil and terrain unit map	Van den Berg *et al.* (2009)	To use the toeslope terrain unit which is closely associated with wetland occurrence
Slope	Weepener *et al.* (2012)	To use slope as percentage rise, derived from the gap-filled SRTM DEM
SPOT 2010 imagery	SANSA (2013)	To digitise the prominent channels
Inland wetland layer	NGI (2012a)	To use as a baseline dataset for the distribution of inland wetland layer pans <5 ha
River lines	NGI (2012b)	To familiarise with the distribution of 1:50 000 river and streams
National Freshwater Ecosystem Priority Area (NFEPA) wetland types	Nel *et al.* (2011)	To familiarise with the distribution of different wetland types

Figure 4.4 indicates the classification steps showing how these hydrogeomorphic wetland units were identified through elimination Using ArcMap 10 software (ESRI 2012). It begins by overlaying the permanent and temporary polygons in the wetness map with: 1) the terrain unit 5 (toeslope areas); 2) the digitized drainage layer coupled with the 1:50 000 river layer; 3) modal slope values of <1%, 1-2% from gap-filled SRTM DEM; and 4) the 1:50 000 inland

wetland layer with contours, and 5) the SRTM DEM to determine the elevation (height above sea level). Following are the wetland classes and their attributes:

(1) **Floodplain** wetlands: All wetland polygons that fall in terrain unit 5 (toeslope) and are characterised by distinct meandering channels and oxbow depressions with secondary channels, indicated by the digitized SPOT 2010 channel layer or from the 1:50 000 river layer (NGI, 2012b).

(2) **Channelled Valley-bottom:** All wetland polygons that occurred in terrain unit 5 (toeslope) and that intersect with defined stream channels digitized from the SPOT 2010 channel layer or from the 1:50 000 river layer (NGI, 2012b).

(3) **Unchannelled Valley-bottom:** All wetland polygons that occurred in terrain unit 5 (toeslope) lacking a well-defined stream channel.

(4) **Depression**: All polygons were classified as such using the 1:50 000 Inland Water Layer category depressions (NGI, 2012a) indicating wetland areas with closed or near closed elevation contours. All wetland polygons were classified as such if the modal slope values of <1%. They can either be upland depressions when ≥50 m.a.s.l. or lowland depressions when <50 m.a.s.l. Lakes (large permanently open water areas) are considered depressions because they function similarly to a permanently inundated depression (SANBI, 2009b) except those with distinct in and out flows (e.g. Kosi Bay lakes).

(5) **Seep:** Polygons that include permanent and temporary open water areas from the wetness map with modal slope values of 1-2%; typically concave midslopes characterised by seepage.

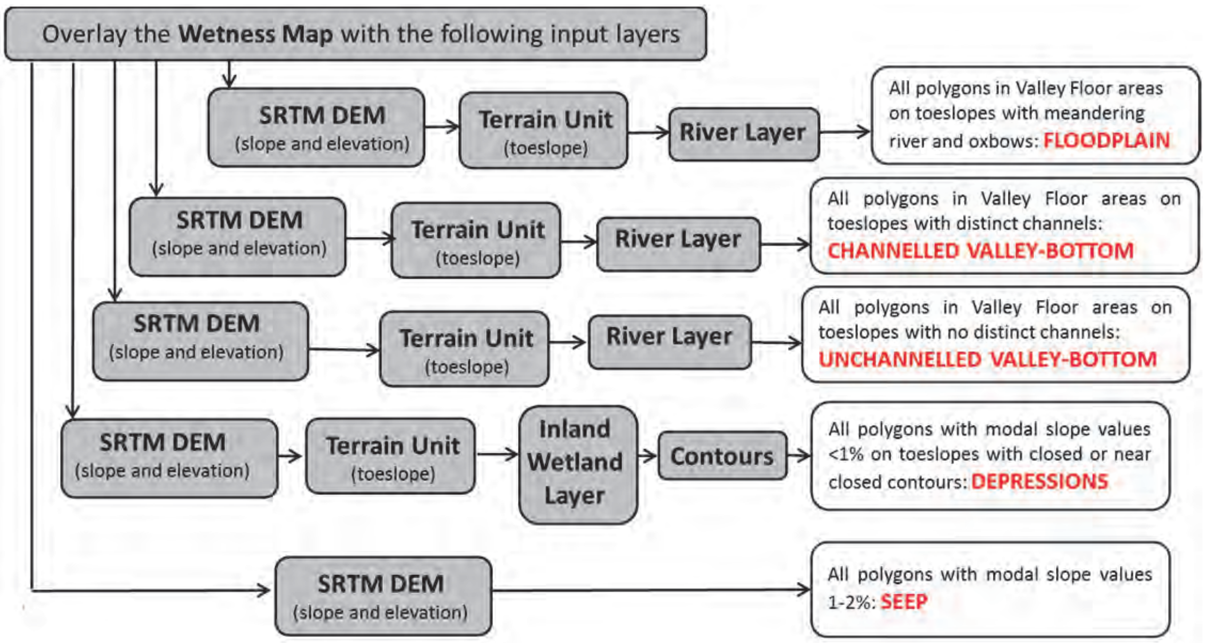


Figure 4.4: Diagram showing the elimination steps part of the hydrogeomorphic classification process.

4.3.8.3 Compare Hydrogeomorphic Wetland Classifications with Groundtruth Sites

No accuracy assessment has been done on the NFEPA wetland type layer (Nel *et al.*, 2011). The fourth specific objective is to compare the National Freshwater Ecosystem Priority Areas (NFEPA) project wetland type layer with the groundtruthed hydrogeomorphic units. The groundtruthed hydrogeomorphic units were identified for the 41 wetland and 1 lake monitoring sites using field groundtruth notes and the Google Earth Elevation Profile tool (Dolliver, 2012). No other independent data set is available.

4.4 RESULTS

4.4.1. Hydrogeomorphic Units

Hydrogeomorphic units identified include temporary or permanent depressions on 1-2% slope, (upland) bench, lowland (plain) and valley floor landscape settings. Temporary or permanent channeled valley-bottoms and unchannelled valley-bottoms on valley floors are characterised by drainage systems that have incised the dunes with steep (4-7 m – determined from the land surveyor's river/stream cross-sections) channels feeding with the Kosi Bay lakes in the east and the Muzi system that drain towards the north. Interdune depressions dominant in the study area occurred on all landscape settings: valley floors, slopes, bench and plains. One floodplain, namely Siyadla River Floodplain, was identified and coastal lakes as depressions. No hillslope seepages linked to a stream were observed in this dune landscape. Each hydrogeomorphic unit is characterised by different water table depth and fluctuation (Figures 4.5 and 4.6). Refer to Figure 4.2 for the location of the monitoring sites. The mean, maximum and minimum for each of the individual sites belonging to a particular hydrogeomorphic unit are presented as a series of box-and-whisker plots for the individual sites grouped according to depressions (Figure 4.5) and unchannelled valley-bottom, floodplain and channeled valley-bottom (Figure 4.6). The valley-bottom wetlands had shallower water tables (<1 m) than the depressions and floodplain (>1 m) with the exception of the depressions on seep with water tables (<1 m). The channeled valley-bottom wetlands had the shallowest water table (average <0.5 m) with the least fluctuations (~0.5 m between shallowest and deepest level), whilst the unchannelled valley-bottom wetlands had an average water table depth of ~ 0.7 m, with larger fluctuations (~ 1 m). The seeps had similar ranges to the unchannelled valley-bottom wetlands, but with a slighter deeper average water table (~ 0.75 m) and somewhat larger fluctuation (~ 1.2 m). The floodplain wetland had a similar fluctuation range to the channeled valley-bottom wetland, and had an average water table depth of 2.4 m. The depressions on upland and lowland exhibited the largest fluctuations (~ 1.7 m) and had the deepest average water table (~ 2.5 m). The unchannelled valley-bottoms and depressions are the two hydrogeomorphic types that occur in upland and lowland areas, as well as within the different rainfall gradients, and both types reflected a general decrease in water table fluctuation from the lower rainfall areas (700-720 mm/annum) to the higher rainfall areas (780-840 mm/annum), whilst the channeled valley-bottoms, floodplain and seeps occur mainly in the higher rainfall, lowland areas, with a smaller range of fluctuations. Various interdune depressions occur throughout the study area in all the different rainfall zones from 700-840 mm (Figure 4.5), namely: perched pans, upland (bench) depressions lowland (plain) depressions and depressions on seep.

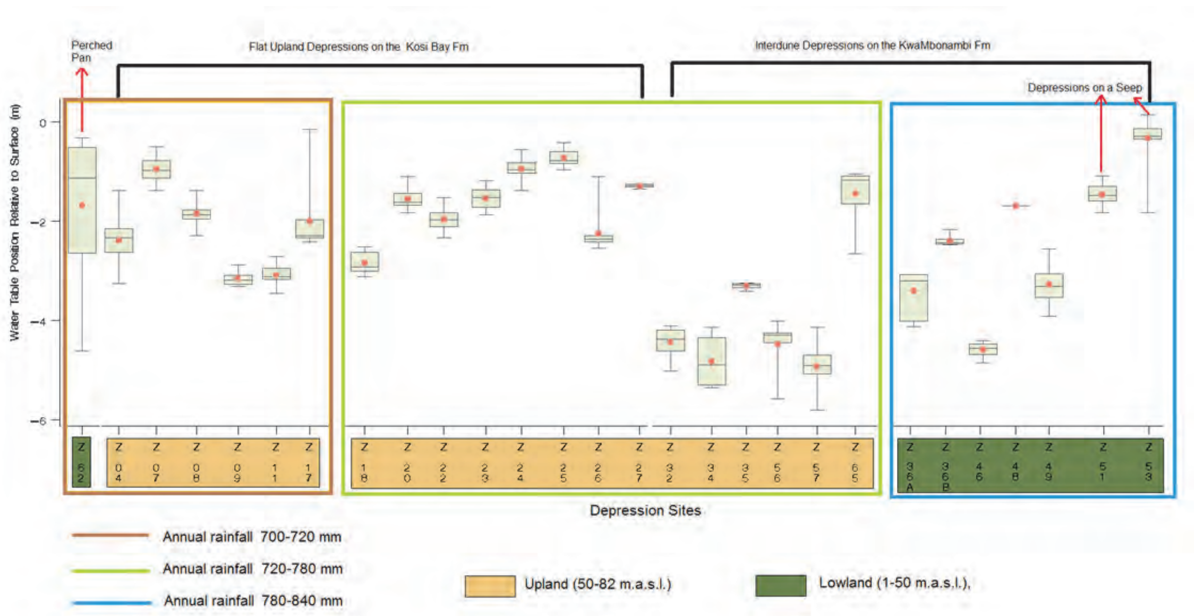


Figure 4.5: Water table depth and variability on upland and lowland depressions. The box represents the lower and upper quartile and includes the median (centre line), mean average (dot) and upper quartile (top of box), while the whiskers are the minimum value and maximum values recorded.

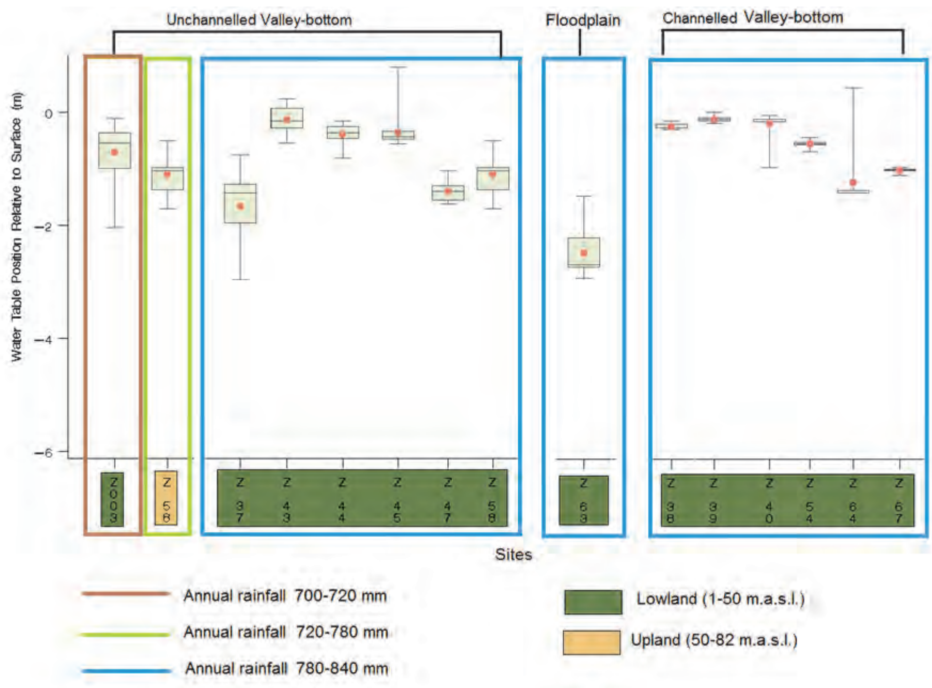


Figure 4.6: Water table depth and variability on upland unchannelled valley-bottom, floodplain and channelled valley-bottom. The box represents the lower and upper quartile and includes the median (centre line), mean average (dot) and upper quartile (top of box), while the whiskers are the minimum value and maximum values recorded.

4.4.2. Drivers and Processes of Hydrogeomorphic Units

Different processes (Figure 4.7A, B, C and D) are evident in the depression types identified, namely:

A) **Perched pans** (no link with regional groundwater – Figure 4.7A). The temporary-perched depressions on valley floor (e.g. Kwamsomi Pan Perched Pan, site Z62) are found in the west at Tembe Elephant Park and are topographically elevated above the Muzi wetland system (channelled valley-bottom on valley floor). The perched pans have relatively large water table fluctuations (Figure 4.5).

B) **Upland (bench) depressions** associated with large, typically elongated depressions; water table rises during significant rainfall events causing inundation or saturation then recedes (Figures 4.7B and C). These are temporary wetland systems, sometimes with localised deeper permanently wet depressions on areas with a partial aquiclude with silty sand and high clay content in the soil profile. Their depth to water table is generally less than 3 m and with an average annual rainfall of 720-780 mm (Figure 4.5). Further east with depressions that overlie the permeable KwaMbonambi Formation (sugar sands) the water tables are deeper (>3 m) (e.g. Z32 and Z35) (Figure 4.5).

C) **Lowland (plain) depressions** at lower elevations to the east (Figure 4.5) are most often permanent or temporary depressions that are linked with the regional water table with various mechanisms of water table fluctuation (Figure 4.7B and C) as well as moderate flow through in the system (Figure 4.7D).

D) **Depressions on a slope** (Figure 4.7D) are characterised by water table fluctuation as well as inflow and outflow in the subsurface zone resembling a flow through system associated with moderate (e.g. Z51 and Z53) to high discharge (e.g. Z35 and Z36B) (Figure 4.5).

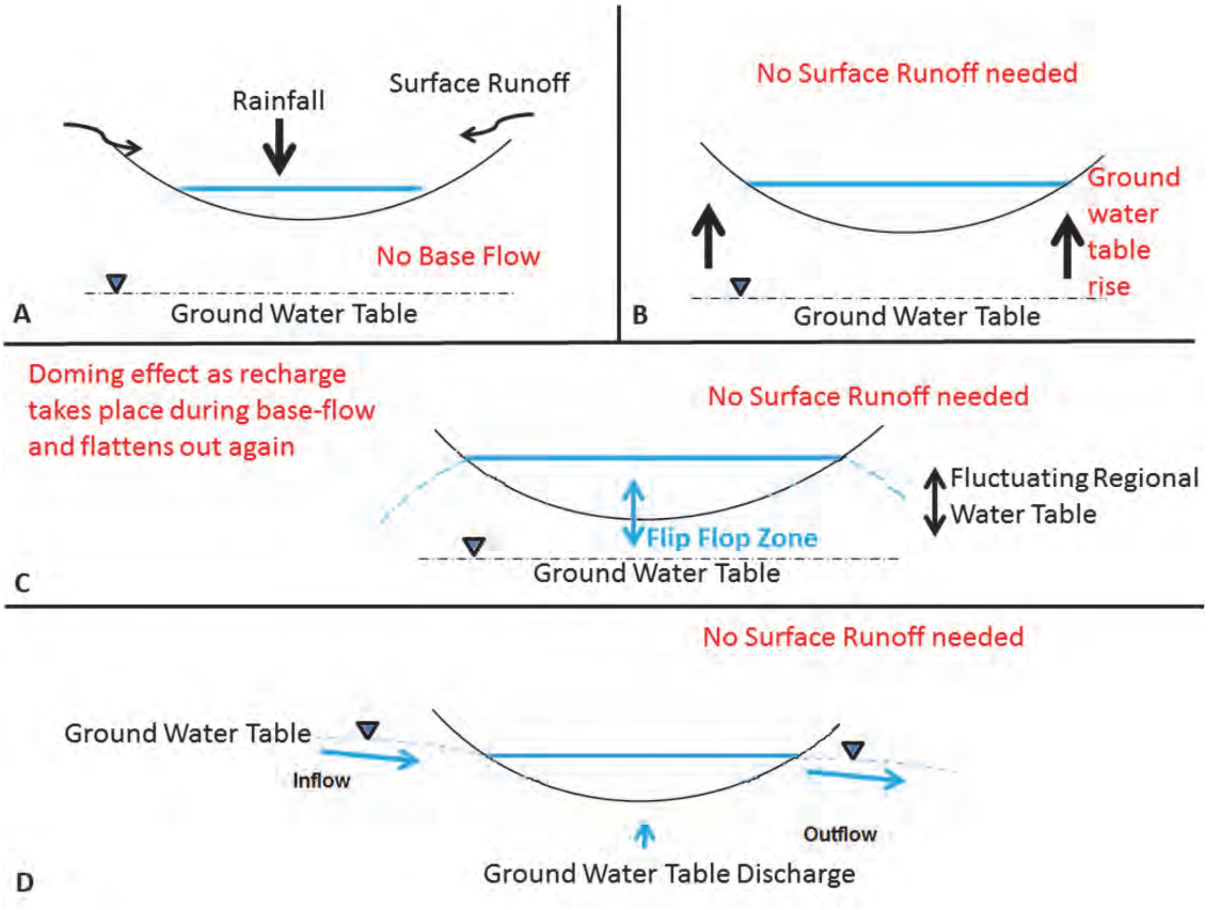


Figure 4.7: Depressions (hydrogeomorphic units) with different functioning processes (diagrams adapted from Semeniuk and Semeniuk (1995) and U.S. EPA (2008)). Typically, A) perched pans, B) depressions on bench or plain and C) and D) depressions on slope.

4.4.3 HYDROGEOMORPHIC CLASSIFICATION

4.4.3.1 Applying the Hydrogeomorphic Classification

Results of the level 4 hydrogeomorphic units classified for the study area based on the NWCS produced distinct types (Figure 4.8), namely channelled valley-bottom, unchanneled valley-bottom, depression and floodplain. The hydrogeomorphic unit map for the study area was created using the Geographic (Datum World Geodetic System 84) projection.

Table 4.3 indicates 35% depressions that vary from perched pans on valley floors, upland (bench) depressions, lowland (plain) depressions and depressions on modal slope values <1% have been identified. The drainage networks include 11% channelled valley-bottom wetlands, 1% floodplains and 36% were unchanneled valley-bottoms. Table 4.3 indicates the surface area (ha) of each hydrogeomorphic type as a percentage of the total study area of wetlands from the wetness map (see Figure 3.7D and section 3.5.1.1).

Table 4.3: Hydrogeomorphic units in percentage and hectares (ha)

Class	HYDROGEOMORPHIC Unit	Count	Total Area (ha)	Percentage
1	Floodplain	1	564	1
2	Channelled valley-bottom	57	4 754	11
3	Unchanneled valley-bottom	204	15 422	36
4	Depressions (modal slope values <1%)	1730	14695	35
5	Seep (modal slope values 1-2%)	5440	3300	8
6	Kosi Bay Lake System	22	3639	9
		7 454	**42 373**	**100**

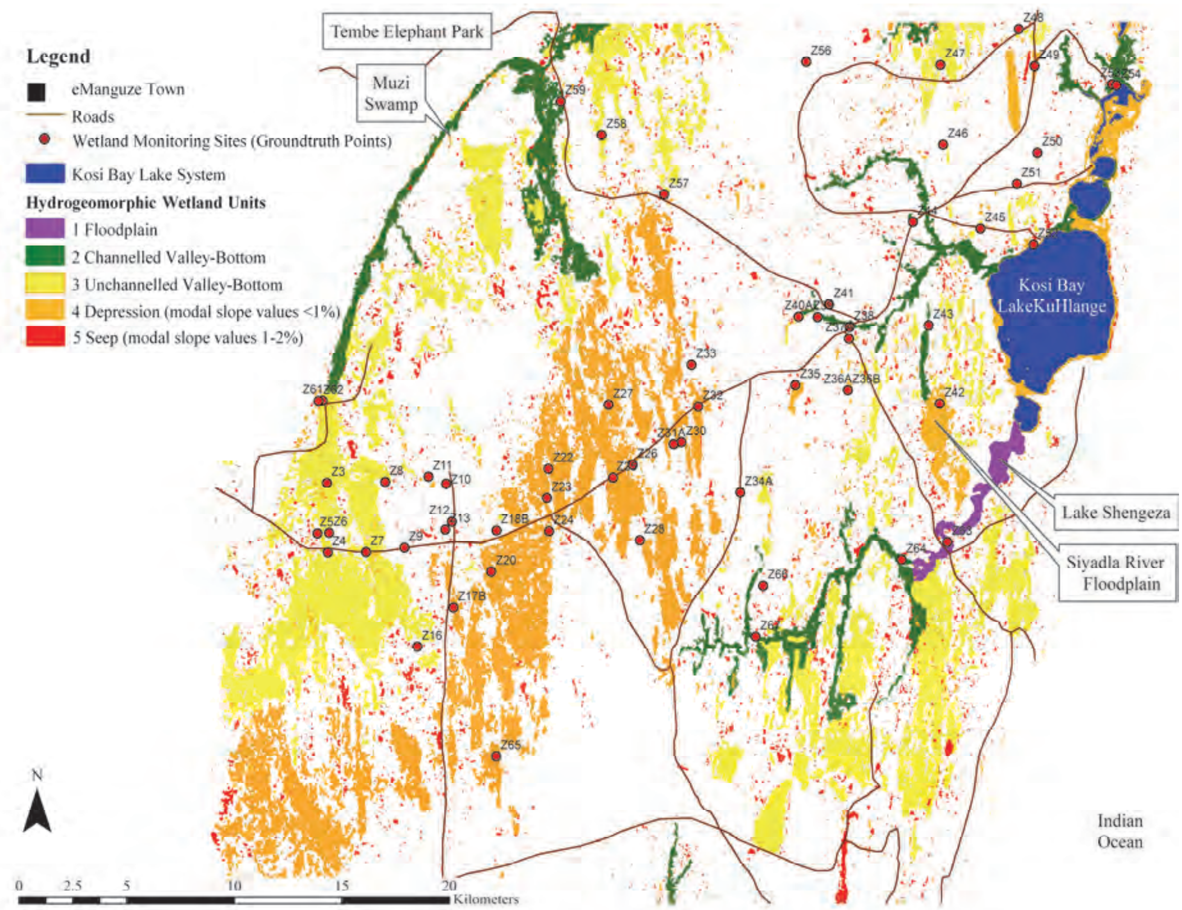


Figure 4.8: Hydrogeomorphic wetland units positioned in the landscape.

4.4.3.2 Evaluation of the Classification Comparison

The NFEPA team used GIS techniques and existing data in an automated approach to classify wetland ecosystem types (Nel *et al.*, 2011; Driver *et al.*, 2011) while a semi-automated approach with the use of ancillary datasets (Table 4.2) was used to create a hydrogeomorphic unit map (Figure 4.8). The main differences between the two approaches are explained in Table 4.4.

Table 4.4: Differences in the classification approach between this study and NFEPA

HGM UNIT MAP (Figure 4.8)	**NFEPA WETLAND ECOSYSTEM TYPES**
In this study the hydrogeomorphic unit classification approach used elevation data from the improved Shuttle Radar Topographic Mission System (SRTM) 90 m x 90 m DEM (Weepener *et al.*, 2012) and terrain unit map (Van den Berg *et al.*, 2009).	A 50 m resolution DEM generated from 20 m contours and spot height data per 1:50 000 data sheets with the ArcGIS 9.3 Landform Tool to buffer distances using mean valley widths (Van Deventer, 2010).
In this study the Wetness layer (permanent and temporary wetlands and open water areas) is used (Grundling *et al.*, 2013).	The landform classes (bench, slopes, plains and valley-floor) were then used in combination with the 1:50 000 pans (depression) GIS layer and river network GIS layer to classify each wetland polygon in South Africa's National Wetland Map v.4 (SANBI, 2009b; SANBI, 2010) into one of the seven hydrogeomorphic wetland units.
In this study the term *landscape setting (units)* for level 3 (i.e. slopes, benches, valley floors and plains) units will be used.	The NFEPA project referred to *landforms* as a GIS product to achieve the landscape unit classes for level 3 (i.e. slopes, benches, valley floors and plains).

The groundtruthed sites with monitored water table data were used to do an accuracy assessment for both the NFEPA hydrogeomorphic wetland ecosystem type (Nel *et al.*, 2011) and the hydrogeomorphic unit map produced (Figure 4.8). The results of the comparison are listed in Table 4.5 and indicate that of the 42 groundtruthed sites, 81% were classified accurately in the hydrogeomorphic wetland unit map (Figure 4.8) compared to the 40% of the NFEPA classification. One seep area was recorded by groundtruth point (Z39, spring feeding channelled valley-bottom swamp forest). The wetland polygon was mapped as channelled valley-bottom in both classifications. The hydrogeomorphic unit map (Figure 4.8) accuracy levels for mapping depressions is 78%, for unchanneled valley-bottoms is 100% and for channelled valley-bottoms is 88% (Table 4.6). Limitations include 3 wetland areas not mapped by hydrogeomorphic unit map produced (Figure 4.8) and 9 wetland areas not mapped by the NFEPA wetland ecosystem layer. If a groundtruthed point was located <100 m from a wetland polygon, it was still considered, but if a groundtruthed point was located ≥100 m from a wetland polygon, it was considered not mapped.

Table 4.5: Hydrogeomorphic comparison results between groundtruthed classification, the semi-automated HGM classification in this study and the automated NFEPA classes

NO	SITE NO	GROUNDTRUTHED	HGM UNIT MAP (Figure 4.8)	NFEPA WETLAND ECOSYSTEM TYPES
1	Z003	Unchannelled VB	Unchannelled Valley-bottom	Channelled Valley-bottom
2	Z004	Depression	Unchannelled Valley-bottom	Unchannelled Valley-bottom
3	Z007	Unchannelled VB	Unchannelled Valley-bottom	Not Mapped
4	Z008	Unchannelled VB	Unchannelled Valley-bottom	Valleyhead Seep
5	Z009	Seep	Seep	Not Mapped
6	Z011	Depression	Not Mapped	Unchannelled Valley-bottom
7	Z017B	Depression	Depression	Seep
8	Z018B	Depression	Depressions	Flat
9	Z020	Depression	Depression	Seep
10	Z022	Depression	Depression	Seep
11	Z023	Depression	Depression	Seep
12	Z024	Depression	Depression	Flat
13	Z025	Depression	Depression	Seep
14	Z026	Depression	Depression	Not Mapped
15	Z027	Depression	Depression	Seep
16	Z032	Depression	Depression	Depression
17	Z034A	Depression	Depression	Seep
18	Z035	Depression	Depression	Depression
19	Z036B	Depression	Depression	Seep
20	Z037	Unchannelled Valley-bottom	Unchannelled Valley-bottom	Unchannelled Valley-bottom
21	Z038	Channelled Valley-bottom	Channelled Valley-bottom	Channelled Valley-bottom
22	Z039	Channelled Valley-bottom	Channelled Valley-Bottom	Channelled Valley-bottom
23	Z040	Channelled Valley-bottom	Unchannelled Valley-bottom	Not Mapped
24	Z042	Depression	Depression	Flat
25	Z043	Channelled Valley-bottom	Channelled Valley-bottom	Channelled Valley-bottom
26	Z044	Channelled Valley-bottom	Channelled Valley-bottom	Channelled Valley-bottom
27	Z045	Unchannelled Valley-bottom	Unchannelled Valley-bottom	Unchannelled Valley-bottom
28	Z046	Depression	Depression	Unchannelled Valley-bottom
29	Z047	Unchannelled Valley-bottom	Unchannelled Valley-bottom	Channelled Valley-bottom
30	Z048	Depression	Unchannelled Valley-bottom	Unchannelled Valley-bottom
31	Z049	Depression	Depression	Flat
32	Z051	Seep	Not Mapped	Not Mapped
33	Z053	Seep	Channelled Valley-bottom	Not Mapped
34	Z054	Channelled Valley-bottom	Channelled Valley-bottom	Not Mapped
35	Z056	Depression	Not Mapped	Not Mapped
36	Z057	Depression	Depression	Flat
37	Z058	Unchannelled Valley-bottom	Unchannelled Valley-bottom	Flat
38	Z062	Depression	Unchannelled Valley-bottom	Not Mapped
39	Z063	Floodplain	Floodplain	Floodplain
40	Z064	Channelled Valley-bottom	Channelled Valley-bottom	Channelled Valley-bottom
41	Z065	Depression	Depression	Seep
42	Z067	Channelled Valley-bottom	Channelled Valley-bottom	Channelled Valley-bottom

Table 4.6: Summary of accuracy levels

HGM UNIT	HGM UNIT MAP (Figure 4.8)	NFEPA WETLAND ECOSYSTEM TYPES	TOTAL	% ACCURATE HGM UNIT MAP (Figure 4.8)	% ACCURATE NFEPA WETLAND ECOSYSTEM TYPES
Floodplain	1	1	1	100	100
Channelled valley-bottom	7	6	8	88	75
Unchannelled valley-bottom	7	2	7	100	29
Depression	18	8	23	78	35
Seep	1	0	3	33	0

4.5 DISCUSSION

The study area can be classified as inland (level 1), Natal coastal ecoregion (level 2) and coastal plain landscape setting (level 3), with important features that include the upland and lowland areas in an undulating dune landscape (Figure 4.2). The study area is characterised by upland (bench), lowlands (plains), coastal dunes, floodplains and relatively deep incised channelled valley-bottoms (Figure 4.3B). The uplands are vital groundwater recharge areas, which eventually provide discharge to wetlands associated with floodplains, channelled valley-bottoms, unchanneled valley-bottoms and depressions in lowland areas (see chapter 6).

The wetness map created in Chapter 3, Figure 3.7D (see section 3.5.1.1) was used as the wetland layer within which polygons were further classified into different hydrogeomorphic units. Smaller polygons (<1 ha) were classified as separate hydrogeomorphic units, but for large polygons (e.g. <6000 ha) the broad hydrogeomorphic unit were classified that could include adjacent polygons sharing similar catchment characteristics.

4.5.1 Hydrogeomorphic Units Identified

4.5.1.1 Floodplain

The only example in the study area is the Siyadla (Malangeni) floodplain entering the Kosi lakes from the south. Interestingly, the depth to water table of the floodplain is much deeper than expected compared to the other hydrogeomorphic sites. The reason might be that the water table level was lower during the dry period when it was monitored. Characteristic of this floodplain and others further south is that the floodplain back-floods into the off-channel lakes during flood events (Grundling, 2001). The water source for floodplains is stream flow and groundwater.

4.5.1.2 Channelled Valley-bottom

The Muzi calcareous mire system in the west is a long, linear channelled valley-bottom system running parallel to the Pleistocene dune ridges. The drainage lines in the east of the study area breach a dune cordon at some point (Figure 4.3B) to flow eastwards to the Kosi Bay lake system (Figure 4.3B). They usually have slightly steeper slopes and larger catchments (upland area) than the unchanneled valley-bottoms (often located in their headwater) (Figure 4.8). Examples are the tributaries of the Siyadla River floodplain and the Gezisa River flowing through the town of eManguze (Figure 4.8). Swamp forests are often an important component of these systems. These are groundwater discharge areas (see Chapter 3) but also receive groundwater and surface water from upstream.

4.5.1.3 Unchanneled Valley-bottom

Most of these systems are orientated parallel to the Pleistocene dune ridges and are usually linked to either coastal lakes or downstream channelled valley-bottoms. They usually have shallower slopes and smaller catchments (upland areas) than the channelled valley bottoms (into which they often drain). Examples are numerous and include the mires in the KwaNovuna area south of Kosi Bay, and the headwaters of the Muzi calcareous mire system (i.e Z3 and Z7) and Z37 to the east (Figure 4.8). These systems are often dominated by reeds, sedges and grasses. The water source is mainly groundwater.

4.5.1.4 Seepage

The Maputaland Coastal Plain topography is fairly flat and as such depressions on modal slope values 1-2% characterised seepage typically concave midslopes where a permanent spring (Z39) feeding a channelled valley-bottom, permanent seep (Z53) and temporary seep (Z9) was observed. These seepage areas, often associated with swamp forest components, occur on slopes of prominent inland dune systems such as the Siyadla River or Swamanzi River. The water source is groundwater and probably intermediate flow in the wetter periods.

4.5.1.5 Depressions

Depressions in the study area occur as primary hydrogeomorphic units (level 4) (Table 4.1). They range from small (<5 ha) flat-bottomed perched pans associated with old paleo-channels, large upland areas depressions with flat-bottoms and round-bottom interdune depressions. Seepage zones are present along the edges of the depression but are regarded as part of it. Because of the scale of the mapping (Figure 4.8) the seepage zones at the edges of the depressions could not be mapped in detail. However, depressions with modal slope values <1% were also mapped. Natural lakes are considered depressions because they function in the same way (SANBI, 2009b). The large upland areas with low to no gradient (0.3% slope) did have depressions characterised by temporary wetlands with high water table fluctuation. The upland areas consist of a sand plain where the buried aeolian sand landscape (Kosi Bay Formation) is exposed, forming large upland depressions with smaller eroded pockets of deeper depressions (see Chapter 3). The base of the depression is closer to the water table and pools of open water can occur after heavy rainfall events. These areas flood only during extreme rainfall events. The source of water to the upland depressions is linked to regional groundwater and recharged by rainfall. Depressions on the lowland areas (lower elevations to the east) (Figure 4.5) are most often permanent or temporary depressions that are linked to the regional water table with various mechanisms of water table fluctuation (Figure 4.7B and C) as well as moderate flow through in the system (Figure 4.7D).

4.5.2 Water Table

The depth and fluctuation of the water table are important characteristics of hydrological functioning. The water table depth and range of fluctuation for each hydrogeomorphic unit differs (refer to Figures 4.5 and 4.6) and is not only a function of rainfall distribution and landscape position but also of the source of water maintaining these wetlands and depth to the water table. The channelled valley-bottom wetlands with shallow water tables are most likely to be linked to the regional water table and the smaller range in fluctuation reflects the moderation effect of groundwater in this sub-tropical climate where high evapotranspiration rates and variable rainfall result in large seasonal water deficits (Figure 4.9). This is reflected in the large water table variation in the depressions of which 27% occur on the uplands (Table 4.3) and which are more dependent on rainwater (Figure 4.9). The seeps with relatively shallow water table have the largest fluctuation and could be a reflection of combined groundwater discharge with subsurface flow that only occurs on a seasonal basis as part of interflow, similar to the unchanneled valley-bottom wetlands (Figure 4.9). The floodplain’s narrow range of fluctuation is not typical of a floodplain. Note that the relatively deep water table at the floodplain site is due to the location of the monitoring point (Z64 elevation 14.72 m.a.s.l.) in the active stream channel with the reference point representing the sediment surface of the floodplain. The fluctuation indicates the high flow contribution from the Mqombo River (tributary of the Siyadla River Floodplain). Other water inputs are from groundwater and probably reflect a constant base flow from extensive groundwater-dependent wetlands (peatlands and swamp forests) in its catchment with higher flows during rainfall events.

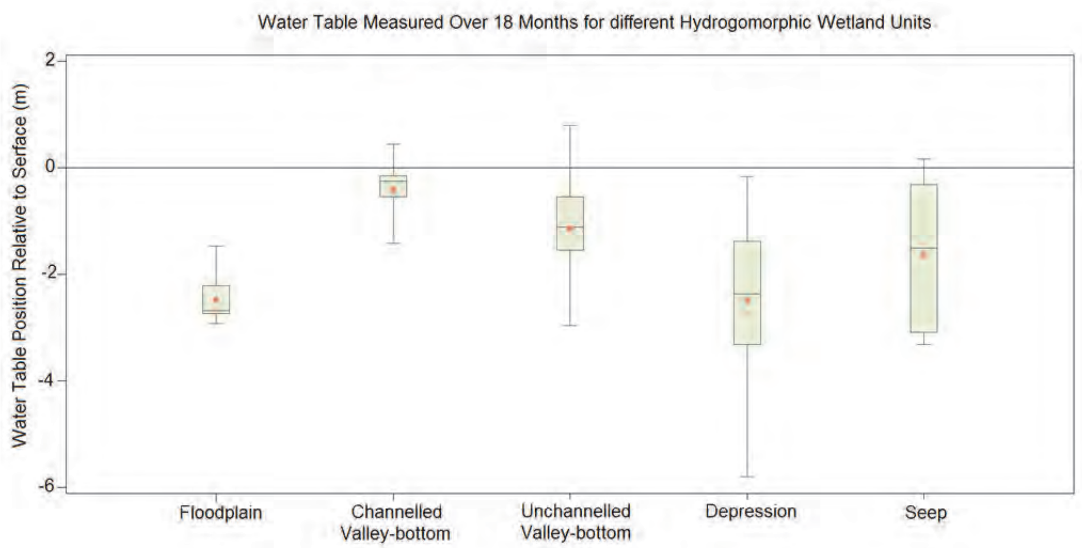


Figure 4.9: Average, minimum and maximum (boxplots) of groundwater depth (GWD) for different hydrogeomorphic wetland units (total n=41) with channelled valley-bottom (n=8), seep (n=3), unchannelled valley-bottom (n=7), depression (n= 22) and floodplain (n=1). The perched depression (Z62) and Lake KuHlange (Z52) were not included. The boxplots represent the 1st and 3rd quartiles, the line is the median, the red dot is the average and the whiskers are maximum and minimum values. Note that all the time series points for each station have been included.

4.5.3 Relationship with Environmental Factors

The nature of the aquifer and topography (Figure 4.10A) with the precipitation (rainfall) gradient (Figure 4.10B) is related to the wetland distribution and temporal character and hydrogeomorphic setting (Figure 4.10C). The topography (Figure 4.2B) reflects the regional geological template that slopes towards the east. There is a distinctly upland plain between the Muzi River system and the lowland plain to the east that hosts the Kosi lakes (Figure 4.2A). The easternmost part of the lowland plain is superimposed by more recent dune formations (highlighted by the dune crests in Figure 4.3B). Note the upland plain has no river channels in the centre (Figure 4.2), due to generally high infiltration rates of the sandy soil. There is also a precipitation (rainfall) gradient: the rainfall decreases from east (>840 mm) to west (640 mm) (ARC-ISCW, 2009) (Figure 4.10B). The east-west gradient of annual precipitation (rainfall) is fairly steep and is reflected in the wetland distribution pattern with wetter systems east of the 750 mm isohyets and temporary systems mostly west thereof. The average precipitation of 850 mm on the coast at Kosi Bay (calculated over 40 years) decreases by 22% about 50 km west at Tembe Elephant Park with a 40% decrease measured at Ndumo, 60 km west of the coast. The long-term rainfall (1989-2012) indicates high summer rainfall (October to March) and lower winter rainfall (April to September). The relationships with environmental factors such as water table, rainfall and elevation were statistically determined using Principal Component Analysis (SAS, 1999). Four groups emerged (Figure 4.10C and Figure 4.11). Group 1 and 2 sites are located in the high rainfall zone (780-840 mm) in the coastal lowland (Figure 4.10C). Group 1 sites are proximal to lakes (Z52 Kosi Lake and Z42 Lake Shengeza). The wetlands in group 1 are 1.5-2.2 m.a.s.l. (except Z42 – 24.5 m.a.s.l.), but the water table persists at or near the surface. Group 2 indicates a strong relationship between water table depth, elevation (varies between 14-49 m.a.s.l.) and predominantly winter rainfall (April to September) and summer rainfall (October to March) events (red values indicate the rainfall month in Figure 4.11). Group 2 received 840 mm average rainfall (ARC-ISCW, 2009) (Figure 4.10C). Group 3 indicates a strong relationship between water table depth, elevation and lower rainfall zone (720-780 mm average rainfall) (ARC-ISCW, 2009) with predominantly summer rainfall (October to March) events (red values indicate the rainfall month in Figure 4.11). Group 3 is located in the centre of the study area predominantly on the Kosi Bay Formation with elevation between 53-82 m.a.s.l. Group 4 indicates a strong relationship between water table depth and elevation as seen in the lowland medium areas with elevations between 43-74 m.a.s.l. and rainfall zone (700-720 mm average rainfall) (ARC-ISCW, 2009). Figure 4.12 summarises the environmental factors influencing hydrogeomorphic unit distribution.

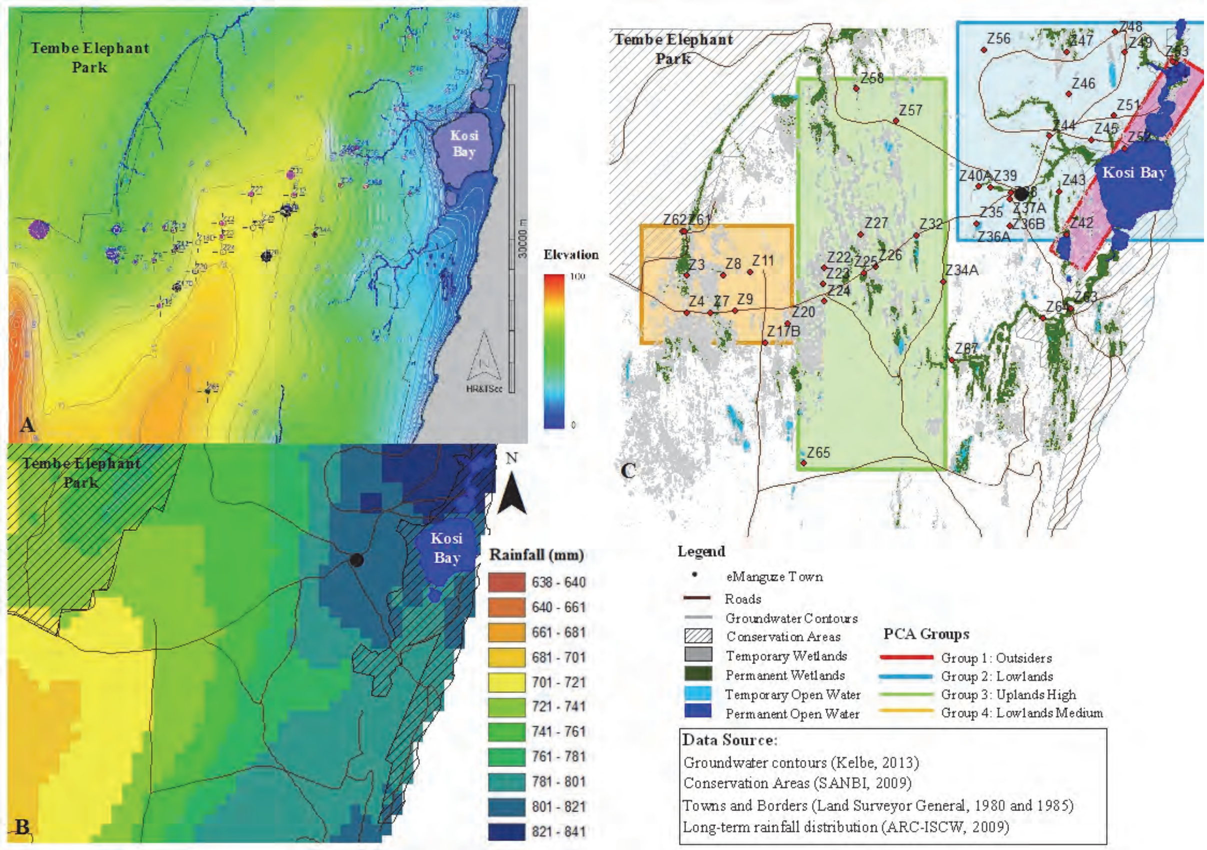


Figure 4.10: Groundwater contours in association with topography (Kelbe and Grundling, 2010) (A) and rainfall gradient (B) is related to the wetland distribution and temporal character (C). The relationships between elevation, water table depth and rainfall are shown in C (4 Principal Component Analysis groupings).

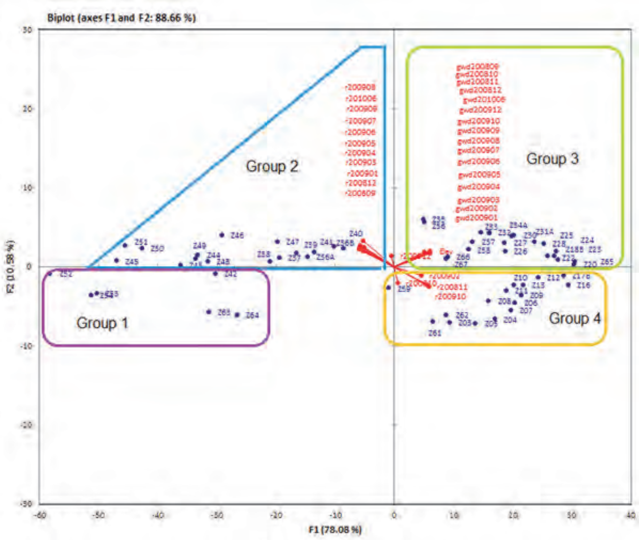


Figure 4.11: Principal Component Analysis results indicating 4 groupings; red values indicate the rainfall month.

4.5.4. Limitations of an Automated and Semi-automated Approach

From the evaluation it was evident that the NFEPA landform (level 3 in Table 4.1) suggested slope, valley floor, plain and bench were found to be too coarse for this study area, e.g. the valley floor areas were too wide. Van Deventer (2010) reported on the incomplete and inaccurate National Wetland Maps v.4 (Mbona *et al.*, 2010) used as input layers for the automated wetland ecosystem type classification. The same problem was also confirmed in this study's accuracy assessment evaluation, e.g. the NFEPA dataset had 10 wetland sites not mapped and the hydrogeomorphic unit map (Figure 4.8) had 6 wetlands not mapped compared to the groundtruth sites. Implications on the accuracy of river or drainage lines can influence whether the wetland is classified as channelled valley-bottom or unchanneled valley-bottom.

4.6 CONCLUSION

The importance of correct wetland classification for the Maputaland Coastal Plain comprises land-use restrictions and management as well as extreme precipitation events and wet and dry seasons. The hydrogeomorphic classification brings into prominence the important underlying features of all wetlands, i.e. land (geomorphology) and water (hydrology) (Semeniuk and Semeniuk, 1995). Ollis *et al.* (2013) expressed the need to know how wetlands function and if the underlying assumption that wetlands belonging to the same hydrogeomorphic unit sharing common features in terms of environmental drivers and processes is correct. The hydrogeomorphic classification was applied in the north-eastern part of the MCP based on wetland position in the landscape with the use of a terrain map highlighting concave areas (footslope and toeslope) and wetland occurrence, i.e. extent and distribution based on mapping in wet and dry years. Sub-regional environmental determinants (water table, rainfall and elevation) were examined to show the link between these and the distribution of hydrogeomorphic units. The results of the relation between rainfall, elevation and depth to water table show an increase in the variety of hydrogeomorphic wetland units in lowland areas (<50 m.a.s.l.) with annual average rainfall of 780-840 mm versus the drier upland (≥50 m.a.s.l) with annual average rainfall of 700-780 mm. However, the presence or movement of water and the landscape setting remain the two principal features that determine the way in which an inland wetland functions (Smith *et al.*, 1995). In this study area wetland occurrence is not dependent on rainfall or elevation but rather depth to water table based on localised topographical features supporting hydrological processes. For example, the presence of a permanent wet, groundwater fed, channelled valley-bottom Muzi wetland system that occurs in the west of the study area (Tembe Elephant Park) in the lower rainfall region (700-720 mm). Furthermore, the study found interdune depressions were the most dominant hydrogeomorphic type (42%), followed by unchanneled valley-bottoms (36%), channelled valley-bottoms (11%) and one floodplain. The depressions have the same hydrogeomorphic unit but occur in contrasting landscape settings and displayed different functioning processes on this primary aquifer (Figure 4.7). Different depressions identified in the study include: 1) perched depressions that rely only on rainwater with no link to the regional groundwater; 2) depressions where the water table rises during significant rainfall events causing inundation or saturation then recedes; 3) depressions on slope where water table fluctuation as well as inflow and outflow in the subsurface zone resembles a flow through system. Accuracy assessment was done by comparing groundtruthed sites with the National Freshwater Ecosystem Priority Areas (NFEPA) project wetland type layer. This need was stressed by Van Deventer (2010) for improvements and testing of the NFEPA wetland ecosystem type layer at sub-regional scale. This study's semi-automated approach to map hydrogeomorphic unit on the MCP was 81% accurate, while the NFEPA wetland ecosystem type was 40% accurate. Both classifications stressed that incomplete and inaccurate input layers (e.g. wetlands layer and river layer) and limited groundtruthed points with substantiated groundwater monitoring data are the major limitations in an automatic approach for hydrogeomorphic wetland classification. The danger in using the hydrogeomorphic unit map created in this study (level 4 in Table 4.1) is that the classification is based on the fundamental factors landscape setting and permanence of water but not on aspects such as: 1) the origin of the landscape setting (e.g. interdunal or fluvial-like floodplains); 2) the importance of the landscape setting (recharge or discharge area); 3) the description of the water source (e.g. water table rise, ponding of rainwater, seepage of groundwater discharge or runoff or through-flow/interflow); or 4) if the wetland is permanent, seasonally or intermittently inundated. All this additional detail can only be added to the hierarchical manner in which the hydrogeomorphic classification is applied when and if the information becomes available. The danger in using the broad hydrogeomorphic classification (level 4) with limited criteria for future land-use planning and assessments is that it permits a direct judgement of a single wetland's value. For example, if one is unaware of the recharge value of a temporal large depression on the upland then predictions and future conservation assessments might not be in agreement for particular wetland sites. This study highlights that the hydrological data of a wetland (i.e. to show interaction with the regional water table, either recharge or discharge function) are much needed for biodiversity management or sustainable aquifer development. However, the study gives a better understanding of the wetland types found on the Maputaland Coastal Plain and how well the hydrogeomorphic classification could be applied. The methods and findings contribute to further refining of the wetland classification work in South Africa and can be applied on similar sandy coastal plains.

CHAPTER 5: SOIL ORGANIC CARBON AND HYDROPERIOD

PHOTO: Althea Grundling

5 SOIL ORGANIC CARBON AND HYDROPERIOD

5.1 INTRODUCTION

Most of the coastal plain consists of geologically recent medium to fine-grained aeolian, sands which are nutrient poor, highly leached and acidic (Van Wyk and Smith, 2001). The sandy soils are characterised by rapid infiltration rates and a low soil water-holding capacity. Large areas of dune sand are generally classified as Hutton form profiles. The yellowish brown Clovelly and grey Fernwood soil forms generally show a sharp reduction of organic matter to less than 0.5% within 30 cm of the surface. The duplex, sodic soils with a prismatic subsoil structure typical of the Estcourt soil form occur on the margins of old dune ridges. The organic-rich Champagne soil form occurs in permanent wetlands (Botha and Porat, 2007). Champagne soil forms are characterised by >10% SOC in the profile that is at least 200 mm thick. Wetland delineation is problematic in sandy coastal aquifers with deep aeolian derived sandy soils, often with grey profile colours and no signs of wetness (i.e. mottles in the profiles) (DWAF, 2005). Wetland indicators, namely terrain unit, vegetation (hydrophytes), soil form (hydromorphic soils) and soil wetness are used in delineating wetlands (DWAF, 2005). Soil wetness indicators are mottling and gleying in the soil profile as a result of long-standing and frequent water saturation (DWAF, 2005). However, soil properties on sandy coastal aquifers also include dark topsoil with high organic carbon content: >4% in temporary zones of saturation and >10% in permanent and seasonally saturation zones (DWAF, 2005). Kotze and Marneweck (1999) described how changes in soil wetness and vegetation composition along the wetness gradient provide an indication of wetland zoning (permanently waterlogged in the middle, seasonally waterlogged and temporarily waterlogged at the edge). In this chapter, SOC content as an indicator of hydroperiod to help delineate and classify permanent, seasonal and temporal wetlands on sandy coastal aquifers, was investigated.

5.2 SPECIFIC OBJECTIVES

1) To determine soil organic carbon content and hydroperiod in different wetness zones.

5.3 METHODS

5.3.1 Study Area

This chapter will focus on the northern and southern study areas (see Figure 1.3 in section 1.5.1).

5.3.2 Rainfall Data

See section 3.3.2.

5.3.3 Geology and Hydrology

Information was assimilated from existing published and unpublished reports and maps (Council for Geoscience, 1986; DME, 1985), as well as by interviewing geologists (Botha, 2008; Roux, 2011; Maud, 2011), hydrogeologists (Schapers, 2008, 2011; Kelbe, 2010) and a soil scientist (Snyman, 2011) who were active in the area, to formulate a clearer understanding of how geology controlled the hydrology in the region.

5.3.4 Northern Study Area: Wetland Selection

During a field visit, Grundling (2010) identified five palustrine wetlands along a 60 km transect between the Tembe Elephant Park in the west and Kosi Bay in the east (Figure 5.1). These wetland systems include: 1) channeled valley-bottom units – the Muzi Swamp Wetland (MS) in the west and the Swamp forest draining to the east; and 2) depressions – a) perched pans (PP) west, and b) Interdune Depressions (IDD) east; all on the lower-lying areas (<50 m.a.s.l.). Upland wetlands on higher ground (≥50 m.a.s.l.) separate the lowland areas west and east. The following wetland systems are indicated with red numbers in Figure 5.1 and illustrated in Figure 5.2:

- Muzi Swamp Wetland (MS) and Perched Pan (PP) (**1**)
- Upland Wetland (PL) (**2**)
- Swamp Forest (SF) (**3**)
- Interdune Depression (IDD) (**4**)

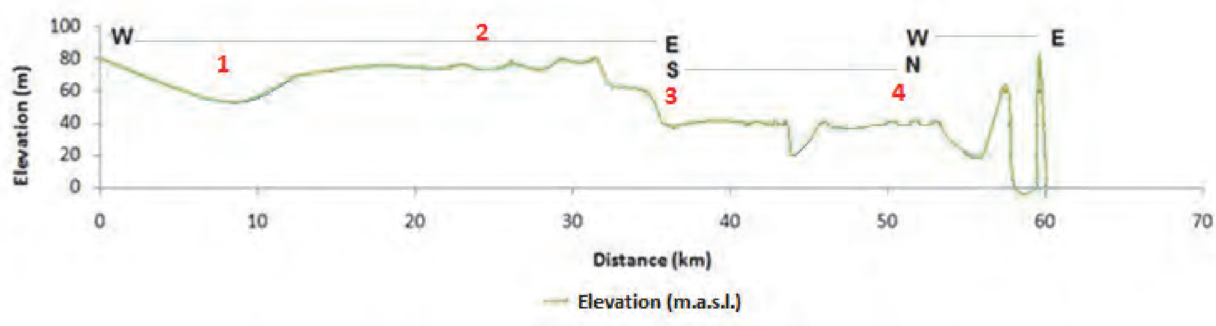


Figure 5.1: Profile of the transect from Tembe Elephant Park in the west to the fourth lake of the Kosi Bay System in the east.

1. Muzi Swamp Wetland System and Perched Pan

2. Upland Wetland **3. Swamp Forest**

4. Interdune Wetland

Figure 5.2: Five wetland systems that occur along the profile of the transect from Tembe Elephant Park in the west to the fourth lake of the Kosi Bay System in the east.

5.3.5 Groundwater Monitoring Sites

Groundwater monitoring sites were identified in the northern study area in order to measure groundwater levels (see section 4.3.3, Figure 4.2 and Figure 5.3). Total random sampling of the northern study area was not an option within the framework of this study. Therefore, sampling existing wells (Still and Nash, 2002) and borehole locations along road no. 522-2S (part of road no. R22) (west-east) and near homesteads provided a cost-effective alternative. Borehole locations were obtained from existing monitoring wells in the Tembe Elephant Park (Ezemvelo KZN Wildlife, 2010) and from contractors working in the area (16 wells monitored by Jeffers and Green (Pty) Ltd; Schapers, 2010). Only the latter wells had been monitored on a regular basis between 2000 and 2008. During the September 2008 fieldwork campaign 54 groundwater monitoring sites were identified and in April 2009 15 additional sites were added to obtain a total of 69. However, due to dried up sites, damaged, collapsed or filled in, data from only 59 *in situ* sites are used in analysis (see Figure 4.2).

From the 59 sites 44 sites included wetlands and lakes whilst 15 were non-wetlands or terrestrial sites. The monitoring sites comprised 11 boreholes (sunk for communal use), 29 wells (open wells dug for communal use), 3 pans, 4 lakes, 6 stream crossings (low-water bridge), 1 spring, 3 wetlands, 2 drains in wetlands and 1 estuary site. Sites that did not have wells represent the surface expression of the regional water table (e.g. estuary site). Monthly readings were taken in the period September 2008 to December 2009, June 2010 and February 2011 with the use of a Solinst water level meter. At some wells, additional PVC wells were installed to access the groundwater levels, especially those wells where the water levels dropped below the surface. The response of the water table after the dry periods with regard to a major rainfall event was measured for 12 sites during 3-7 March 2012 (Tropical Storm Irina).

The sites in the northern study area were selected based on their accessibility, permission from the community to measure the water levels and to have reference points not only from west to east along the transect but also points north and south to gain an overview of the groundwater distribution. The groundwater monitoring sites were 3-10 km apart. Appendix 1 lists the groundwater monitoring points. Groundwater electrical conductivity (EC) in micro-siemens per metre was measured at the Muzi System and some other sites with the use of an electrical conductivity meter.

5.3.6 Elevation

A land surveyor was contracted in June 2010 to measure the elevation at each groundwater monitoring site as well as cross-sections of the drainage lines (accuracy 3-6 mm) (see section 4.3.5).

5.3.7 Soil Investigations and Percentage SOC

5.3.7.1 Carbon Analysis Methods

The SOC from the southern transect was determined by using the dry combustion (Total C) method and from the northern transect by the rapid oxidation (Walkley-Black) method (The Non-Affiliated Soil Analysis Work Committee, 1990). The question was raised at the first inaugural Reference Group meeting (15 April 2009) as to how accurate the different SOC methods are with regard to analysing wetland soils on the MCP. Three carbon analysis methods, namely: Loss on Ignition (LOI = Total C), dry combustion (Total C) and rapid oxidation method [Soil Organic Carbon (SOC) – Walkley-Black (W-B)], were compared. Statistical analysis of the SOC data was done using MS Excel 2007.

5.3.7.2 Soil Surveys

Soil surveys have been carried out to complement the geological compilation (yellow points in Figure 5.3). (Pretorius, 2011; Pretorius, *in progress*). Soil surveys were done at the five wetlands identified along the 60 km transect (Grundling *et al*., 2010; Grundling *et al*., 2011) (see Figures 5.1 and 5.2 in section 5.3.4). The technique used to describe and sample the soil was either by soil/peat auguring or by describing a soil profile in an open pit. The following data were acquired in-field in June 2010 for each soil sample site: elevation, groundwater level, soil form and family and dominant vegetation type. The soil types were described using the procedure for describing soil profiles at ARC-ISCW (Turner, 1991). Sites that indicate peat resources from a survey done by Grundling *et al*. (1998) were also mapped (Figure 5.3). Laboratory analysis included the following: % SOC analysed with the Walkley-Black method.

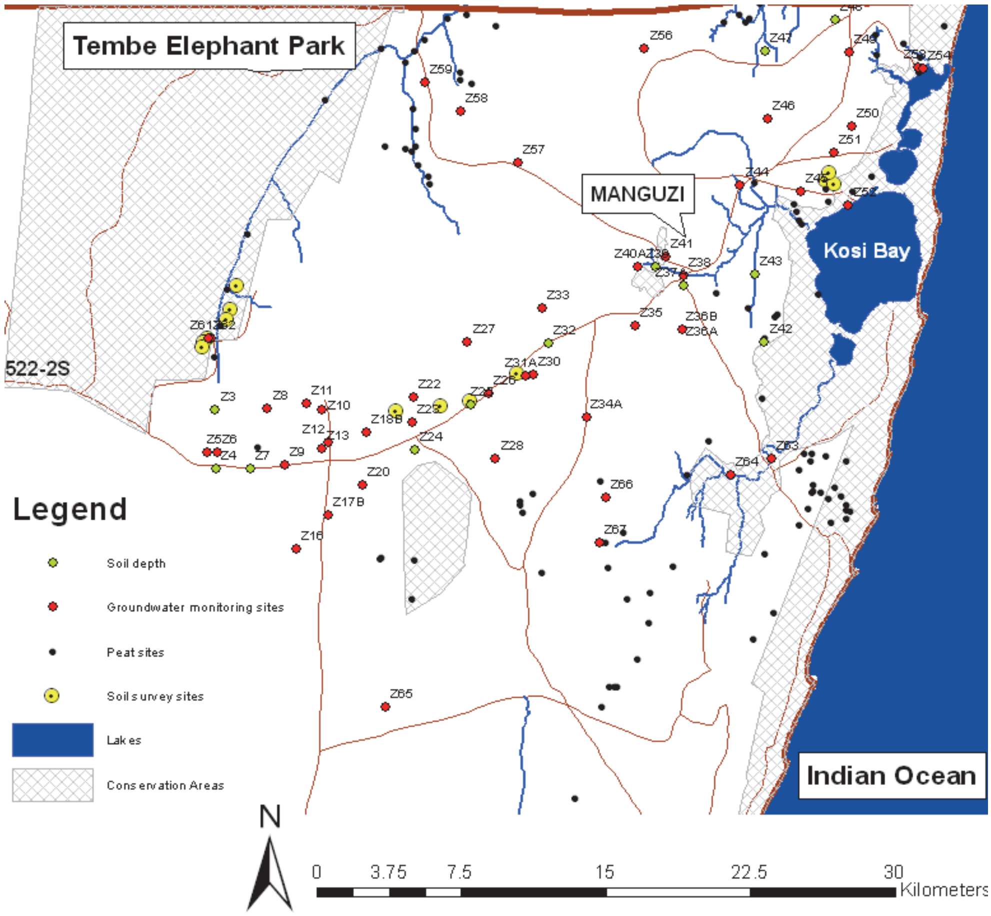


Figure 5.3: The red points indicate the groundwater monitoring sites. Soil surveys include: 1) survey in September 2011 to find impermeable layer (green points), 2) soil profile description sites (Pretorius, 2011; Pretorius, *in progress*) (yellow points) and 3) peat survey sites (black points) in the northern study area.

5.3.8 Wetlands

Existing datasets on wetland distribution include the National Freshwater Ecosystem Priority Areas (NFEPA) wetland type layer (Nel *et al*., 2011; Driver *et al*., 2011) based on the National Wetland Inventory (NWI) layer from SANBI (2010b). Other datasets include the KwaZulu-Natal (KZN) wetland layer (beta version) (Scott-Shaw and Escott, 2011) and Swamp Forests and Sub-tropical Freshwater Wetlands vegetation from VegMap 2006 (Mucina and Rutherford, 2006), as well as the results of Chapter 3 that indicate the permanent or temporary wetland distribution mapped with the use of Landsat TM imagery (see Figure 3.7D).

5.3.9 Vegetation Surveys

Three wetland repetitions of each of the four identified wetland systems that occur on the existing transect were selected based on accessibility, safety, land owner consent and data availability in order to duplicate results for statistical viability. Pretorius (2011) reported on the vegetation classification and description of the four wetland systems and their respective zones in the northern study area. These include the Muzi Swamp Wetland, Perched Pan, Upland Wetland and Interdune Depression. The Swamp Forest Wetland type occurring in the area was not included in the study due to budget and time constraints. The exclusion of this system is motivated by the ease with which the swamp forests can be delineated due to their terrain setting in steep valley-bottoms associated with drainage channels as well as the distinctive swamp forest vegetation. A lot of research has also been conducted on swamp forests, while the other systems merit some attention.

Relevés were compiled in each plot. The Braun-Blanquet cover abundance scale was used to allocate a value to each occurring plant species (Westhoff and Van der Maarel, 1978). Plots were 2 m x 2 m, based on the size and variety of the plant communities present in the wetlands. Vegetation and environmental data was collected according to the "South African Wetland Vegetation Survey Field Data Form" for each plot. Unknown plant species were collected, oven-dried and identified at the South African National Biodiversity Institute (SANBI) and the HGWJ Schweikerdt Herbarium at the University of Pretoria. Additional vegetation information was obtained from Gordon-Gray (1995), Pooley (1998), Van Oudtshoorn (2002), Cook (2004), Glen and Steyn (2010) and the SANBI website (SANBI, 2011a, 2011b). However, for the purpose of this report only basic descriptive vegetation data was linked with the wetland zones (permanent, seasonal and/or temporary, and terrestrial). These are the four zones present in Figures 5.4, 5.5, 5.6 and 5.7 for each wetland.

<u>**Muzi Swamp Wetland**</u>

The Muzi North Wetland system is a long, linear, valley-bottom with a channel (Figure 5.4). This system flows through the Tembe Elephant Park towards Mozambique in the north. Sampling was done within the Park in order to obtain undisturbed vegetation and soil samples. The western margin of the system is nestled against a steep dune. The sampling was therefore conducted on the eastern margin of the system where the slope is gradual and a greater variety of wetness zones are present. The system itself is a mosaic of micro-relief changes with associated vegetation communities and soil wetness regimes. The permanent zone of the system is also very trampled, probably by large animals. This complicated the intended sampling of the transect along a gradient of increasing wetness with associated SOC and vegetation.

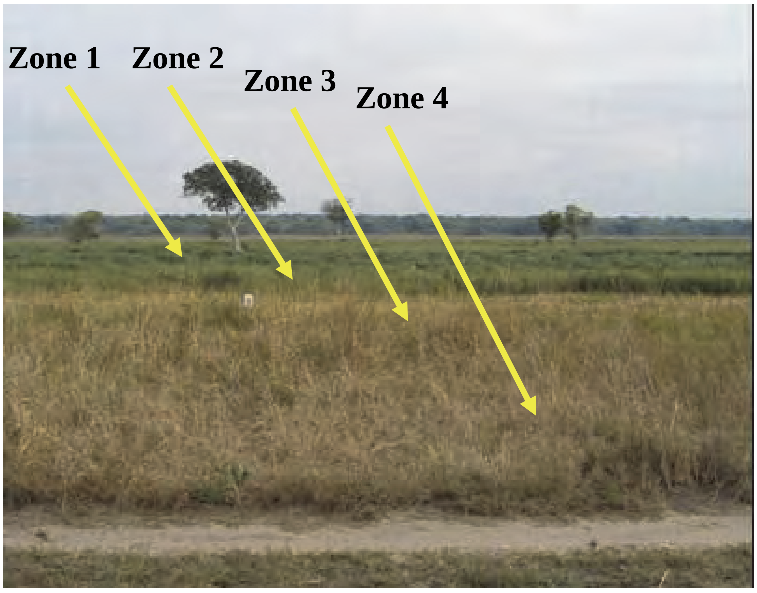
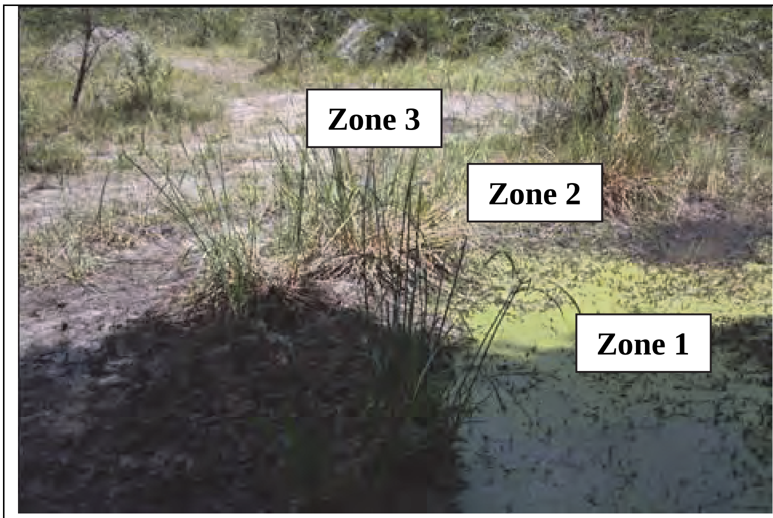


Figure 5.4: Muzi Swamp wetland with four vegetation zones.

Perched Pan

This system consists of a series of seasonal pans occurring parallel to the Muzi Swamp system on duplex soils (Figure 5.5A). The pans inside the Tembe Elephant Park occur as open areas surrounded by Bushveld. Outside the Park where the pans are being burnt, drained and utilised for cattle grazing the systems are more open and degraded. These pans are not linked with the regional water table, and are almost exclusively replenished by rainwater (Figure 5.5B). High clay content in the soil results in a perched water table for several months of the year.



A

B

Figure 5.5: A) Perched Pan system with three vegetation zones and B) dry soil profile with water table level on top.

Upland Wetland

This system is a moist grassland system on the upland area between Tembe Elephant Park and eManguze (Figure 5.6). The system is characterised by slightly undulating Lala Palm veld, with interspersed spaces of open, moist grassland. These moist grassland areas are flooded once every 10 years, according to local knowledge.

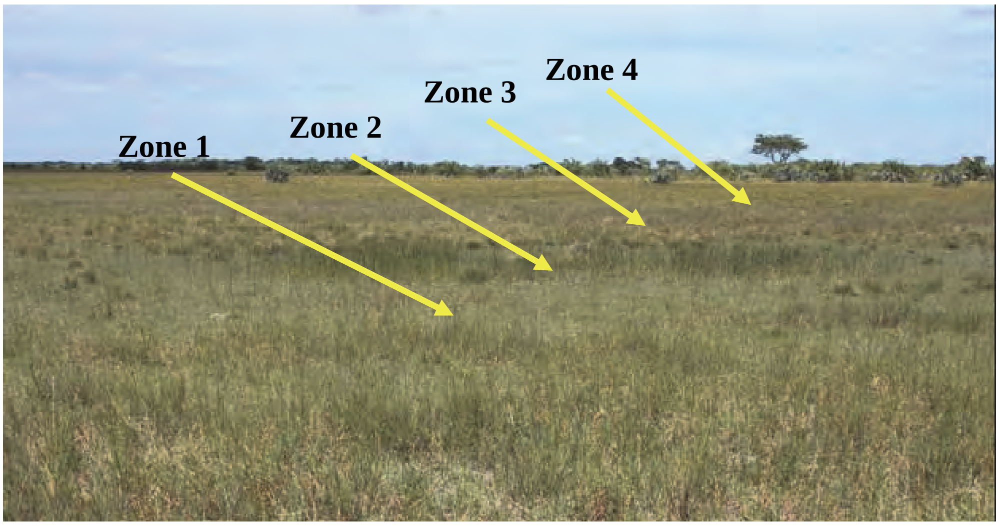


Figure 5.6: Upland Wetland system with four vegetation zones.

Interdune Depression

This system consists of depression type wetlands occurring between vegetated coastal dunes a few kilometres west of the shoreline (Figure 5.7). These depressions are linked with the regional water table. The soils of the undisturbed wetlands in this system are often high in SOC and peaty in character (Grundling *et al.*, 1998; Grundling, 2001). There is a high occurrence of local utilisation of the fertile peat soils for sustainable agriculture in these wetlands.

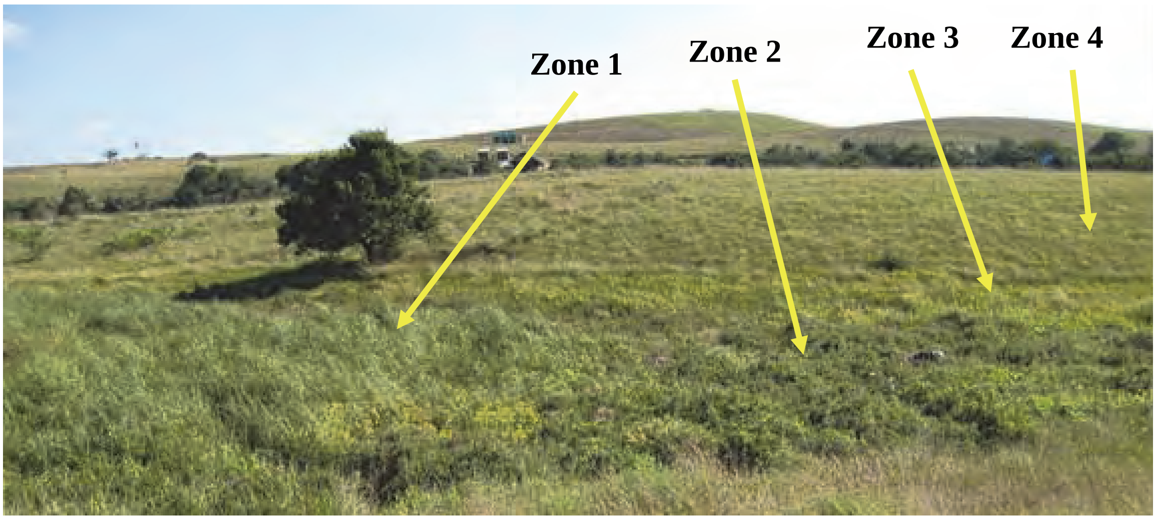


Figure 5.7: Interdune Depression system with four vegetation zones.

5.4 SOUTHERN STUDY AREA: LOCAL SCALE

The southern transect is a 2.15 km stretch situated across the south-western point of the Mfabeni mire system (Figure 5.8) (see section 1.5.1). The location of the southern transect was selected to work in symbiosis with WRC project K5/1857, supplementing the transects studying the hydrology of the Mfabeni Mire system. The transect consisted of wetlands that occur on an undulating plain with a central drainage line and a swamp forest. Six wetlands were selected along the 2.15 km transect that vary from permanently, seasonally and temporarily wet wetlands. In each wetland, different hydrological zones were selected on a west-facing catena (except for wetland no. 6 which is east-facing) with the use of descriptive vegetation communities. The following datasets were acquired for each site listed in Appendix 1: elevation, groundwater table level, soil form, % SOC and vegetation description.

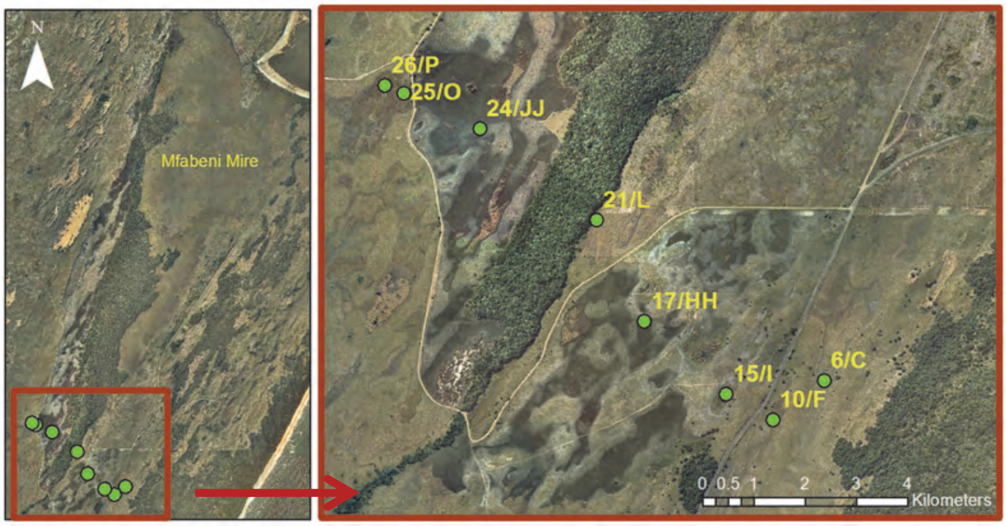


Figure 5.8: Groundwater monitoring sites in six wetlands on the Eastern Shores (green points).

5.4.1 Elevation

A land surveyor measured a total of 29 elevation points along the 2.15 km transect in June 2010 (accuracy 3-6 mm) (Figure 5.8). Of the 29 elevation sites, four sites were merely height points in the landscape while two included elevation points positioned at the dune crest (e.g. on the dune crest of wetland next to tar road (7/DD) and on the dune crest of wetland next to swamp forest (18/II)). Therefore, 23 sites along the transect included midslope, footslope and valley-bottom and two sites were spread in between the transect (17/HH and 24/JJ).

5.4.2 Groundwater Monitoring Sites

At each of the six wetland sites on the southern transect, PVC perforated pipes (wells) were installed vertically in the soil profile to a depth of 1.53-5.19 m in order to measure groundwater table fluctuation (Figure 5.9). Each well was protected with a steel pipe against veld fires, and was painted green and marked with a numbered plate. The top of each well was elevated to 200 mm above the surface. Therefore, the water table measurement readings were reduced by 200 mm. Bi-weekly readings were taken between the period June 2010 to February 2011 and January to March 2012. The Solinst water level meter (with a brake and carrying handle for 30 m depth capacity) was used to take the groundwater measurements.

Figure 5.9: Example of a groundwater monitoring site on the Eastern Shores. Note the PVC well with steel protection and numbered tag.

5.4.3 Soil Investigations and Percentage SOC

At these well sites, soil samples were collected for the Swamp Forest on 27 and 28 April 2009 and in December 2009, and for the remaining five wetlands soil samples were collected in December 2009. Additional pits were dug in June 2010, according to recommendations by the second Reference Group meeting held on 22 April 2010 in St. Lucia. A soil profile pit was dug to a depth of 1.2 m in each vegetation zone of the six wetlands to classify the soil form (Soil Classification Working Group, 1991) and to collect soil samples for SOC analysis. Soil and environmental data were collected using the Minimum Dataset for Describing Soil Form supplied by ARC-ISCW. Photos were taken of each soil profile. Soil and peat augers were used to take samples. Soil samples were air-dried, large pieces of plant debris were removed, and a porcelain mortar and pestle was used to grind sub-samples to pass a 2 mm sieve. The % SOC from the southern transect was determined using the dry combustion (Total C) method and from the northern transect by the rapid oxidation (Walkley-Black) method (The Non-Affiliated Soil Analysis Work Committee, 1990). Although the method of carbon analysis differs between the two transects the Total C and Walkley-Black methods have been shown to have a 1:1 relationship (Grundling *et al*., 2010). Statistical analyses for the SOC data were done using MS Excel 2007.

5.4.4 Vegetation Descriptions

Vegetation surveys were conducted by Dr. Erwin Sieben on 1-5 November 2010. A similar methodology approach to the northern study area was followed (see section 5.3.9).

5.5 RESULTS

5.5.1 Rainfall Data

See section 3.3.2, Figures 3.1 and 3.2.

5.5.1.1 Soil Samples and Percentage SOC

5.5.1.1.1 Soil Organic Carbon

Some limitations became evident during the SOC data analyses. The wetland repetitions – even though part of the same system – have been found to differ significantly in terms of SOC content, probably due to previous extensive sustainable agricultural practices in the wetlands in this area. For this reason one wetland repetition of the Interdune Depression (IDD) system was omitted using only two wetland repetitions in this study.

Both the IDD system and the Muzi Swamp (MS) wetland are regarded as peat wetlands (Grundling *et al*., 1998). This explains the similarity between the two systems, as can be observed in Figure 5.10A and B. These two systems have significantly higher SOC content than both Perched Pan (PP) and Upland (PL) wetland systems (Figure 5.10C and D). The IDD system was found to contain the highest SOC content of all the systems, with an average of 21.14% C in the top 100 mm of the soil in zone 1. The PL and PP systems are surprisingly similar, despite the fact that characteristically these systems are considerably different from each other. The soil profiles of these two systems are similar in terms of SOC content, as well as SOC distribution between the different zones.

In both the IDD system as well as the MS system it can be observed that there is a clear distinction between the first two zones with high SOC and the last two zones. SOC thus decreases sharply between zones 3 and 4 in both these systems. An interesting phenomenon is illustrated by Figure 5.10A and C where SOC seems to be higher in the 50-100 mm horizon than in the top 50 mm. This may be due to disturbance of the topsoil in the wet zones of the wetlands – in the IDD system due to sustainable agriculture and in the MS system due to trampling of the topsoil by animals. Zones 1 and 2 of both the IDD and MS systems are very similar up to 500 mm. The SOC profile of zones 3 and 4 of the MS system is relatively high in comparison to the SOC profile of zones 3 and 4 of the IDD system, which decreases sharply. This can be explained by the sharp rise in elevation in the IDD system in comparison to the gradual rise in slope in the MS system.

In a local landscape, texture and drainage of soils are a huge determinant of SOC content. According to Adhikari *et al*. (2009) soil organic matter is generally higher in clay soils than in sandy soils due to the increases in nutrients and water-holding capacity of fine-textured soils. The smaller pores in these soils also restrict aeration and reduce the rate of organic matter oxidation. In poorly drained soils, the high moisture supply promotes litter production and the poor aeration inhibits organic matter decomposition. This was not found to be true on the MCP. The PP and PL systems (Figure 5.10C and D) are good examples of sandy and clay systems and both have similar SOC profiles. In comparison with the MS and IDD systems, the PL and PP systems have a much more gradual decrease of SOC in the top 50 mm, and the range of SOC variability is also much smaller. In both these systems SOC content reaches less than 0.5% at 500-600 mm. In Figure 5.10C it can be observed that SOC in the top 50 mm is much higher in zone 2 than in zone 1. This is contradictory to what has been found so far, but might be explained by trampling of animals in the inundated zone during dry months (when sampling was done) in order to access drinking water.

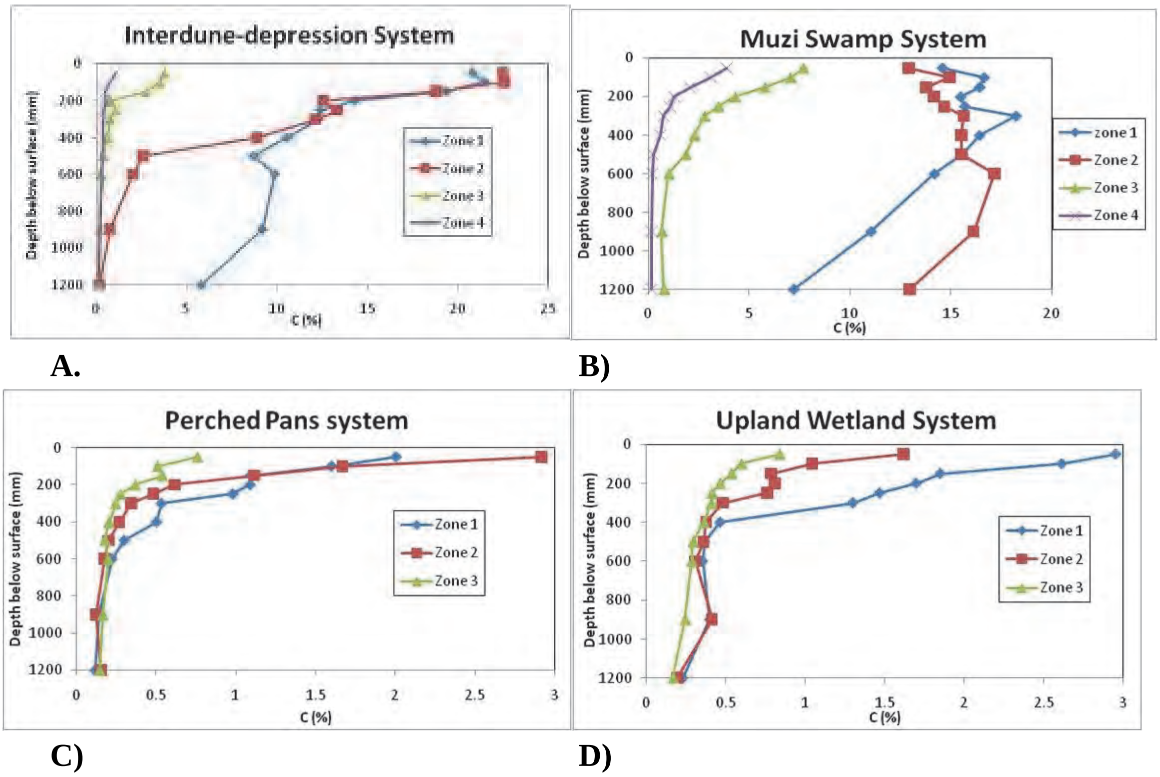


Figure 5.10: Soil organic carbon content in the A) Interdune Depression system, B) Muzi Swamp system, C) Perched Pan system and D) Upland Wetland system.

5.5.1.2 Descriptive Vegetation Communities

<u>System 1: Muzi Swamp</u>

Zone 1: *Phragmites australis* zone

Zone 1 of the MS system was found to be dominated by *Phragmites australis-Phyla nodiflora* communities. *Stenotaphrum secundatum* was also found in association with *Phyla nodiflora*. *Phragmites australis* usually dominates swamps and shallow water at the margins of wetlands. *Phyla nodiflora* usually occurs around the edges of lakes or in seepage areas and floodplains. All the species, with exception of the facultative *Stenotaphrum secundatum*, are obligate wetland species.

Zone 2: *Cladium mariscus* zone

Zone 2 of the MS system is dominated primarily by a *Cladium mariscus* stand with strong association with an undergrowth layer dominated by *Cynodon dactylon*. As discussed above, *Cladium mariscus* is coupled to high water table and high SOC content.

Zone 3: Graminoid zone

Zone 3 is dominated primarily by *Imperata cylindrica-Dactyloctenium aegyptium* communities, with *Cynodon dactylon* and *Phragmites australis* present with low cover values. *Imperata cylindrica* is a facultative wetland plant found frequently in seasonally wet places. *Dactyloctenium aegyptium* is regarded an opportunistic plant, known to occur in disturbed moist areas.

Zone 4: Graminoid-herbaceous zone

In zone 4 the non-wetland species *Hyperthelia dissoluta* is most frequent and has strong association with the dominant species *Dichrostachys cinerea* and *Eragrostis heteromera*. Other common species present include *Acalypha villicaulis, Acacia nilotica* and *Cymbopogon excavates*. These species are typical open woodland species. All the species in this zone are regarded as non-wetland species, with the exception of *Eragrostis heteromera* which is a facultative species growing in damp areas.

System 2: Perched Pan

The PP system is a series of pans with a water table perched on a clay layer. During summer months the pans are filled with water with hydrophytic and hydrophilic plant species present within this waterlogged area of the pan. The second vegetation zone surrounding the hydrophytic zone 1 is usually sparsely vegetated (due to trampling by animals). The third zone is the densely vegetated surrounding bushveld.

Zone 1: Hydrophytic/hydrophilic zone

Zone 1 of this system is characterised by the submerged aquatic plant species *Ludwigia sp.* and *Lemna gibba,* as well as *Cyperus fastigiatus-Echinochloa colona* sedge and graminoid communities. *Ludwigia sp.* is a submerged, floating, emergent or seasonally submerged plant species. *Lemna gibba* is a perennial, obligate wetland species which occurs in a wide range of aquatic habitats as a free-floating hydrophyte. *Cyperus fastigiatus* is an obligate wetland species growing in open water or towards margins where rhizomes are periodically inundated. *Echinochloa colona* is the only facultative species in this zone but is known to occur in pans or vleis where rain collects, often in trampled, overgrazed loam or clay soils.

Zone 2: Graminoid-herbaceous zone

This zone is dominated by the sedge *Cyperus fastigiatus;* graminoids *Cynodon dactylon* and *Eragrostis rotifer;* and herbaceous *Ocimum americanum* communities. *Cyperus fastigiatus* is an obligate wetland species occurring in permanent pools, wet marshy areas, or margins of pools. *Cynodon dactylon* and *Eragrostis rotifer* are both facultative wetland plants growing on margins of wetland areas. *Ocimum americanum* is regarded as a non-wetland species.

Zone 3: Woodland zone

This zone is dominated by *Acacia karroo-Panicum maximum* communities, with some strong associations with *Cynodon dactylon*. These species are known for their ability to tolerate seasonally wet soils, although they are not recognised as wetland species.

System 3: Upland Wetlands

This system is regarded as a seasonally moist grassland system. The vegetation zones differentiate into three to four zones, all of which are seasonal to terrestrial.

Zone 1: *Centella asiatica* zone

Zone 1 is a slight depression dominated by the ever-present *Centella asiatica* in association with various graminoid and sedge species, namely *Cynodon dactylon, Stenotaphrum secundatum, Cyperus solidus* and *Cyperus natalensis. Centella asiatica* is a facultative species known to occur in mostly damp or soggy grasslands or seasonal wet areas. The rest of the dominant species occurring in this zone are all facultative wetland species known to occur next to dams, vleis or seasonally wet wetlands.

Zone 2: Graminoid zone

Zone 2 surrounds the slight depression considered as zone 1. The vegetation composition stays very similar to zone 1, but with different dominant species. The most dominant plant species are the graminoids *Cynodon dactylon* and *Hemarthria altissima* in association with the herbaceous *Centella asiatica.* These are all facultative wetland species known to occur in seasonally wet areas.

Zone 3: *Cyperus natalensis* zone

This zone is distinguished from the other zones by the dominant presence of *Cyperus natalensis.* Other dominant species include *Bulbostylis contexta*, *Eragrostis inamoena* and *Hemarthria altissima*. *Cyperus natalensis* is found in water but mostly acts as a sand-binder, growing in coastal grasslands on a sandy substrate. *Eragrostis inamoena* is a hygrophillous grass found in areas with a high water table, and also in sandy to organically rich soils around margins of seasonally flooded areas. *Bulbostylis contexta* and *Eragrostis biflora* are regarded as mesophytic, non-wetland species which often occur in sandy areas.

Zone 4: Graminoid zone

Zone 4 is characterised by mainly *Sorghastrum stipioides.* This species is regarded as a facultative wetland species often encountered in moist grasslands. The graminoids *Eragrostis lappula*, *Eragrostis heteromera* and *Eragrostis gummiflua* are also dominant in this zone. These species are found in damp sandy soils surrounding wetlands.

System 4: Interdune Depression

Zone 1: Sedge zone

Zone 1 of the IDD system is dominated by *Cladium mariscus.* In the wetland repetitions where *Cladium mariscus* was absent from zone 1, strong *Schoenoplectus corymbosus* and *Cyperus sphaerospermus* associations dominated. Other species with lower cover values in this zone include *Cyperus natalensis, Thelypteris interrupta* and *Persicaria lapathifolia. Cladium mariscus* is regarded a perennial, obligate, hydrophytic wetland species, which often dominates in shallow permanent or semi-permanent water. On the northern transect all the relevés containing *Cladium mariscus* are associated with high water table and the Champagne soil form (in most cases peat soil). This species was also found in the Muzi Swamps. All the other species found in zone 1 are obligate wetland species, except for *Persicaria lapathifolia,* which is a facultative wetland species.

Zone 2: Graminoid-herbaceous zone

Zone 2 of the IDD system is dominated by *Hemarthria altissima,* a perennial, obligate wetland graminoid species. One of the repeat wetlands displayed a dominant *Dissotis canescens-Persicaria serrulata* association. Both these species are also considered obligate wetland species occurring in marshes. *Imperata cylindrica* occurs as well, but with a much lower cover value. This species is known to occur in seasonally wet places.

Zone 3: Graminoid zone

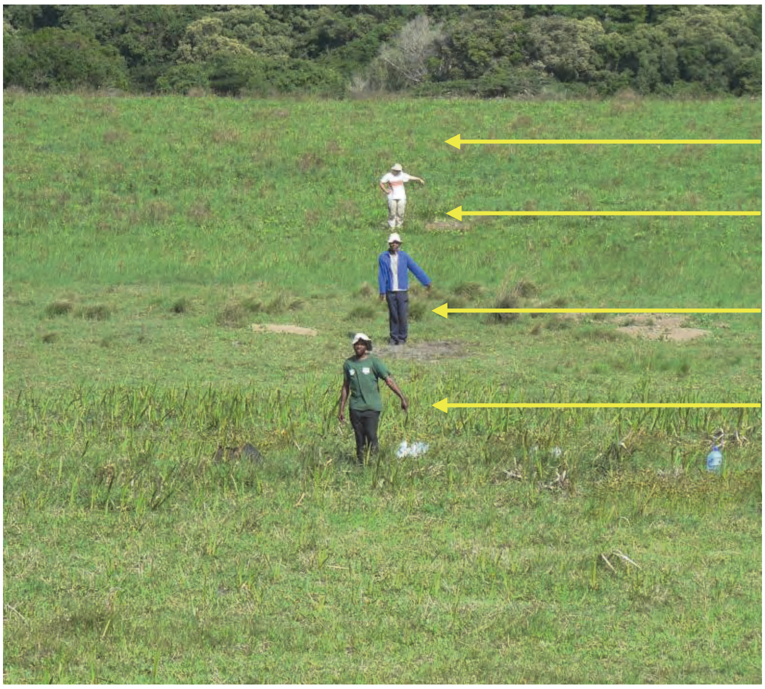
Zone 3 of the IDD system consists of a variety of terrestrial plant species with one occurrence of a facultative wetland species. The non-wetland species include *Trachypogon spicatus, Vernonia oligocephala, Themeda triandra* and *Digitaria eriantha.* Although these species are not regarded as wetland species, they are often encountered near wet places. *Sorghastrum stipoides* is the only facultative wetland species in this zone, but is quite dominant.

5.5.2 Southern Study Area

5.5.2.1 Soil and Vegetation Descriptions and Percentage SOC

Wetland 1

Wetland 1, zone 1 was only inundated for about two weeks from 22 February to 2 March 2011 during the ten months (June 2010 - February 2011) that the groundwater table levels were monitored (N.B. monitoring is still ongoing). Wetland 1 has the second highest elevation (zone 1 elevation is 7.45 m.a.s.l.) in comparison with the other five wetlands. However, it can be expected that zone 1 in wetland 1 could be wet during very wet years or during flooding events due to the presence of facultative vegetation species. The groundwater table depth stays consistent over distance (i.e. zones 1 to 4) and only fluctuates over time. The groundwater table does not follow the topography but drops towards the east (Indian Ocean) (Grundling, 2009; Taylor *et al*., 2006). Therefore, due to the rising elevation, zones 2, 3 and 4 become significantly drier than zone 1 (Figures 5.11 and 5.12).



Zone 4, site 3/A
Zone 3, site 4/CC

Zone 2, site 5/B

Zone 1, site 6/C

Figure 5.11: Wetland 1 and the position of the different wetness zones with their site number.

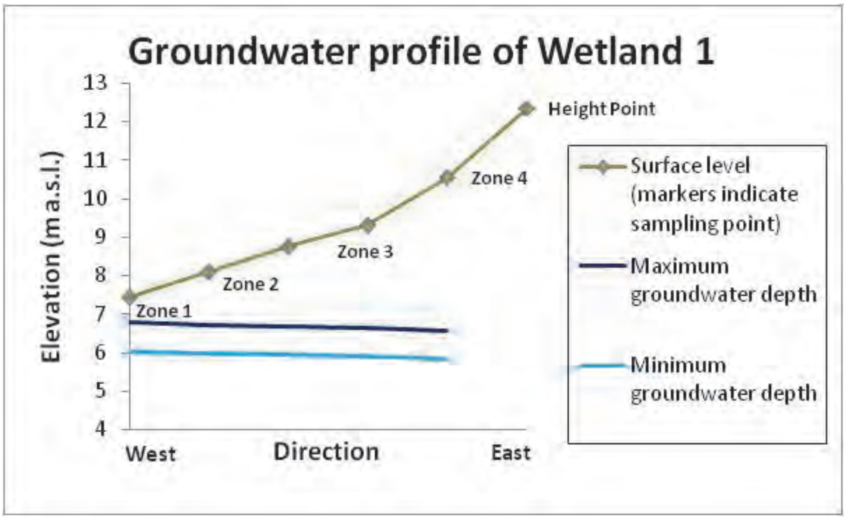


Figure 5.12: Groundwater profile of Wetland 1.

The SOC graph indicates a much higher SOC percentage in the top 50 mm of the profile in zone 1 (4%) than the other zones (Figure 5.13). Up to a depth of 150 mm the SOC content seems indicative of this zone. This is due to the elevated water table. Zones 2, 3, and 4 appear to be quite similar, despite the anomaly in the first 300 mm of zone 2. SOC content for zone 2 is significantly higher than for zones 3 and 4.

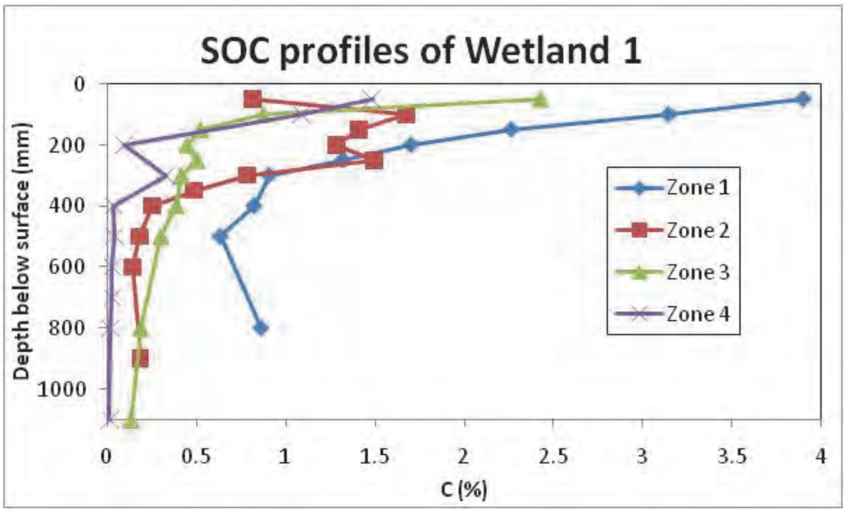


Figure 5.13: Soil organic carbon profiles of Wetland 1.

Vegetation Description in Zone 1 (6C)

Although zone 1 was inundated for two weeks during the time of monitoring, the vegetation still indicates a wet zone. The facultative wetland plant *Stenotaphrum secundatum* is usually found near water, growing mostly in sandy soils in warm regions. This species was found to dominate zone 1 in wetland 1. Other species occurring with lower cover values are *Centella asiatica*, *Cyperus sphaerospermus* and *Hemarthria altissima*. *Cyperus sphaerospermus* is often found growing in moist alluvium along margins of swamps. *Hemarthria altissima* is a perennial graminoid tolerant of waterlogging, and is also regarded a facultative wetland species.

Vegetation Description in Zone 2 (5B)

Centella asiatica is an herbaceous, mesophytic perennial plant regarded as a facultative wetland plant.

Vegetation Description in Zone 3 (4CC)

This zone is characterised mainly by graminoid species. *Trachypogon spicatus* is mostly encountered in undisturbed grassland, often near, but not in, vleis. The species *Sporobolus subtilis* is regarded as a facultative wetland plant known to grow in damp places, while *Ischaemum fasciculatum* is regarded an obligate, emergent hydrophyte.

Vegetation Description in Zone 4 (3A-2BB)

This zone is primarily characterised by the occurrence of the graminoids *Helichrysum kraussii, Schizachyrium sanguineum* and *Themeda triandra*. These species are all known to occur in open grassland in high rainfall areas, but none are regarded wetland plant species.

<u>Wetland 2</u>

Zone 1 in wetland 2 has the highest elevation for all six wetlands at 7.82 m.a.s.l. (Figure 5.14). The water table in this wetland is at least 1 m beneath the surface during the wet season, and almost 2 m beneath the surface during dry months (Figure 5.15). Zone 1 is probably only inundated during periods of incessant rain, during very wet years, or during times of flooding. The groundwater table stays consistent over distance and only fluctuates over time. Therefore, due to the higher elevation at zones 2, 3 and 4, they are significantly drier than zone 1. As in wetland 1, the SOC graph indicates a very high SOC content (6.8% in the top 50 mm of the profile) that is significantly higher than in zones 2 and 3 (Figure 5.16). Zones 2 and 3 are very similar, as in wetland 1.

Zone 1, site 10/F

Zone 2, site 9/E

Zone 3, site 8/D

Zone 4, site 7/DD

Figure 5.14: Wetland 2 and the position of the different wetness zones with their site number.

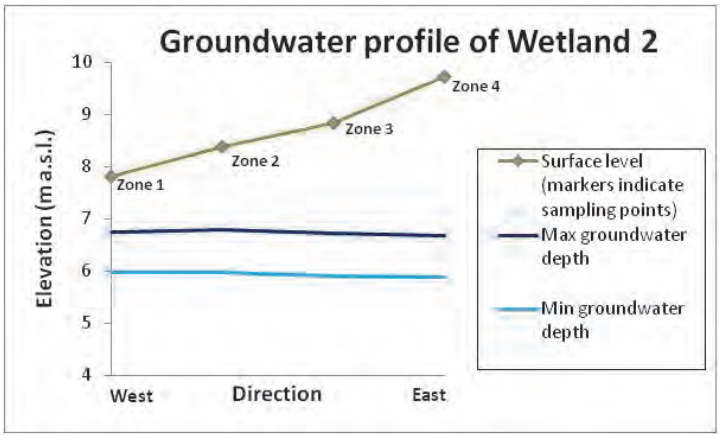


Figure 5.15: Groundwater profile of Wetland 2.

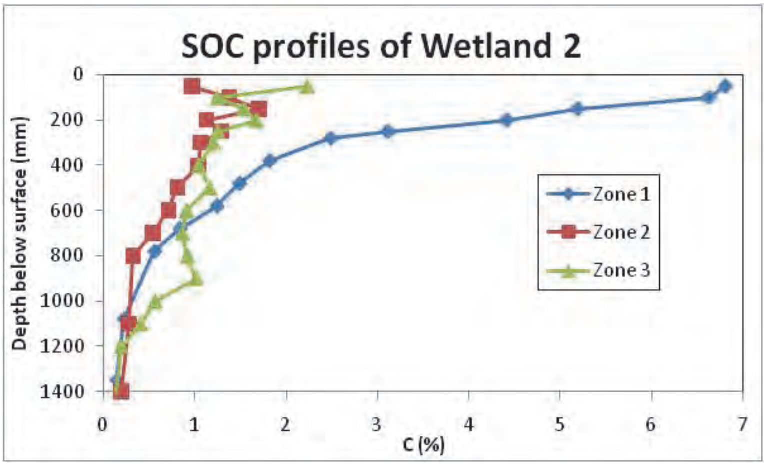


Figure 5.16: Soil organic carbon profiles of Wetland 2.

Vegetation Description in Zone 1 (10F)

Centella asiatica dominates the zone with a high cover value, while the graminoid *Paspalum vaginatum* occurs sporadically. *Paspalum vaginatum* is an obligate wetland plant growing in or near water-bearing places such as dams, rivers or vleis in high rainfall areas.

Vegetation Description in Zone 2 (9E)

This vegetation zone is dominated by a *Sporobolus subtilis*-*Restio zuluensis* community. *Sporobolus subtilis* is regarded a facultative wetland species, while *Restio zuluensis* is regarded an obligate wetland species that grows in seasonally waterlogged wetland areas.

Vegetation Description in Zone 3 (8D)

This zone is dominated by *Sporobolus subtilis*. As discussed above, this species is regarded as a facultative wetland plant known to grow in damp places. *Schizachyrium sanguineum* also occurs.

Vegetation Description in Zone 4 (7DD)

This zone is characterised by an association of five species (*Aristida sp.*, *Fimbristylis sp.*, *Helichrysum kraussii*, *Stylosanthes fruticosa* and *Ischaemum fasciculatum*) with equal cover values. These are typical plant species and a typical plant community structure of an area located outside regions of inundation. *Ischaemum fasciculatum*, however, is regarded as an obligate wetland plant.

Wetland 3

Zone 1 of wetland 3 is inundated for 3 months a year from 4 January to 2 March 2011 during the ten months (June 2010 - February 2011) that the groundwater table levels were monitored (Figure 5.17). During dry months the water table drops at least 1 m (Figure 5.18). The SOC profiles for this wetland indicate that it is a peat wetland, with a very high SOC content in zone 1 (25.41% in the top 50 mm of the profile, Figure 5.19). SOC content in zones 2, 3 and 4 appears to correlate with wetland 1, zones 1, 2 and 3. The high SOC is probably due to the high water table for most of the year. This also explains the dominant vegetation in zone 1.

Photo A: 21 May 2008

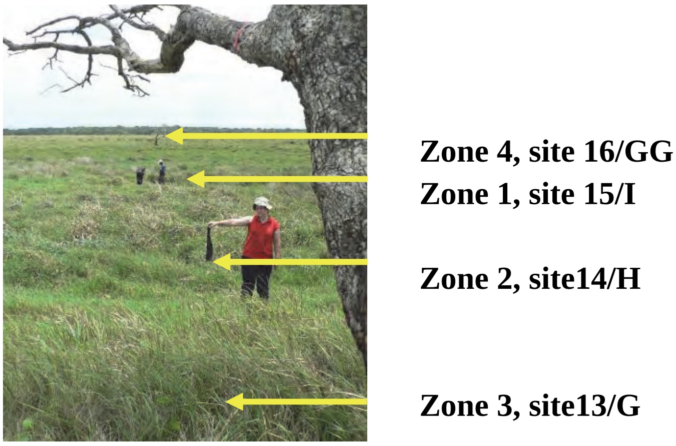


Photo B: 8 December 2009

Photo C: 2 November 2010

Photo D: 22 February 2011 – water table 0.13 m above surface

Figure 5.17: Wetland 3 vegetation and surface water during different months and years.

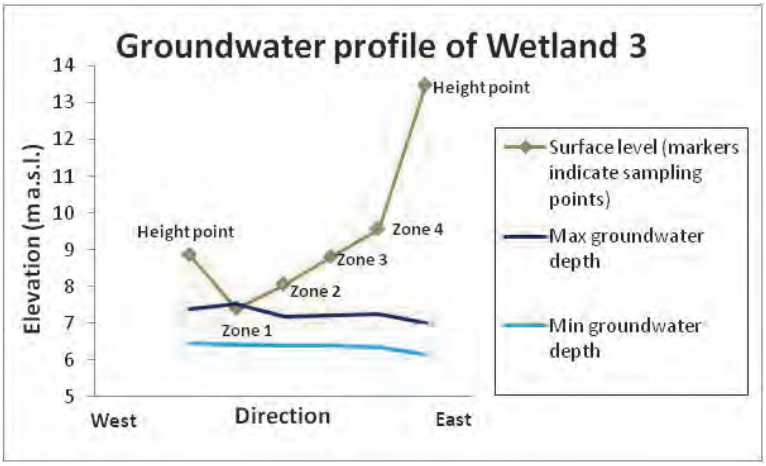


Figure 5.18: Groundwater profile of Wetland 3.

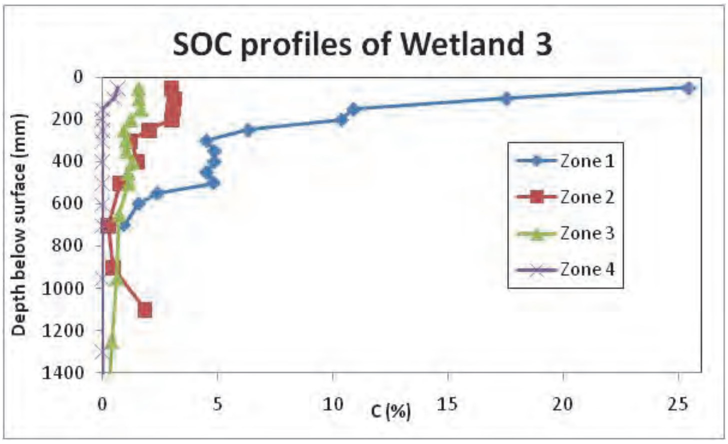


Figure 5.19: Soil organic carbon profiles of Wetland 3.

Vegetation Description in Zone 1 (15I)

This zone is dominated by *Eleocharis limosa*, a species present in sandy soils in vleis, either in the permanently wet areas or in margins where levels fluctuate.

Vegetation Description in Zone 2 (14H)

Paspalum vaginatum has the highest cover value in this zone. As discussed above, *Paspalum vaginatum* is an obligate wetland plant growing in or near water-bearing places. *Centella asiatica* is also present with a slightly lower cover percentage, as well as *Hydrocotyle bonariensis*, an herbaceous species that favours wet sand by brackish lagoons, peaty depressions and in ditches.

Vegetation Description in Zone 3 (13G)

This zone is characterised by the graminoids *Imperata cylindrica*, *Hemarthria altissima* and *Panicum glandulopaniculatum*. All the species in this zone, with the exception of *Panicum glandulopaniculatum*, are regarded as facultative wetland species.

Vegetation Description in Zone 4 (12FF and 16GG)

This zone, like the other upland wetland zones, is characterised by mainly *Helichrysum kraussii*, a species known to occur in open coastal grassland in high rainfall areas, but not regarded as a wetland plant species.

Wetland 4

Although soil and elevation data were collected in zones 1 and 2, the vegetation for these two zones was similar and incorporated into one vegetation community (Figure 5.20). No water table data exists for zone 1. The groundwater table data monitored over a period of 10 months indicates that from 4 January to 2 March 2011 the water table was above, at, or 0.50 m below the surface in zone 2. Therefore zones 1 and 2 are seasonally inundated (Figure 5.21).

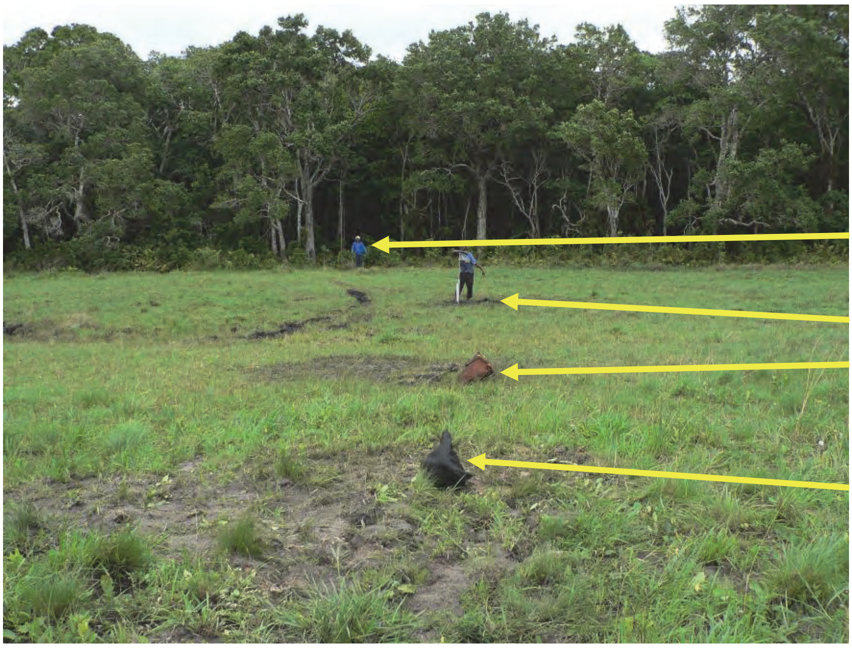


Figure 5.20: Wetland 4 and the position of the different wetness zones with their site number.

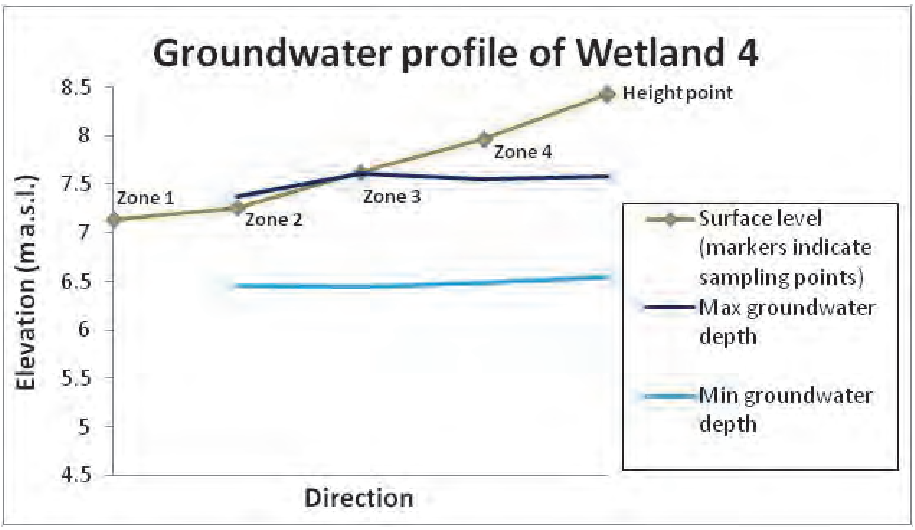


Figure 5.21: Groundwater profile of Wetland 4.

The only difference between the two zones can be seen in the SOC content in the top 50 mm of the profile (zone 1: 12.35% SOC; zone 2: 10.19% SOC). In both these zones the soil can be classified as Champagne soil form due to the high SOC content (>10%) (Figure 5.22). Zones 3 and 4 have a significantly lower SOC content in the top 50 mm of the profile (zone 3: 4.60% SOC; zone 4: 1.59% SOC), probably due to the lower water table. These hydrology and soil characteristics result in the distinguished plant communities.

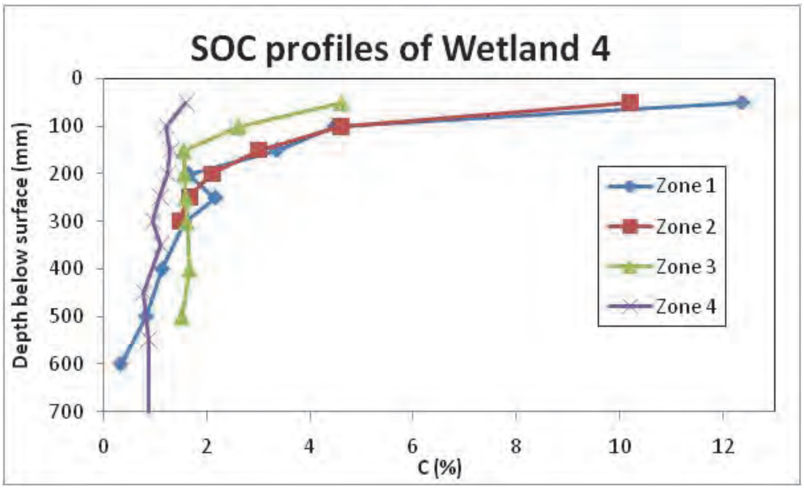


Figure 5.22: Soil organic carbon profiles of Wetland 4.

Vegetation Description in Zone 1 & 2 (22M & 21L)

This community is characterised by *Ischaemum fasciculatum*, *Centella asiatica* and *Rhynchospora rubra*. All these species are regarded as obligate wetland species.

Vegetation Description in Zone 3 (20K)

In this zone, *Ischaemum fasciculatum* (obligate wetland species) dominates with a slightly higher cover value than *Themeda triandra*, also dominant in this zone.

Vegetation Description in Zone 4 (19J)

This zone is distinguished by a variety of facultative and non-wetland species, namely *Alloteropsis semialata, Sporobolus subtilis, Setaria sphacelata, Lobelia sp., Trachypogon spicatus* and *Gerbera sp*. These species are all common in grassland and moist grasslands. All the species present in this community have near to equal cover percentages.

Wetland 5

Figure 5.23D illustrates the swamp forest conditions. Although there was no surface water on 30 November 2009 (Figure 5.23B), the peat soils were wet with the water table near the surface for the entire period that the groundwater was monitored (June 2010 - February 2011). The permanently saturated zone 1 in the swamp forest consists of peat soils with 28.79-40.09% SOC (Figure 5.23C) while zone 2 shows a sharp reduction in SOC content to 1.67% (Figures 5.23D and 5.24).

Photo A: Swamp forest after a rain event on 21 September 2008.

Photo B: Swamp forest with no surface water (30 November 2009).

Photo C: Peat substrate found in the swamp forest (zone 1, site 23/N). A peat auger was used to sample every 20 cm starting at 40 cm at site ES SF2. Note the sand layer at a depth of 155 cm.

Photo D: Soil sample site in zone 2 on the edge of the swamp forest in the terrestrial zone.

Figure 5.23: Swamp forest conditions illustrated with photos A to D.

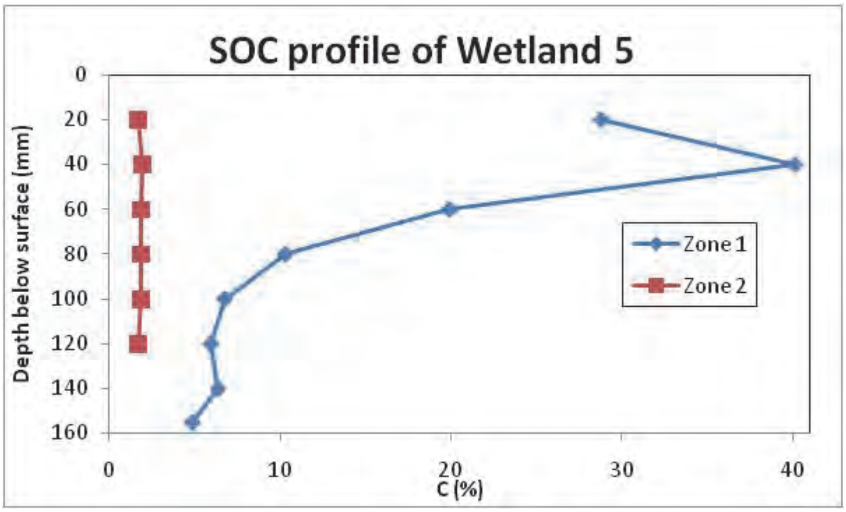


Figure 5.24: Soil organic carbon profiles of Wetland 5.

Vegetation Description in Zone 1 (23N)

This zone is characterised by typical swamp forest plant species. The dominant species found in this zone are *Barringtonia racemosa, Nephrolepis biserrata* and *Stenochlaena tenuifolia*.

Wetland 6

Both zones 1 and 2 are inundated during the wet months (Figure 5.25) with 11.85% SOC in zone 1 and 6.96% SOC in zone 2 in the top 50 mm of the profile. Figure 5.26 shows that zone 2 is more of a seepage zone (confirmed by the lower SOC content as well as the plant species). In the topsoil the difference between the zones in terms of SOC content is well defined (Figure 5.27). In the subsoil, however, SOC content appears to be the same in zones 1, 2 and 3 at a depth of more or less 450 mm.

Figure 5.25: Wetland 6 and the position of the different wetness zones with their site number.

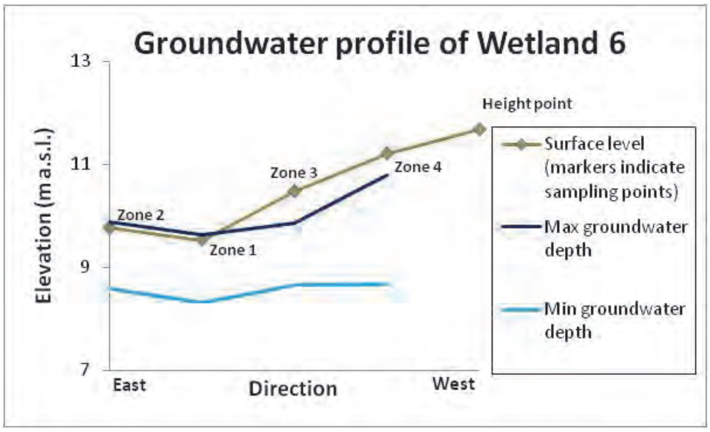


Figure 5.26: Groundwater profile of Wetland 6.

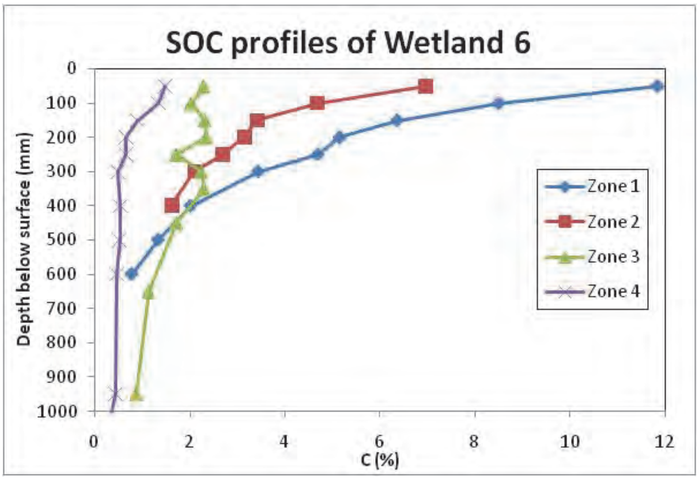


Figure 5.27: Soil organic carbon profiles of Wetland 6.

Vegetation Description in Zone 1 (26P)

This zone is strongly dominated by *Ischaemum fasciculatum*, an obligate wetland species.

Vegetation Description in Zone 2 (25O)

This zone is strongly dominated by *Panicum glandulopaniculatum*, a facultative wetland species.

Vegetation Description in Zone 3 (27Q)

This zone is characterised by a mixture of obligate and facultative species. *Centella asiatica* is present with a slightly higher cover value, with *Restio zuluensis*, *Eragrostis sarmentosa* and *Themeda triandra* occurring with lower cover values.

Vegetation Description in Zone 4 (28R)

Eugenia albanensis, a non-wetland species occurring on coastal grasslands, dominates this zone along with *Elephantorrhiza elephantine*, also a non-wetland species. Co-occurring, but with lower cover percentages, are the facultative wetland species *Helichrysum kraussii, Imperata cylindrica* and *Eragrostis sarmentosa*.

5.6 DISCUSSION

5.6.1 Wetland Type Characteristics

The elevation, hydroperiod (above, at, or 0.50 m from surface), soil form, % SOC (0-200 mm) and vegetation group (data for each monitoring site) in the four wetland types on the northern study area are summarised in Table 5.1. Likewise Table 5.2 summarises the environmental factors in each zone of the six wetlands surveyed on the southern study area. The detailed data sheets for % SOC values and water table readings are given in Appendix 2, 3, 4 and 5.

The vegetation composition of wetland zones in different wetland systems on the north-eastern MCP has provided a valuable contribution to our knowledge on the main drivers of plant communities to aid wetland delineation in the MCP. The results from the study indicate that different plant species groupings are characteristic of the wetland zones and the major determinants are the substrate and hydrological regime (Pretorius, 2011). However, wetland delineation using vegetation composition varies between the different wetland types, e.g. swamp forest have clear boundaries with species exclusive to the specific wetland, whereas the rest of the wetlands on predominantly sandy substrate have species not exclusive to the type of wetland.

Primary accumulation of SOC was correlated with the hydrological regime – higher organic production in lower-lying landscape positions. The % SOC content is directly linked to the period of inundation (hydroperiod) (Figure 5.28). According to the definition the Champagne soil form contains organic carbon of 10% at 0-200 mm and is for long periods saturated with water (Soil Classification Working Group, 1991), while peat comprises at least 30% (dry mass) of dead organic matter (IPS/IMCG, 2010). The SOC content measured 0-50 mm from the soil surface in wetlands that were saturated for 3 months of the year had ≥10% SOC, while wetlands saturated for 10 months of the year had ≥25% SOC. However, soils classified as Champagne soil form in the field had only 4.97% and 7.97% SOC with a hydroperiod that varied from 3-13 months saturated during the full monitoring period of June 2010 to February 2011 and January to March 2012 respectively. The SOC profiles indicated no significant difference between the seasonally and temporarily saturated zones, especially on the wetlands occurring on the higher elevations because of the large groundwater fluctuation (0-2 m). In all the wetlands, average % SOC (0-200 mm soil depth) in the terrestrial zone is low (0.32-1.67%) in the topsoil. The results indicate that the Walkley-Black method is the most suitable to measure SOC in order to determine the hydroperiod for the delineation and classification of permanent, seasonal and temporal wetlands on sandy coastal aquifers. Should cost not be a factor, the dry combustion method can be considered as an alternative.

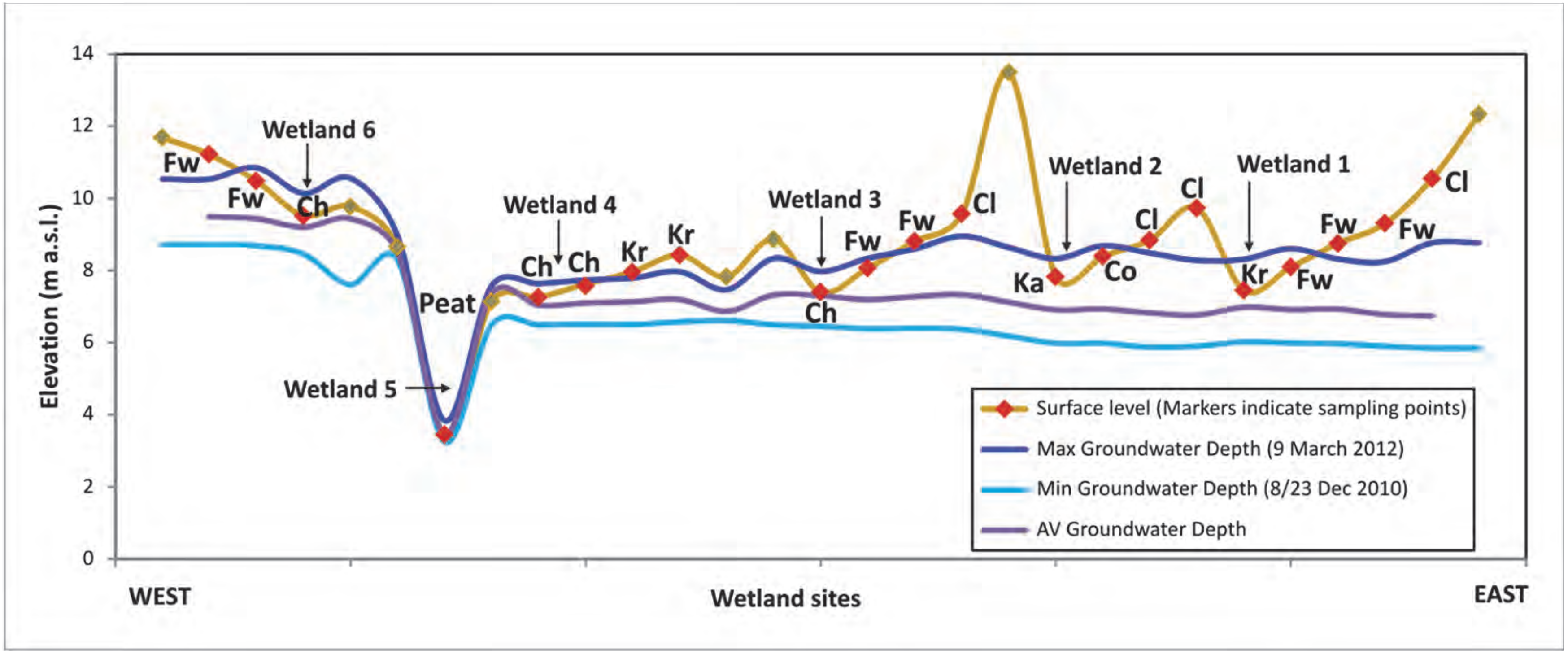


Figure 5.28: Groundwater profile and soil forms along the southern transect. Fw = Fernwood; Ch = Champagne; Kr = Kroonstad; Cl = Clovelly; Co = Constantia; Ka = Katspruit.

Table 5.1: Environmental factors for the five wetland systems on the northern study area

Zone and Site No.	Elevation (m.a.s.l.)	Hydroperiod (no. of months) 0 = no hydroperiod	Average % SOC (0-200 mm)	Soil Form	Vegetation	
					Plant Classification	Species composition
Perched Pans						
Zone 3:	50	-	0.64 (top 100 mm)	Sterkspruit	Non-wetland plants	*Acacia nilotica, Acacia karroo, Justicia flava, Panicum maximum*
Zone 2:	50	?	2.00 (top 100 mm)	Sterkspruit/ Katspruit	Facultative Obligate	*Cyperus fastigiatus, Echinochloa colona*
Zone 1:	50	6-8	1.80 (top 100 mm)	Katspruit	Submerged aquatic sp. Obligate Facultative	*Lemna gibba*
Muzi Swamp Wetland						
Zone 4:	47	-	2.20 (top 100 mm)	Longlands	Non-wetland plants	*Acacia nilotica, Hyperthelia dissoluta*
Zone 3:	46	?	6.80 (top 100 mm)	Cf. Westleigh	Facultative	*Imperata cylindrica*
Zone 2:	45	Permanent	13.94 (top 100 mm)	Champagne	Obligate	*Cladium mariscus, Phragmites australis, Stenotaphrum secundatum, Cynodon dactylon, Dactyloctenium aegyptium*
Zone 1:	45	Permanent	15.61 (top 100 mm)	Champagne	Obligate	
Upland Wetlands						
Zone 3:	77	-	0.72 (top 100 mm)	Longlands	Non-wetland plants Hygrophilous grass	*Cyperus natalensis, Bulbostylis contexta*
Zone 2:	77	-	1.34 (top 100 mm)	Fernwood	Facultative	*Cyperus natalensis, Centella asiatica, Hemarthria altissima, Eragrosits heteromera*
Zone 1:	77	-	2.79 (top 100 mm)	Fernwood	Facultative	
Interdune Wetlands						
Zone 4:	20	-	0.92 (top 1000 mm)	Fernwood	Non-wetland plants	*Themeda triandra, Trachypogon spicatus*
Zone 3:	18		3.65 (top 100 mm)	Fernwood	Facultative	*Cladium mariscus, Cyperus natalensis, Hemarthria altissima, Thelypteris interrupta*
Zone 2:	17	Permanent	22.57 (top 100 mm)	Champagne Peat	Obligate	
Zone 1:	17	Permanent	21.14 (top 100 mm)	Champagne Peat	Obligate	
Swamp Forest						
Zone 1:		Permanent	31.98 (top 400 mm)	Peat	Obligate	

Table 5.2: Environmental factors for the five wetland systems on the southern study area

Zone and Site No.	**Elevation (m.a.s.l.)**	**Hydroperiod (no. of weeks or months)** 0 = no hydroperiod	**Average % SOC (0-200 mm)**	**Soil Form**	**Vegetation**	
					Plant Classification	**Species Composition**
Wetland 1						
Zone 5: 2/BB	10.55	0	0.06	Clovelly	Non-wetland plants	*Helichrysum kraussii, Schizachyrium sanguineum, Themeda triandra*
Zone 4: 3/A	9.31	0	0.89	Fernwood		
Zone 3: 4/CC	8.75	0	1.07	Fernwood	Facultative Obligate	*Trachypogon spicatus, Sporobolus subtilis, Ischaemum fasciculatum*
Zone 2: 5/B	8.10	2 weeks	1.29	Fernwood	Facultative	*Centella asiatica*
Zone 1: 6/C	7.45	8 months	2.75	Kroonstad	Facultative	*Stenotaphrum secundatu, Centella asiatica, Cyperus sphaerospermus, Hemarthria altissima, Cyperus sphaerospermus*
Wetland 2						
Zone 4: 7/DD	9.73	0		Clovelly	Non-wetland plants with one Obligate	*Aristida sp., Fimbristylis sp., Helichrysum kraussii, Stylosanthes fruticosa, Ischaemum fasciculatum*
Zone 3: 8/D	8.85	0	1.67	Clovelly	Facultative	*Sporobolus subtilis, Schizachyrium sanguineum*
Zone 2: 9/E	8.39	2 weeks	1.30	Constantia	Facultative Obligate	*Sporobolus subtilis, Restio zuluensis*
Zone 1: 10/F	7.82	4 months	5.75	Katspruit	Obligate	*Centella asiatica, Paspalum vaginatum*
Wetland 3						
Zone 4: 12/FF	9.57	0	0.32	Clovelly	Non-wetland plants	*Helichrysum kraussii*
Zone 3: 13/G	8.81	0	1.52	Fernwood	Facultative	*Imperata cylindrica, Hemarthria altissima, Panicum glandulopaniculatum*
Zone 2: 14/H	8.07	3 months	3.07	Fernwood	Obligate	*Paspalum vaginatum, Centella asiatica, Hydrocotyle bonariensis*
Zone 1: 15/I	7.40	13 months	16.05	Champagne	Obligate	*Eleocharis limosa*
Zone 4: 6/GG	8.87	0		Fernwood	Non-wetland plants	*Helichrysum kraussii*

Wetland 4						
Zone 4: 19/J	7.96	0	1.34	Kroonstad form Morgendal family	Non-wetland plants Facultative	*Alloteropsis semialata, Sporobolus subtilis, Setaria sphacelata, Lobelia sp., Trachypogon spicatus, Gerbera sp.*
Zone 3: 20/K	7.63	0	2.58	Kroonstad Morgendal family (1000)	Obligate	*Ischaemum fasciculatum, Themeda triandra*
Zone 2: 21/L	7.27	3 months	4.97	Looked like Champagne	Obligate	*Ischaemum fasciculatum, Centella asiatica, Rhynchospora rubra*
Zone 1: 22/M	7.14	13 months	5.45	Looked like Champagne	Obligate	
Wetland 5						
Zone 1: 23/N	3.45	20 months	28.79	Peat	Obligate	*Barringtonia racemosa, Nephrolepis biserrata, Stenochlaena tenuifolia*
Wetland 6						
Zone 2: 25/O	9.77	7 months	4.56	Kroonstad	Facultative	*Ischaemum fasciculatum*
Zone 1: 26/P	9.53	13 months	7.97	Looked like Champagne	Obligate	*Panicum glandulopaniculatum*
Zone 3: 27/Q	10.48	0	2.25	Fernwood	Facultative Obligate	*Centella asiatica, Restio zuluensis, Eragrostis sarmentosa, Themeda triandra*
Zone 4: 28/R	11.22	0	1.10	Fernwood	Non-wetland plants	*Eugenia albanensis, Elephantorrhiza elephantine, Helichrysum kraussii, Imperata cylindrical, Eragrostis sarmentosa*

5.7 CONCLUSION

The delineation of the wetland zones as described in the wetland delineation document of the Department of Water Affairs and Forestry (DWAF, 2005) is problematic on the MCP, and defining the period of inundation (hydroperiod) could therefore be of value in wetland delineation in this region. Soil organic carbon content is directly linked to the period of inundation (hydroperiod) in a wetland.

During this study wetlands were inundated for 3-12 months of the year with 4.56-7.97% SOC within the top 50 mm of the soil profile. The SOC content of wetlands that were saturated for $\geq$12 months varied from 13.94-28.79% in the 0-400 mm layer. Therefore, SOC ($\geq$25%) can be used to identify the permanently wet zones. This information can help to group these clearly distinctive wetlands together, as they will function similarly. Wetlands occurring at a higher elevation (65-75 m.a.s.l.) have been found to be drier with lower SOC content, and can therefore not be compared to SOC values found in wetlands in low-lying areas (e.g. the swamp forest).

SOC is therefore a good indicator of hydroperiod and can be used to delineate and classify permanent, seasonal and temporal wetlands on sandy coastal aquifers. The vegetation indicators in combination with the SOC content data provide the best options not only to define different wetland systems but also individual wetness zones.

CHAPTER 6: CHARACTERISING LANDSCAPE PROCESSES

PHOTO: Lulu Pretorius

6 CHARACTERISING LANDSCAPE PROCESSES

6.1 INTRODUCTION

The sub-tropical freshwater wetlands found on the Maputaland Coastal Plain are important for the maintenance of the rich biodiversity in the area (Mucina and Rutherford, 2006; Taylor *et al.*, 2006; Rivers-Moore *et al.*, 2007) as well as for subsistence agriculture (Louw, 1984; Taylor, 1988; Sliva, 2004; Grobler, 2009). However, the prolonged period of drought (2002-present) and land-use such as cultivation, forestry plantation and urbanisation (see Chapter 3) have rendered these wetlands vulnerable. Schmera and Baur (2011) emphasised the need for research on the underlying processes shaping patterns of biodiversity, as landscape and site characteristics are now required in conservation planning and biodiversity management.

Several theories have been developed to explain patterns and processes of vegetation community organisation in the landscape, e.g. abiotic factors as the major environmental determinant (Schmera and Baur, 2011). MacDevette (1989) identified two major vegetation gradients on the MCP, namely north to south and east to west. Wetlands on the MCP include *permanent* wetlands (peatlands, swamp forests and reed/sedge wetlands) and sedge/moist grasslands which are mostly *temporary* wetlands (see Figure 3.7D). Several authors described the drivers of wetland distribution on the Maputaland Coastal Plain, namely:

- ***Rainfall:*** The distribution of wetlands is related to the distribution of rainfall. Eastern South Africa receives more rain than other parts of the country and consequently most of the wetlands occur in the east of the country. Matthews *et al.* (2001) and Taylor *et al.* (2006) indicated that rainfall distribution controls the vegetation gradient. Extreme rainfall events like subtropical cyclones play a role in recharging the aquifer (Kelbe *et al.*, 1995, p. 6 and p. 8). On the other hand, prolonged periods of drought reduced the availability of groundwater (Rawlins and Kelbe, 1998), which can impact the distribution of wetlands in these groundwater-dependent ecosystems (Colvin *et al.*, 2007). However, the specific consequences of drought and how they affect wetlands are unknown.
- ***Aquifer:*** Colvin *et al.* (2007) suggest the Maputaland Coastal Plain consists of aquifer- rather than rainfall-dependent ecosystems (such as wetlands, moist grasslands and forests) and that the hydrology of the area defines/influences the ecological patterns and processes. It is postulated that the aquifer is the source of water for rivers, springs, lakes and wetlands in dry periods and is recharged by these systems in wet periods (Taylor *et al.*, 2006; Colvin *et al.*, 2007; Kelbe and Germishuyse, 2010).

- ***Topography:*** More permanent wetlands such as peatlands occur in areas where the rainfall exceeds 600 mm/year and at elevations between sea level and 50 m.a.s.l. (Grundling, 2001). Grundling (2001) stated that peatlands only occur below 50 m.a.s.l. This could be related to the topography dominated by the series of north-south orientated dune ridges (Botha and Porat, 2007).
- ***Hydrogeology:*** Grundling *et al.* (1998) and Marneweck *et al.* (2001) suggested that there could be a strong relationship between the spatial distribution of wetlands and the regional or sub-regional hydrology and geology.

Van Wyk (1991b) and Matthews (2007) reported on the *interrelated effects* of topography, water table and soil type as the main ecological driving factors on the MCP. Goge (2003) and Taylor *et al.* (2006) confirmed that groundwater and soil moisture play a dominant role in vegetation composition and structure. In line with the above theory of general drivers, Maltby and Barker (2009) described hydrology as the controlling driver for a wetland type. The interaction between groundwater, surface waters and atmospheric moisture play a role in the processes that drive wetland functioning. The particular hydrology of a wetland controls biogeochemical processes central in ecosystem functioning that include carbon, phosphorus and nitrogen cycling. This in turn influences the structure of the wetland ecosystem and mediates the accumulation of organic matter (Maltby and Barker, 2009). Therefore, the weight of evidence suggests that the primary process driver on the Maputaland Coastal Plain is rainfall modulated by the geological and topography (geomorphological template) and aquifer characteristics. The hydraulic characteristics of the aquifer, the regional geology formations which slope east towards the coast and rainfall distribution (diminishing away from the coast) are the drivers of spatial and temporal variability in wetland and open water distribution (Grundling *et al.*, 2013). This chapter focuses on the landscape processes shaping the wetland's presence, dynamics and character and links back to previous chapters, i.e. the extent and distribution of permanent and temporary wetlands in Chapter 3 and the spatial distribution of hydrogeomorphic wetland types on a sub-regional scale in Chapter 4.

6.2 SPECIFIC OBJECTIVES

1) To classify wetland types within the study area on the basis of their structure and function.
2) To characterise the landscape processes shaping the dynamics and distribution of the wetland types (on the above basis).

6.3 ENVIRONMENTAL FACTORS

6.3.1 Climate

See sections 2.3.1 and 3.3.2 and Figure 4.10B.

6.3.2 Geology and Hydrology

The geology of the MCP (Table 6.1) consists of Jurassic basalt and rhyolite lava of the Lebombo Group that underlie the coastal plain (Botha and Porat, 2007). The terrestrial and recent marine sediments of the Zululand Group (Mid- to Late-Cretaceous) were deposited on top of the volcanic rocks (Van Wyk and Smith, 2001). Except for the Makatini Formation, all consist of sedimentary deposits formed by marine and/or fluvial environments, presently or historically (Briggs, 2006). The Zululand Group consists of Cretaceous conglomerates, grit and sandstones in the basal section and fossiliferous glauconitic marine siltstone in the top layers. The Maputaland Group (Mid-Pliocene to Late Pleistocene) consists of Tertiary calcarenite, conglomerates and sand partly overlaying the Cretaceous sediments. The younger, more recent Pleistocene sediments cover the Cretaceous and Tertiary and include alluvium, fine-grained aeolian redistributed sands, clayey sand, dune and beach sands, washout-fan gravels and small outcrops of diatomaceous earth (Van Wyk and Smith, 2001).

Table 6.1: The geology of the Maputaland Coastal Plain (adapted from Roberts *et al.*, 2006). The position of the sequences is generally as shown, from top to bottom (see Figure 2.2)

Lithostratigraphic Unit		**Age and Lithology**
Maputaland Group	Sibayi Formation	Brown and orange-brown aeolian sands (cover sands) Coastal Barrier Dune Cordon (<10 ka)
	KwaMbonambi Formation	Remobilised underlying dune sand (20-8 ka) Alluvium and Interdune peat (<10 ka)
	Isipingo Formation	(Upper): Interlayer calcareous sandstones and uncemented sands (Eemian beach deposits~125 ka) (Lower): Carbonate cemented sandstones (Pleistocene aeolianite~200 ka)
	Kosi Bay Formation	Orange to yellowish brown silty sands (older aeolian sands) Forms core of coastal dune (Middle to Late Pleistocene, >300 ka) Note: Clay enriched
	Port Durnford Formation	Lacustrine mud and clayey carbonaceous sand (Early to Middle Pleistocene)
	Unconformity	
	Umkwelane Formation	Aeolianite and calcarenite (Early Pliocene)
	Uloa Formation	Littoral and shallow marine coquina and sandstone (Mio-Pliocene) – karst weathered surface
Unconformity		
Zululand Group		Siltstone, limestone, sandstones, conglomerates (Cretaceous)
Lebombo Group		Lebombo lavas: basalts and rhyolites (Jurassic)

6.3.2.1 Aquifer

The Port Durnford sediments in the east and the underlying Cretaceous siltstone of the Zululand Group sediments in the central and western parts of the MCP are characterised by low permeability and form a basal aquiclude (Rawlins and Kelbe, 1998). The Zululand Group have low groundwater yields (potential saline waters) (Schapers, 2012) and according to Maud (1998) act as an impermeable layer.

There are two primary aquifers present on the Maputaland Coastal Plain, roughly characterised as shallow and deep:

i) The hummocky dune systems comprise the KwaMbonambi Formation, representing sand mobilisation, alluvium and peat deposits that occurred during the last glacial cycle. These make up the shallow, unconfined aquifer known as the Maputaland Coastal Aquifer

(Colvin *et al.*, 2007). The sandy sediments of the Pleistocene and Holocene (cover sands) are well sorted, highly porous and permeable (high transmissivity values compared to the low transmissivity values of the Port Durnford lacustrine mud). However, the sandy sediments do not occur everywhere. There are some localised occurrences of relatively low permeability, e.g. ferricrete (Roux and Thomas, 1993). Rainfall infiltrates the sandy soils and percolates to the water table, then flows laterally to discharge at a lower elevation as a surface water source (Kelbe, 2010). This shallow aquifer is characterised by short residence time for the groundwater because of the high recharge values; the water table is typically shallow (<5 mbgl), especially in low-lying areas (Schapers, 2012).

ii) The deeper, semi-confined aquifer of the Uloa and Umkwelane Formations contains high yields of generally good quality groundwater (Maud, 1998). How it is recharged is still unknown (Maud, 1998; Kelbe, 2010; Roux, 2011; Schapers, 2012).

The hydrogeological characteristics of the Maputaland Group, Zululand Group and Lebombo Group's lithostratigraphy at eManguze are shown in Figure 6.1. Schapers (2012) classified the regional aquifers of the northern Maputaland Coastal Plain as:

i. KwaMbonambi Formation (often at higher elevations) typified by localised perched conditions at the contact with the Kosi Bay Formation. The KwaMbonambi Formation (sugar sands) is presumed to be composed of more recent, medium to coarse-grained sands forming an unconfined aquifer with a high water yield.
ii. The Kosi Bay and Isipingo Formations, which form partial aquicludes that may, because of sandy silts with slight to moderate clay content, low yield and high adhesive forces, act as a confining and/or semi-confining layer to the underlying geology. The rubified palaeosol in the Kosi Bay Formation marks the existence of a buried aeolian sand landscape (Cooper and Kensley, 1991).
iii. The Uloa/Umkwelane Formation (Calcrete), which consists of calcareous sands, clays and gravels to form the confined and/or semi-confined aquifer.

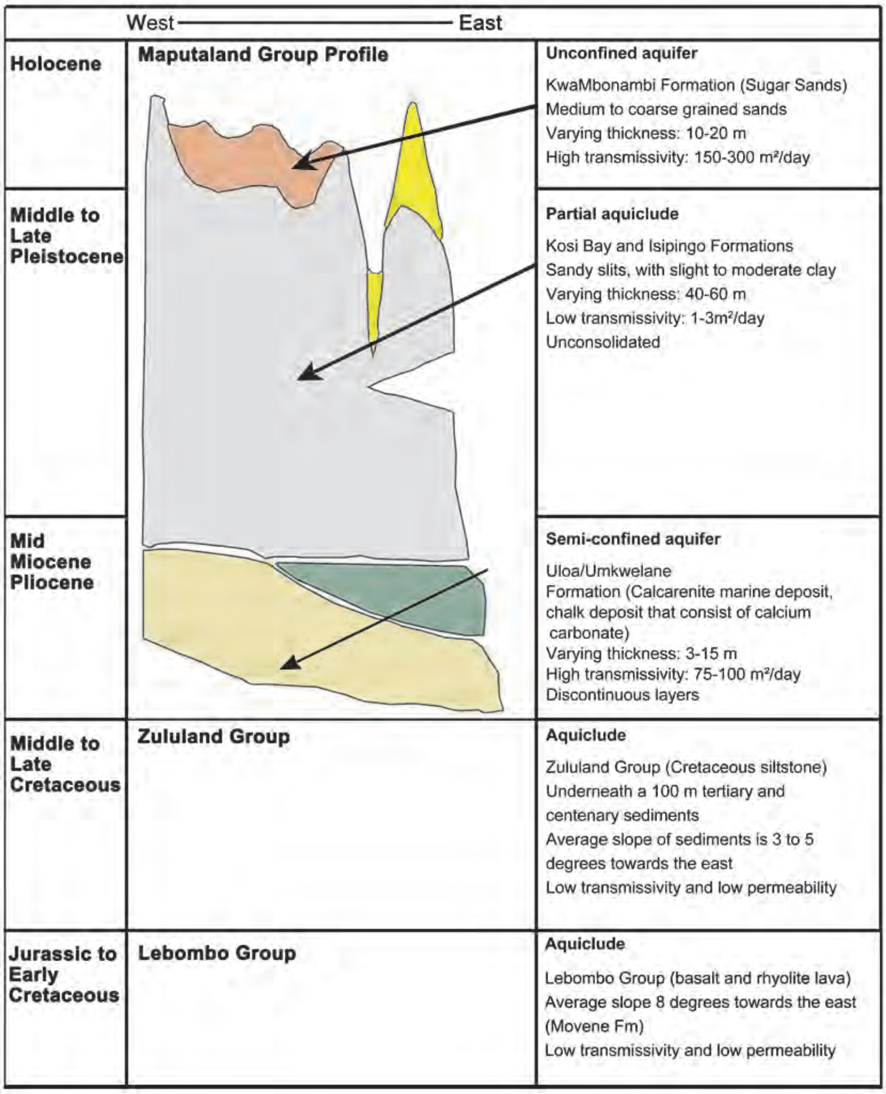


Figure 6.1: Interpreted geohydrological characteristics of the Maputaland Group lithostratigraphic layers at the eManguze area (modified after Porat and Botha (2008) and Schapers (2012).

6.3.3 Soil

Most of the coastal plain consists of geologically recent medium to fine-grained aeolian sands that are nutrient poor, highly leached and acidic (Van Wyk and Smith, 2001). The sandy soils are characterised by rapid infiltration rates and a low water-holding capacity. Botha and Porat (2007) described the soil forms on the MCP by well defined soil catena that vary from red, yellowish brown to grey, which generally show a sharp reduction of organic matter to less than 0.5% >0.3 m below the surface. The duplex, sodic soils with a prismatic subsoil structure occur on the margins of old dune ridges, while organic-rich soil and peat occurs in permanent wetlands (Botha and Porat, 2007).

6.3.4 Vegetation

The dominant vegetation types which can be found on the hydrological zones in the wetland, are reed marsh (*Phragmites australis* [Cav.] Steud.), bulrush marsh (*Typha capensis*) in permanently waterlogged areas, sedge marsh (*Cyperus latifolius)* in permanently to seasonally waterlogged areas, and wet grassland in temporarily waterlogged areas (Kotze, 1999). Dominant swamp forest species include *Raphia australis*, *Ficus trichopoda*, *Voacanga thouarsii* and *Barringtonia racemosa* (Grundling *et al.*, 2000; Grobler, 2009).

6.4 METHODS

6.4.1 Northern Study Area

This chapter will focus on the northern study area (sub-regional scale) (see Figure 1.3 in section 1.5.1).

6.4.2 Classifying Wetland Types

Temporary wetlands are ephemeral and transitional and thus difficult to characterise, yet characterising wetlands is needed to provide a basis for better landscape management. Various classifications of wetland type have been developed; for example, Semeniuk and Semeniuk (1995) applied the geomorphic approach to wetland classification in the Darling system in Australia with a drier climate and a limited range of basic landscape units (settings or landforms) that host temporary wetlands, similar to the MCP.

The wetland classification used in this present study was based on biophysical characteristics and functional attributes (landscape setting, water table, vegetation and soil). Classification names are similar to those in the Classification System for Wetlands and other Aquatic Ecosystems in South Africa (Ollis *et al.*, 2013; SANBI, 2009b) that adapted the hydrogeomorphic (HGM) classification system.

6.4.3 Transect

A 60 km long transect was selected from the inland Tembe Elephant Park (west) to Kosi Bay Lake at the coast (east) spanning a range of hydrogeomorphic settings and wetland systems. The transect selection was based on: 1) availability of data (e.g. existing wetland studies, as well as accessible groundwater, rainfall and soil information); 2) variety of different wetland types; and 3) accessibility and safety.

6.4.4 Rainfall

To address the spatial-temporal variability of rainfall, total monthly rainfall data for the northern study area were acquired from ARC-ISCW (2011) for the period January 1989 to December 2011 (see section 3.3.2). The rainfall measured during Tropical Storm Irina (3-7 March 2012) was obtained at the Tembe Elephant Park office and the Mission Station at the town of eManguze.

6.4.5 Elevation

See section 5.3.6.

6.4.6 Hydrology

6.4.6.1 Monitoring

See section 5.3.5.

6.4.7 Soils

See section 5.3.7. Additional general soil observations and classifications (i.e. organic or mineral soil) were made at each of the 59 groundwater monitoring sites. In September 2011, 12 sites along the 60 km transect were augured to depths that vary from 2.35 m to 10.75 m to investigate the depth (if present) of a low-permeability sediment layer (green points in Figure 5.3 in Chapter 5). Laboratory analyses included % SOC (Walkley-Black method), clay content (particle size determination) and pH (water and KCl solution methods) (De Ligny and Rehbach, 1960).

The comparison of wetland distribution and areas with clay soils was performed using the final filtered version of the 2008 Landsat TM classification dataset for the entire Maputaland Coastal Plain (which includes this study area) created for Chapter 3 accuracy assessment error matrix. Wetland classes include sedge/moist grassland (~8%), swamp forest (~1%) and open water (~5%) calculated using the 2008 Landsat TM classification and compared with clay classes for the semi-detailed soil map created for KwaZulu-Natal (Van den Berg *et al.*, 2009). Area calculations were done for the wetland pixels that also overlap clay and water classes. The percentages were calculated for the full 2008 classification. Peatland surveys conducted by Grundling *et al.* (1998) have been acquired and locations where peat was documented (black points in Figure 5.3 in Chapter 5) were mapped to add information on the type of wetlands distributed in the landscape (see Figure 3.7D in Chapter 3). Pit locations indicating materials used for road building (Roux and Thomas, 1993) were studied.

The Kosi Bay Formation acts as an impeding layer (note the difference in hydraulic conductivity (K) between the formations above and below the red line in Figure 6.2). This impeding layer represents the template on which the different temporal and permanent wetlands are formed. The weathered clay-enriched soil profiles found in valley-bottom wetlands throughout the northern transect confirm the existence of this impeding layer (Botha and Porat, 2007). The general K values for the different lithologies were obtained from Freeze and Cherry (1979) and refined, where possible, from the site specific results of Worthington (1978).

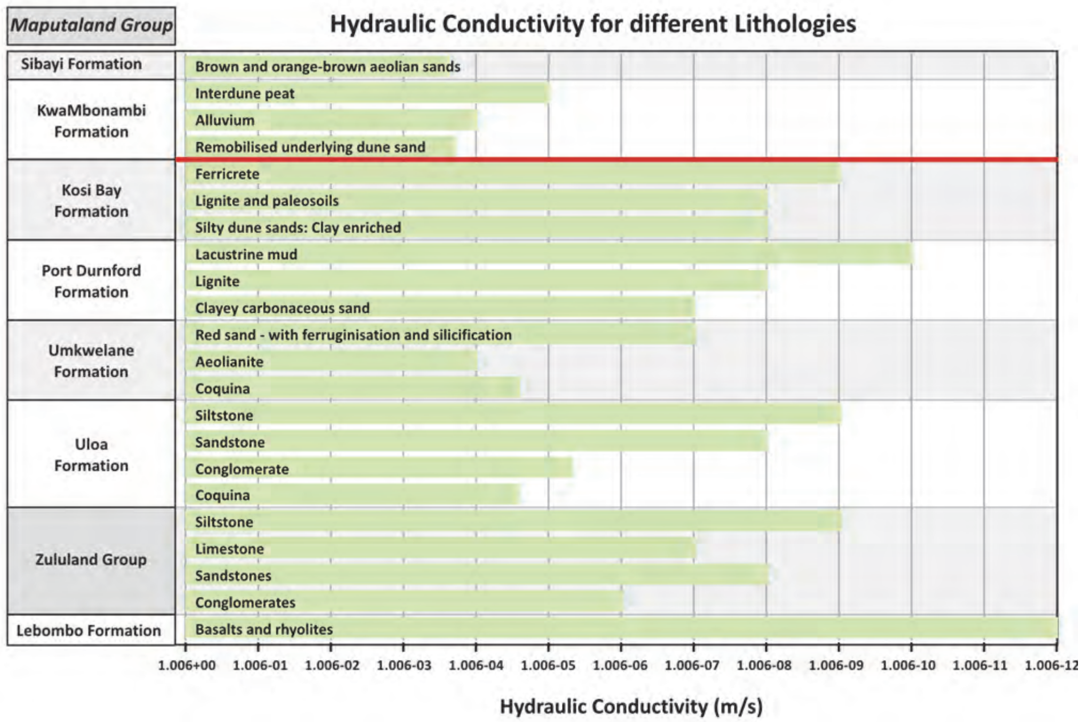


Figure 6.2: The difference in hydraulic conductivity of the different lithologies of the MCP (Grundling and Grundling, 2010).

6.5 RESULTS

6.5.1 Rainfall

See section 3.4.2.1 and Figure 3.6.

6.5.2 Wetland occurrence in Relation to Terrain Features and Clay Content

6.5.2.1 Impeding Layers

Eight of the 12 sites surveyed showed evidence of impeding layers, i.e. either an abrupt change in clay content or a hardened layer in the profile. The results of the 8 sites with an impeding layer are listed in Table 6.2 with summarised description of the possible impeding layers found that include: 1) clay layer in a drainage line, 2) buried paleo-peat layers, 3) buried ferricrete and 4) siliceous cementation of a hard formed layer, enough to impede water flow because of the change in hydraulic conductivity of the different layers in the soil (expert opinion from Nell (2012)). The laboratory analyses were done for the Muzi system, and for perched pans similar to Z62, Z3, Z4, Z32 and Z37 (see Figure 5.3 for locations). Sites Z7 and Z39 already had convincing evidence of an impeding layer (Table 6.2). Additional results for the Muzi wetland and perched pans (similar to Z62) were obtained from Pretorius (2011).

Table 6.2: Summary of samples where an impeding layer was found

No.	Wetland	Soil	Depth (cm)	% Clay	Description of soil profile
Muzi	Muzi wetland	Peat	50-400	26-38	• 16% clay at 0-50 cm • >32% clay at 50-400 cm • chalk (marl) deposits observed in the peat profile
Z62	Kwamsomi Pan Perched Pan	Calcified sand	0-20 cm	25	• 24.8% clay at 0-20 cm • 1.27% SOC at 0-20 cm • pH 7.08 • Water table: 0.59 m above soil surface
Z3	Headwaters of Muzi	Peat	100-120	8	• 14-30% clay from 0-100 cm • 8% clay at 100-120 cm • Water table depth: 0.74 m
Z4	Pan with buried organic layer	Sand	420-480	10	• 0-4 % clay from 0-360 cm • 10% clay at 420-480 cm (distinct buried black clay/organic matter) • Water table depth: 0.270 m
Z7	Wetland site next to borehole	Sand	420-480	-	• Buried Ferricrete at 400-600 cm • Water table depth: 1.23 m
Z32	Dry well (upland)	Sand	100-120 1000	10 6	• Change in clay from 0-10% • Change in clay from 0-6% • Water table depth: 4.90 m
Z37	Well near drainage line	Sand	196 235	16 22	• Change in clay from 0-16% • Change in clay from 16-22% • Water table depth: 2.20 m
Z39	Spring near drainage line	Sand	520	-	• Change in grain size, texture and black colour • Buried paleo-peat layer • Water table depth: 0.64 m

Figure 6.3A shows the surface elevation relative to mean sea level based on the SRTM DEM. The clay occurrence map (Van den Berg *et al.*, 2009) is shown in Figure 6.3B and indicates the weathered clay-enriched soil found in soil profiles, which corresponds well with the wetlands mapped in Chapter 3 (see Figure 3.7D). Comparing the clay occurrence with wetland distribution indicates that ~49% of permanent wetlands in the study area are associated with areas with >16% clay content. In contrast, ~63% of wetlands occur on soil with <5% clay content, and correspond with the distribution of temporary wetlands (Table 6.3 and Figure 6.3C).

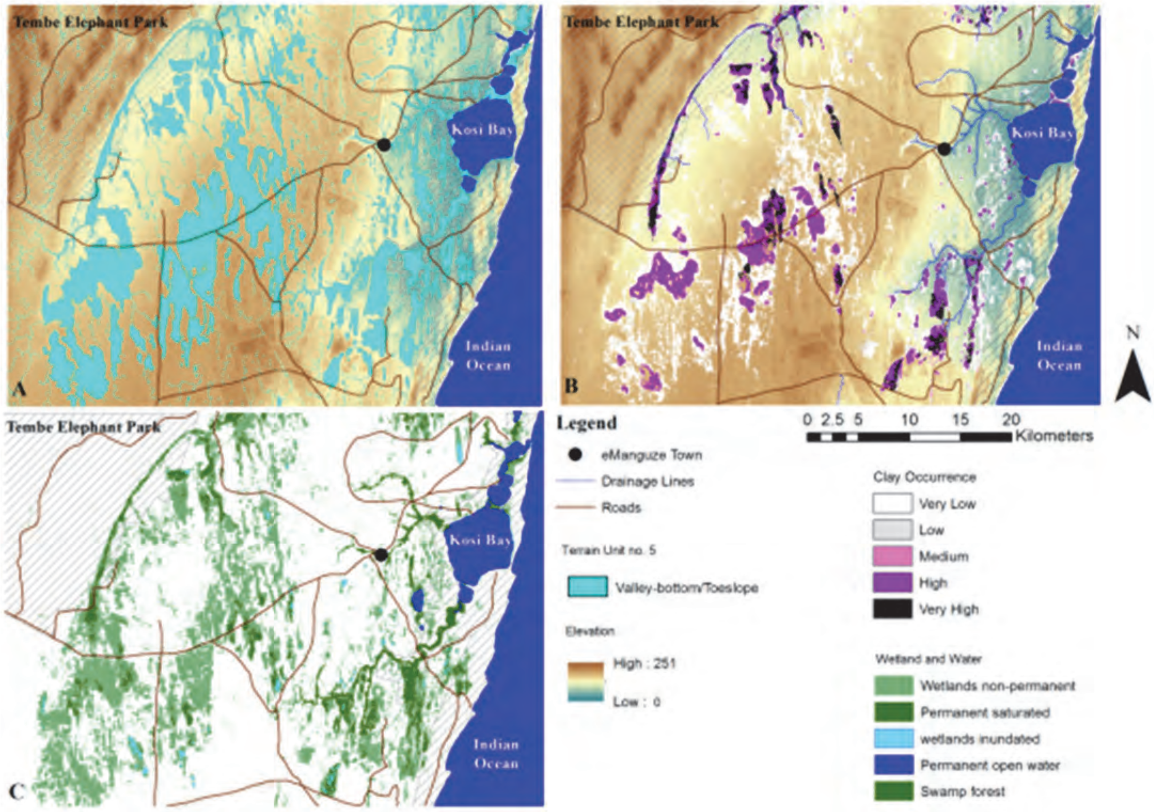


Figure 6.3: Elevation and terrain unit 5 (A), clay occurrence (B) and wetland distribution (C).

Table 6.3: Wetland overlap with clay occurrence (%)

Clay Class	Temporary Wetland	Permanent Wetland	Temporary Open Water	Permanent Open Water
Wetlands on Clay 1 (Very low – 0-5%)	63	35	36	1
Wetlands on Clay 2 (Low clay – 6-15%)	12	15	7	0
Wetlands on Clay 3 (Medium clay – 16-35%)	1	1	0	0
Wetlands on Clay 4 (High clay – 36-55%)	18	29	14	0
Wetlands on Clay 5 (Very high clay – >55%)	5	18	11	0
Wetlands on Clay content unknown	1	2	32	99
	100	100	100	100

6.6 DISCUSSION

6.6.1 Landscape Setting

The landscape setting classes of the Classification System for Wetlands and other Aquatic Ecosystems in South Africa (Ollis *et al.*, 2013) (level 3) are slopes, benches, valley floors and plains. The geomorphic approach takes into account the variability of wetland occurrence resulting from its geomorphic position (Brinson, 1993; Smith *et al.*, 1995). Semeniuk and Semeniuk (1995) indicated landscape settings that may contain water or retain water to potentially form a wetland, and include slopes, flats (bench or plains), channels (valley floor) with specific landform and basins (depressions) (Figure 6.4).

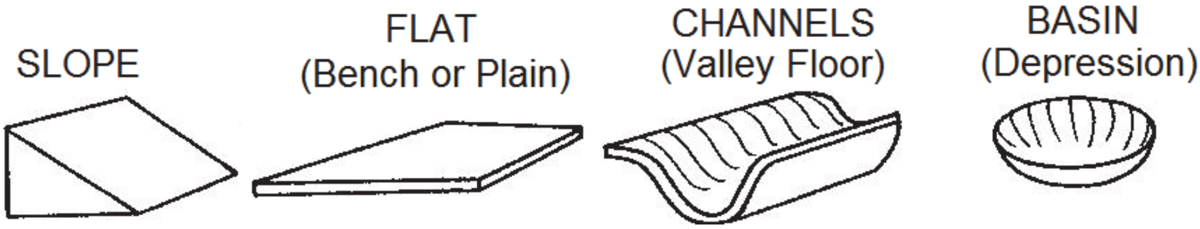


Figure 6.4: Landscape units associated with wetlands in the study area (after Semeniuk and Semeniuk, 1995).

6.6.2 Conceptual Model

The Wetland Hydrodynamic Conceptual Model (Figure 6.5) illustrates the rainfall gradient, landscape setting, underlying geological template and the high and low water table positions with water flow lines. Water table depth and variability at 16 selected representative wetland sites and one lake along the transect and their landscape positions are shown in the graph above the schematic diagram. The west side of the 60 km transect (Figure 6.5) is situated at Tembe Elephant Park and follows Road no. 522-2S / R22, east-north-east from the Muzi wetland, through the town of eManguze (not shown) to the Kosi Bay lake system in the east (see Figure 5.3 for transect position and landmarks). The model outlines the regional geology, which is exposed in formations unevenly parallel to the coast, and slopes to the coast at 3-5^{o} (Meyer *et al.*, 2001). The troughs and ridges formed the template in terms of major topography that plays an important role on a sub-regional and local level to support wetland formation. The clay from the Kosi Bay Formation washes out/down and accumulates/deposits in the lower horizons of the soil profile in the flat bottomed depressions on the upland, while the loose sand on top could be blown away and deposited elsewhere. In the upland the buried impeding layers of ferricrete, paleo-peat or clay restrict recharge and are thus essential to wetland formation. In contrast, drainage lines and valleys presently (e.g. Muzi) or formerly (e.g. swamp forests to the east) associated with fluvial systems are areas of sustained surface and groundwater sources.

Recharge is a function of the rainfall distribution, modified by the soil permeability, geomorphic setting and evapotranspiration rate. In the MCP, where potential evapotranspiration exceeds precipitation (Clulow *et al.*, 2012), there are periods of water deficit such that wetlands are most likely to occur in areas where there is a drainage impediment (i.e. confining layer) and/or where there is surface and/or groundwater discharge. Lower average annual rainfall in the western part of the transect (700-720 mm) (Figure 6.5) exacerbates the potential water deficit. Here, the dominant wetland system occurs along a channelled valley-bottom (Muzi wetland system), and small wetlands occur parallel to the channelled valley-bottom (temporary-perched depressions, e.g. Z62) (Figure 6.5). The flow lines east of Z3 suggest groundwater discharge, and some of these temporary-partially perched depressions on a slope (e.g. Z4 (buried paleo-peat), unchannelled valley-bottom Z3 and Z7 (buried ferricrete)) (Table 6.2) and seeps (Z9) may benefit from this as water might be discharged as it flows towards the lower valley floor. Both Z3 (headwaters of the Muzi wetland system) and Z4 have a relatively small range of water table depths (Figure 6.5), a characteristic of groundwater fed systems. Others such as temporary-perched depressions (e.g. Z62) are more topographically elevated above the Muzi valley floor, and have relatively large water table fluctuations (Figure 6.5). This site also has a high clay content (25%) at 0-20 cm in the soil profile (Table 6.2), suggesting a perched system.

The upland wetlands (Z23, Z25, Z32) in the central part of the transect receive an average annual rainfall of 720-780 mm. These are temporary or permanent depressions on bench (upland). Their elevated position suggests they are recharge features, and consequently their presence is reliant on restricted drainage. Without a groundwater source they are typically temporarily wet, although a small part of the relatively large Z25 system is permanently wet. Where these depressions directly overlay the Kosi Bay Formation (i.e. Z23 and Z25), a partial aquiclude with silty sand and high clay content (Figure 6.2 and Tables 6.2 and 6.3), their depth to water table is generally less than 3 m (Figure 6.5). Further east, where depressions overlie the permeable KwaMbonambi Formation (sugar sands) (Z32 and Z35), the water tables are deeper (>3 m). Here, localised illuviation of fine sediments causes perched, typically temporary wetlands to occur. The lowlands plain (lower elevations to the east) host permanent peatlands, either swamp forest or sedge wetlands, where the average water table is <0.2 m deep and fluctuates within a small range (Z38, Z39 and Z44 and seeps (i.e Z53) associated with low to moderate discharge.

Figure 6.5 also shows an abrupt difference with a higher water table on the Kosi Bay Formation compared to the upland area of the KwamBonambi Formation, then increasing in the KwamBonambi Formation towards the lowland/discharge systems. Except for the Muzi River Wetland system, most wetland types in the west or central areas tend to be temporary or weak seasonal systems compared to the wetlands at discharge areas, which are typically strong seasonal to permanently wet systems, including the swamp forests associated with drainage lines.

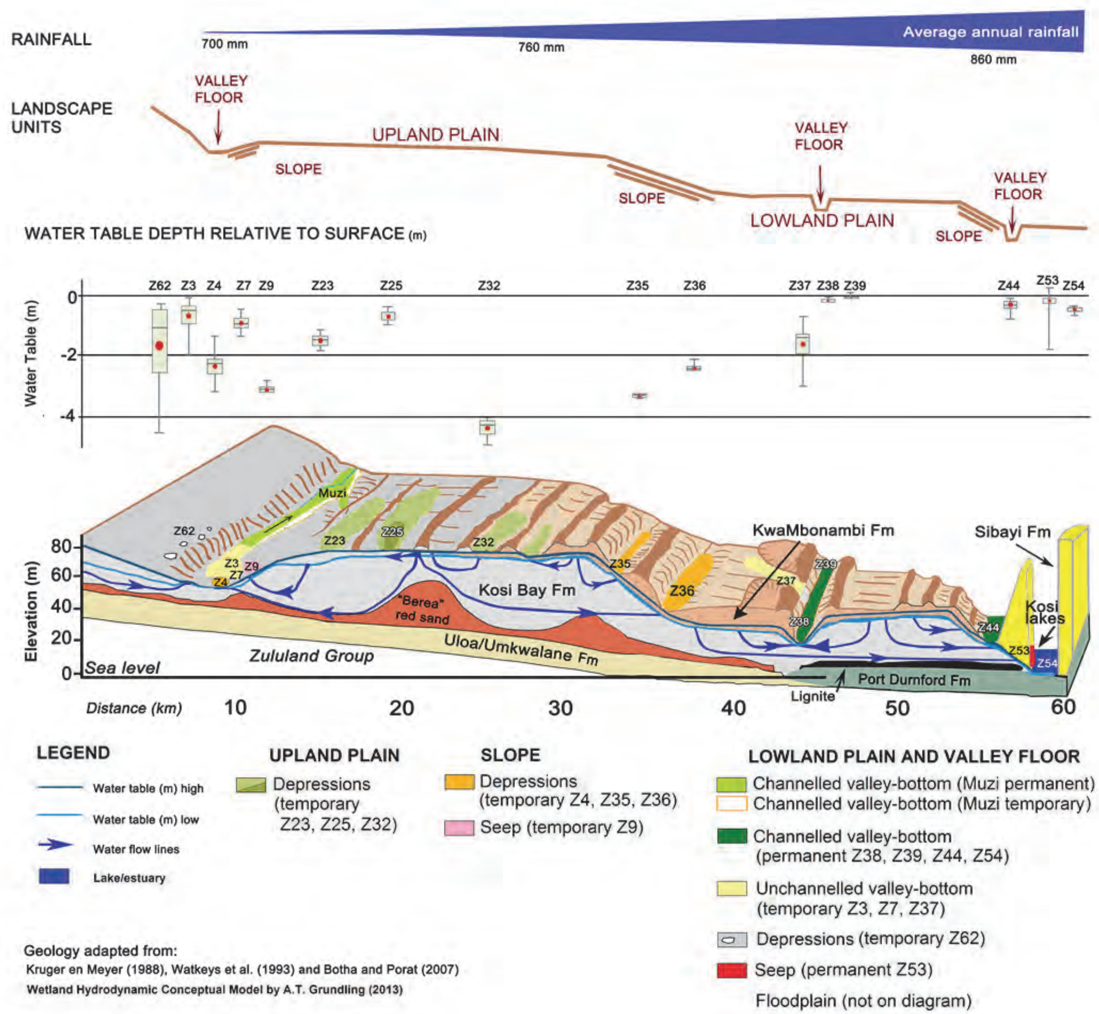


Figure 6.5: Wetland Hydrodynamic Conceptual Model. Schematic illustration of wetland types identified and their respective position in the landscape (Grundling, 2014). The location of these wetland types is indicated by their site numbers. Box-and-whisker plots are as described in Figures 3.5 and 3.6.

6.7 CONCLUSION

It was previously suggested that the wetland distribution on the Maputaland Coastal Plain follows an east-west pattern and mirrors the rainfall pattern to a large extent. However, this research confirms that the patterns and wetland form and function are predominately shaped by the hydrogeomorphic setting and not the rainfall distribution, although some wetland types such as peatlands do occur in areas where the rainfall exceeds 600 mm/year and at elevations between sea level and 50 m.a.s.l. (Grundling, 2001).

Groundwater is an important driver in wetland distribution on the MCP and it was therefore assumed that the wetlands are aquifer dependent, but the results indicate that some wetlands are perched systems and not dependent on the aquifer. Groundwater is the principal source of water for rivers, lakes and permanent wetlands. However, pans parallel with the Muzi system (associated with large floodplains of paleo-channels) show shallow perched conditions above the regional aquifer. Furthermore, the temporary upland depressions are also unlikely to be derived from an external groundwater source, although locally perched conditions or deeper low permeability sediments (e.g. Kosi Bay Formation) can retain groundwater in a way that sustains wetland processes. Wetlands formed by groundwater discharge rely more heavily on shallow aquifer contributions. The underlying geology does influence wetland distribution and more permanent inundated wetlands such as peatlands occur where the clay enriched Kosi Bay Formation weathering profiles are exposed.

Landscape processes clearly contribute to the dynamic nature and character of wetlands on the MCP and control the extent and distribution of wetlands. Together with the vegetation structure and hydrological functioning they also provide a basis to classify wetland types.

CHAPTER 7: CONCLUSION

PHOTO: Althea Grundling

7 CONCLUSION

The aim of this project was to understand the regional environmental factors that control the distribution, characteristics and function of different wetland types on the Maputaland Coastal Plain in north-eastern KwaZulu-Natal, including interactions with the underlying Maputaland Coastal Aquifer. The primary focus of the study was based on the three main themes of mapping, classifying and characterising the different wetland types.

This study has demonstrated the capability of using Landsat remote sensing imagery with ancillary datasets to establish wetland extent and permanence, as well as land-use activities (plantations, cultivation and urban classes) and change, bearing in mind the spatial limitations of Landsat (e.g. wetlands and croplands <1 ha and cultivated fields in swamp forests will be difficult to map). The ambiguity between classes: cultivation and grassland; temporal wetland and grassland; and bare soil and cultivation were highlighted. These classes are closely related and they could not be classified without support from ancillary datasets such as vegetation maps.

An important outcome of this part of the study showed that wetland loss is a significant problem for the local communities on the MCP that depend on these wetlands as a natural resource and illustrates the need for improved management by all stakeholders. The permanent and temporary wetland map and land-use impact assessment on wetlands can be used to emphasise wetland functions (eco-services) and vulnerability. It can guide land-use practices that have a direct and indirect effect on them.

A wetland classification for the MCP with its extreme precipitation events and wet and dry seasons remains a challenge. The hydrogeomorphic classification brings into prominence the important underlying features of all wetlands, i.e. land (geomorphology) and water (hydrology) (Semeniuk and Semeniuk, 1995). The hydrogeomorphic classification was applied in the northeastern part of the study area based on wetland position in the landscape. Sub-regional environmental determinants (water table, rainfall and elevation) were examined to show the link between these and the distribution of hydrogeomorphic units. The relationships between rainfall, elevation and depth to water table show an increase in the variety of hydrogeomorphic wetland units in wetter lowland areas compared to drier upland areas. In this study area it was found that wetland occurrence is not dependent on rainfall or elevation but rather depth to water table based on localised topographical features supporting hydrological processes.

An accuracy assessment and comparison was done as part of the study. The semi-automated approach to map hydrogeomorphic units on the Maputaland Coastal Plain was 81% accurate, while the NFEPA wetland ecosystem type was 40% accurate compared to groundtruthed sites. Both classifications stressed that incomplete and inaccurate input layers (e.g. wetlands layer and river layer) and limited groundtruthed points with substantiated groundwater monitoring data are the major limitations in an automatic approach for hydrogeomorphic wetland classification.

The risk in using the hydrogeomorphic unit map created in the study (level 4 in Table 4.1) is that the classification is based on the fundamental factors landscape setting and permanence of water but not on aspects such as: 1) the origin of the landscape setting (e.g. interdunal or fluvial like floodplains); 2) the importance of the landscape setting (recharge or discharge area); 3) the description of the water source (e.g. water table rise, ponding of rainwater, seepage of groundwater discharge or runoff or through-flow/interflow); or 4) if the wetland is permanent, seasonally or intermittently inundated. All this additional detail can only be added to the hierarchical manner in which the hydrogeomorphic classification is applied when or if the information becomes available. Using the broad hydrogeomorphic classification (level 4) with limited criteria for future land-use planning and assessments is problematic in that it permits a direct judgement of a single wetland's value.

This study highlights that the hydrological data of a wetland (i.e. to show interaction with the regional water table, either recharge or discharge function) are much needed for biodiversity management or sustainable aquifer development. However, this study gives a better understanding of the wetland types found on the MCP and how well the hydrogeomorphic classification could be applied. The methods and findings contribute to further refinement of wetland classification in South Africa and can be applied on similar sandy coastal plains.

The delineation of wetland wetness zones as defined by the period of inundation (hydroperiod) is of importance in wetland management. This study found that soil organic carbon content is a good indicator of hydroperiod and can be used to delineate and classify permanent, seasonal and temporal wetlands on sandy coastal aquifers. The vegetation indicators in combination with SOC content provide the best options to define different wetland systems and individual wetness zones.

It was previously suggested that the wetland distribution on the Maputaland Coastal Plain follows an east-west pattern and mirrors the rainfall pattern to a large extent. However, this study confirms that the patterns and wetland form and function are predominately shaped by the hydrogeomorphic setting and not the rainfall distribution, although some wetland types such as peatlands do occur in areas where the rainfall exceeds 600 mm/year and at elevations between sea level and 50 m above mean sea level (Grundling, 2001). Groundwater is an important driver in wetland distribution on the MCP and it was therefore assumed that the wetlands are aquifer dependent, but the results indicate that some wetlands are perched systems and not dependent on the aquifer. Groundwater is the principal source of water for rivers, lakes and permanent wetlands. Furthermore, the temporary upland depressions are also unlikely to be derived from an external groundwater source, although locally perched conditions or deeper low permeability sediments (e.g. Kosi Bay Formation) can retain groundwater in a way that sustains wetland processes. Wetlands formed by groundwater discharge rely more heavily on shallow aquifer contributions.

This study clearly demonstrates that landscape processes contribute to the dynamic nature and character of wetlands on the Maputaland Coastal Plain and control the extent and distribution of wetlands and different types. In investigating the regional environmental factors that control the distribution, characteristics and function of different wetland types, the main objectives of the project were achieved: the distribution of wetlands in wet and dry years was defined and mapped as well as land-use changes in recent decades and the impacts on wetlands; soil organic carbon as a method to measure hydroperiod in the different wetness zones was determined; and wetlands were classified using different hydrogeomorphic approaches. Finally the relationships between landscape processes and wetland type, distribution and extent were established.

7.1 RECOMMENDATIONS

This study improved our knowledge of the different wetland types and gave valuable insights into holistic environmental processes, thus aiding in the development of practical solutions for managing the effects of climate variability, land-use planning and development and implementation of informed rehabilitation strategies. The recognition of the environmental problems associated with the mismanagement of wetlands should lead to improved management by all stakeholders with the aim of re-establishing natural wetland functioning and re-initiating peat-forming processes.

- Significant investment is needed to fund research in this area, particularly given the scarcity of wetland ecosystem management response data.

- Appropriate groundwater monitoring programmes, e.g. the South African Environmental Observation Network (SAEON), need to be implemented on the entire MCP.

- Socio-economic aspects impacting on wetlands and water security (which were not part of this study) should be studied and alternative land-use practices investigated.

- Future research focus areas:
  - Improvements to the remote sensing method used in this study can be applied to similar coastal areas, such as the MCP in Mozambique, supporting future research (e.g. Landsat imagery with supporting ancillary data such as maps for wetland vegetation, cultivation and urban classes from high resolution spectral and spatial resolution imagery).
  - A ground and surface monitoring network should be installed in the different wetland zones on the northern transect to monitor wetland ecosystem responses to land management change.

CHAPTER 8: REFERENCES

PHOTO: Althea Grundling

8 REFERENCES

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CHAPTER 9: CAPACITY BUILDING, TECHNOLOGY TRANSFER AND EQUIPMENT

Althea Grundling and Lulu Pretorius

Enos Mthembu, Siphiwe Mfeka and Althea Grundling

Victoria Nkambule

9 CAPACITY BUILDING, TECHNOLOGY TRANSFER AND EQUIPMENT

9.1 CAPACITY BUILDING

Capacity building actions during WRC project K5/1923 included the following:

- Ms. Althea Grundling's PhD studies at the University of Waterloo, Canada. The ARC-ISCW core-funded research project and the WRC project form the basis of her thesis. Ms. Grundling will complete her PhD thesis in 2014.

- Ms. Lulu Pretorius's MSc studies at UNISA. Ms. Pretorius completed her MSc study entitled "A vegetation classification and description of five wetland systems and their respective zones on the Maputaland Coastal Plain" (Pretorius, 2011). The soil component of her MSc thesis expanded into a PhD study at UNISA with co-supervision from the University of the Free State. Her research on the soils in the northern study area complemented the third objective to test and refine soil organic carbon as an indicator of hydroperiod. Ms. Pretorius's work fell directly under the main project's supervision. . Ms. Lulu Pretorius's research work on the soil properties extended to further PhD studies at UNISA (Pretorius, *in progress*).

- Mr. Siphiwe Mfeka from the local community was identified and trained as a field assistant. He was employed on a 1-3 month contract basis by ARC-ISCW to monitor the groundwater levels in boreholes and shallow wells along the northern (Tembe Elephant Park to Kosi Bay) and southern (Eastern Shores) transects. Both Mr. Mfeka and Mr. Enos Mthembu (Tembe Tribal Authority) frequently helped with fieldwork and fell directly under the main project's supervision.

- Ms. Victoria Nkambule (BTech student from TUT) presented at the National Wetlands Indaba 2010 on the application of a monitoring system for wetland rehabilitation – Rietvlei wetland case study. Her registration and accommodation costs were covered by the WRC Mobility fund.

9.2 TECHNOLOGY TRANSFER

9.2.1 Conferences and Seminars

Table 9.1 lists events where preliminary results from the project were presented.

Table 9.1: Conferences and seminars

<table>
<tr><th>Conference/Seminar</th><th>Presentation Title</th></tr>
<tr><td>Flood Pulse Symposium (2-5 February 2010 in Maun, Botswana)</td><td>The role of pulsing precipitation events in maintaining wetlands on primary aquifers (Grundling, A.T., Price, J.S., Malherbe, J., Van Zyl, D. and Grobler, R.)</td></tr>
<tr><td>International Mire Conservation Group 2010 Field Symposium & Scientific Conference (5-17 July 2010 in Slovakia and Poland)</td><td>Wetland distribution and characteristics on the Maputaland Coastal Plain of north-eastern South Africa (Grundling, A.T., Price, J.S. and Grootjans, A.P.)</td></tr>
<tr><td>National Wetlands Indaba 2010 (26-29 October 2010 in Kimberley)</td><td>An examination of hydro-geomorphic and wetland vegetation types on the Maputaland Coastal Plain, north-eastern KwaZulu-Natal (Grundling, A.T., Price, J.S., Kotze, D. and Pretorius, M.L.)</td></tr>
<tr><td>Combined Congress (17-20 January 2011 in Pretoria)</td><td rowspan="2">Comparing three carbon analysis methods for wetland soils in north-eastern KwaZulu-Natal (Grundling, A.T., Pretorius, M.L., Beukes, D.J. and Price, J.S.)</td></tr>
<tr><td>*ARC-ISCW World Wetland Day Seminar (18 February 2011 in Pretoria), co-hosted by the International Mire Conservation Group</td></tr>
<tr><td>National Wetlands Indaba 2011 (18-21 October 2011 in KwaZulu-Natal)</td><td>Remote sensing of wetlands in north-eastern KwaZulu-Natal, South Africa (Grundling, A.T., Van den Berg, E.C. and Price, J.S.)</td></tr>
<tr><td>ARC-ISCW/IMCG World Wetland Day Seminar (10 February 2012)</td><td>Water, wells and people: Water scarcity in north-eastern KwaZulu-Natal (Grundling, A.T.)</td></tr>
<tr><td>SA GEO Symposium (11-12 September 2012 in Cape Town)</td><td>Monitoring the extent and distribution of wetlands in north-eastern KwaZulu-Natal, South Africa (Grundling, A.T. Van den Berg, E.C. and Price, J.S.)</td></tr>
<tr><td>National Wetlands Indaba 2012 (23-26 October 2012 in Limpopo)</td><td>Impact of climate variability and land-use practices on wetlands in KwaZulu-Natal (Grundling, A.T., Van den Berg, E.C., Pretorius, M.L. and Price, J.S.)</td></tr>
<tr><td>National Wetlands Indaba 2013 (23-26 October 2013 in Eastern Cape)</td><td>Soil organic carbon in association with hydroperiod, Eastern Shores of Lake St. Lucia, KwaZulu-Natal Coastal Plain (Grundling, A.T. and Pretorius, M.L.)</td></tr>
<tr><td colspan="2">* The seminar was well attended and the participants came from various government organisations, ARC institutes, consultants and universities. Media representatives gave exposure to the seminar on AgriTV and in The Water Wheel and DAFF News.</td></tr>
</table>

9.2.2 Reports and Publications

Deliverable 1: First Research Note

Grundling, A.T. (2009) Regional environmental factors and processes on the Maputaland Coastal Aquifer in north-eastern KwaZulu-Natal. ARC-ISCW Report No. GW/A/2009/42.

Deliverable 2: Second Research Note
Grundling, A.T. (2010) Hydro-geomorphic wetland units on the Maputaland Coastal Plain. ARC-ISCW Report No. GW/A/2010/19.

Deliverable 3: Third Research Note (Phase 1)
Grundling, A.T., Pretorius, M.L. and Beukes, D.J. (2010) Comparison of three carbon analysis methods for wetland soils on the Maputaland Coastal Aquifer (north-eastern KwaZulu-Natal). ARC-ISCW Report No. GW/A/2010/33.

Deliverable 4: Conference Report
Grundling, A.T. (2010) International Mire Conservation Group 2010 Field Symposium and Congress. ARC-ISCW Report No. GW/A/2010/66.

Deliverable 5: Fourth Research Note on Groundwater Distribution
Grundling, A.T. and Grundling, P. (2010) Groundwater distribution on the Maputaland Coastal Aquifer (north-eastern KwaZulu-Natal). ARC-ISCW Report No. GW/A/2010/73.

Deliverable 6: Third Research Note (Phase 2)
Grundling, A.T., Pretorius, M.L. and Van den Berg, E.C. (2011) Soil organic carbon content as an indicator of hydroperiod for wetland soils on the Maputaland Coastal Aquifer (north-eastern KwaZulu-Natal). ARC-ISCW Report No. GW/A/2010/74.

Deliverable 7: Draft Final Research Report
Grundling, A.T., Van den Berg, E.C. and Pretorius, M.L. (2012) Hydrogeomorphic analysis of wetlands on the Maputaland Coastal Plain, KwaZulu-Natal, South Africa: Coupling vegetation, terrain attributes and hydrology at different spatial scales. ARC-ISCW Report No. GW/A/2012/03.

Articles
Grundling, A.T. (2011) Traditional water sources – lifeline in a time of need. *The Water Wheel*. September/October 2011, 10(5): 36-39.

Grundling, A.T. (2013) Traditional water sources – lifeline in a time of need. *The Water Wheel*. Groundwater Special Edition: 26-29.

Grundling, A.T., Van den Berg, E.C. and Price, J.S. (2013) Assessing the distribution of wetlands over wet and dry periods and land-use change on the Maputaland Coastal Plain, north-eastern KwaZulu-Natal, South Africa. *South African Journal of Geomatics* 2: 120-139.

MSc Thesis
Pretorius, M.L. (2011) A vegetation classification and description of five wetland systems and their respective zones on the Maputaland Coastal Plain. MSc Thesis. University of South Africa.

PhD Thesis
Grundling, A.T. (2014) Remote sensing and biophysical monitoring of vegetation, terrain attributes and hydrology to map, characterise and classify wetlands of the Maputaland Coastal Plain, KwaZulu-Natal, South Africa. PhD Thesis. University of Waterloo, Canada.

9.3 EQUIPMENT

An acoustic Solinst water level meter was purchased and was used by Mr. Siphiwe Mfeka to monitor groundwater levels on the Eastern Shores of Lake St. Lucia, and in the area between Tembe Elephant Park and Kosi Bay.

APPENDICES

Appendix 1: Monitoring points for the Northern and Southern Transects.

NORTHERN MONITORING POINTS		
No.	**LAT**	**LONG**
Z3	27.0566	32.4958
Z4	27.0847	32.4958
Z5	27.0771	32.4913
Z6	27.0769	32.4967
Z7	27.0847	32.514
Z8	27.0563	32.5231
Z9	27.0829	32.532
Z10	27.057	32.5517
Z11	27.054	32.5434
Z12	27.0723	32.5545
Z13	27.0758	32.5511
Z16	27.1233	32.538
Z17B	27.1073	32.5548
Z18B	27.0678	32.5751
Z20	27.0928	32.5726
Z22	27.0509	32.5996
Z23	27.063	32.5988
Z24	27.0762	32.5997
Z25	27.0546	32.6296
Z26	27.0494	32.6389
Z27	27.0251	32.6278
Z28	27.0803	32.6423
Z30	27.0404	32.6619
Z31A	27.0412	32.6583
Z32	27.0259	32.6699
Z33	27.0088	32.6667
Z34A	27.0608	32.6898
Z35	27.0172	32.7152
Z36A	27.0193	32.7399
Z36B	27.0193	32.7399
Z37A	26.9983	32.7405
Z38	26.9935	32.7408
Z39	26.9894	32.726
Z40A	26.9893	32.7168
Z41	26.9846	32.7313
Z42	27.0253	32.783
Z43	26.993	32.7779
Z44	26.9509	32.7705
Z45	26.9538	32.8021

Z46	26.9194	32.7848
Z47	26.8871	32.7836
Z48	26.8723	32.8202
Z49	26.8875	32.8276
Z50	26.9228	32.8289
Z51	26.9355	32.8193
Z52	26.9602	32.827
Z53	26.895	32.8637
Z54	26.8955	32.8659
Z56	26.8857	32.7208
Z57	26.9396	32.6542
Z58	26.9152	32.6245
Z59	26.9014	32.6059
Z61	27.0228	32.494
Z62	27.0231	32.4922
Z63	27.0811	32.7868
Z64	27.0885	32.7651
Z65	27.1987	32.584
Z66	27.0989	32.7
Z67	27.1206	32.6964

SOUTHERN MONITORING POINTS		
No	LAT	LONG
1/AA	28.20539	32.50513
2/BB	28.20505	32.50513
3/A	28.205	32.50499
4/CC	28.20494	32.50485
5/B	28.20489	32.50468
6/C	28.20486	32.50452
7/DD	28.20646	32.50319
8/D	28.20641	32.50299
9/E	28.20641	32.50286
10/F	28.20625	32.50258
11/EE	28.2058	32.50172
12/FF	28.20556	32.50121
13/G	28.20547	32.50105
14/H	28.20544	32.50102
15/I	28.20533	32.50083
16/GG	28.20509	32.50053
17/HH	28.20258	32.4978
18/II	28.19876	32.49634
19/J	28.19888	32.49617
20/K	28.19885	32.49612
21/L	28.1988	32.49601
22/M	28.19878	32.49577
23/N	28	32
24/JJ	28.19534	32.49161
25/O	28.19404	32.48875
26/P	28.19377	32.48806
27/Q	28.19361	32.48765
28/R	28.19358	32.4875
KK	28.19348	32.48735

Appendix 2: Soil organic carbon data for the Northern Transect.

Interdune-depression System				
Zone No	Bottom depth (mm)	Carbon Content (%)	Carbon Content (%)	Average Carbon content (%)
		Wetland repetition A	Wetland repetition B	All repetitions
1	50	20.52	21.11	20.81
	100	19.88	23.06	21.47
	150	23.33	15.35	19.34
	200	17.52	11.03	14.27
	250	13.94	10.83	12.39
	300	12.14	12.41	12.27
	400	13.19	7.95	10.57
	500	11.37	6.11	8.74
	600	10.58	9.24	9.91
	900	9.57	8.87	9.22
	1200	5.97	5.67	5.82
2	50	22.25	22.79	22.52
	100	21.43	23.78	22.61
	150	23.09	14.54	18.82
	200	17.84	7.24	12.54
	250	21.91	4.72	13.31
	300	21.97	2.27	12.12
	400	16.79	1.03	8.91
	500	4.38	0.83	2.60
	700	3.62	0.44	2.03
	900	1.61	0.50	1.06
	1000	1.61	0.16	0.89
3	50	5.66	1.91	3.78
	100	5.17	1.87	3.52
	150	4.55	0.91	2.73
	200	1.20	0.39	0.79
	250	1.74	0.33	1.04
	300	1.25	0.27	0.76
	400	0.99	0.23	0.61
	500	0.59	0.17	0.38
	600	0.31	0.11	0.21
	900	0.17	0.24	0.21
	1200	0.14	0.05	0.10
4	50	1.08	1.09	1.08
	100	0.88	0.63	0.76
	150	0.41	0.53	0.47
	200	0.59	0.41	0.50
	250	0.44	0.36	0.40
	300	0.46	0.32	0.39
	400	0.42	0.29	0.35
	500	0.36	0.31	0.33
	600	0.44	0.24	0.34
	900	0.18	0.19	0.19
	1200	0.15	0.13	0.14

Muzi Swamp System					
Zone No	**Bottom depth (mm)**	**Carbon content (%)**	**Carbon content (%)**	**Carbon content (%)**	**Average Carbon content (%)**
		Wetland repetition A	**Wetland repetition B**	**Wetland repetition C**	**All repetitions**
1	50	11.45	20.31	11.98	14.58
	100	11.47	24.72	13.73	16.64
	150	10.29	23.35	15.60	16.41
	200	5.42	25.34	15.68	15.48
	250	5.53	23.39	18.14	15.68
	300	4.51	27.05	23.09	18.22
	400	3.24	22.59	23.43	16.42
	500	1.23	24.50	21.01	15.58
	600	0.58	22.87	19.10	14.18
	900	0.35	11.79	20.99	11.04
	1200	0.33	1.40	19.91	7.21
2	50	12.98	8.42	17.36	12.92
	100	15.57	8.32	20.97	14.95
	150	12.99	10.82	17.53	13.78
	200	10.30	11.14	21.14	14.19
	250	10.46	13.18	20.42	14.69
	300	10.18	11.39	25.35	15.64
	400	11.86	15.32	19.41	15.53
	500	19.72	9.34	17.47	15.51
	600	15.20	11.87	24.42	17.16
	900	17.08	10.50	20.80	16.13
	1200	9.32	7.81	21.77	12.97
3	50	7.70	8.93	5.79	7.47
	100	4.83	7.23	6.34	6.13
	150	3.90	5.42	4.50	4.60
	200	3.20	3.20	3.44	3.28
	250	3.20	2.48	1.65	2.44
	300	2.06	2.04	1.19	1.76
	400	1.60	1.61	0.69	1.30
	500	0.39	0.50	0.92	0.60
	600	0.19	0.16	0.21	0.19
	900	0.19	0.17	0.44	0.27
	1200	0.30	0.38	0.23	0.30
4	50	2.32	5.01	0.38	2.57
	100	1.77	3.44	0.27	1.83
	150	0.51	2.15	0.29	0.98
	200	0.20	1.55	0.42	0.72
	250	0.25	1.68	0.48	0.81
	300	0.02	0.72	0.25	0.33
	400	0.02	0.39	0.21	0.21
	500	0.06	0.19	0.18	0.14
	600	0.18	0.18	0.26	0.20
	900	0.26	0.16	0.07	0.17
	1200	0.01	0.08	0.12	0.07

Perched Pans System					
Zone No	**Bottom depth (mm)**	**Carbon content (%)**	**Carbon content (%)**	**Carbon content (%)**	**Average Carbon content (%)**
		Wetland repetition A	**Wetland repetition B**	**Wetland repetition C**	**All repetitions**
1	50	1.87	1.70	2.43	2.00
	100	1.24	1.05	2.50	1.60
	150	0.38	0.84	2.05	1.09
	200	0.49	0.88	1.89	1.09
	250	0.47	0.74	1.72	0.98
	300	0.43	0.62	0.55	0.53
	400	0.34	0.29	0.87	0.50
	500	0.33	0.24	0.32	0.30
	600	0.32	0.20	0.15	0.22
	900	0.20	0.09	0.14	0.14
	1200	0.26	0.03	0.06	0.12
2	50	2.91	1.84	4.00	2.92
	100	2.57	0.86	1.58	1.67
	150	1.86	0.67	0.80	1.11
	200	0.47	0.78	0.58	0.61
	250	0.29	0.63	0.53	0.48
	300	0.17	0.50	0.36	0.34
	400	0.15	0.37	0.29	0.27
	500	0.05	0.30	0.24	0.20
	600	0.04	0.27	0.21	0.18
	900	0.01	0.23	0.13	0.12
	1200	0.00	0.25	0.22	0.15
3	50	0.67	0.72	0.89	0.76
	100	0.41	0.52	0.59	0.51
	150	0.77	0.47	0.37	0.54
	200	0.37	0.51	0.22	0.37
	250	0.20	0.38	0.24	0.28
	300	0.18	0.32	0.22	0.24
	400	0.08	0.32	0.22	0.20
	500	0.05	0.25	0.23	0.18
	600	0.01	0.29	0.29	0.20
	900	0.02	0.19	0.28	0.17
	1200	0.02	0.14	0.27	0.14

Upland Wetland System					
Zone No	Bottom depth (mm)	Carbon content (%)	Carbon content (%)	Carbon content (%)	Average Carbon content (%)
		Wetland Repetition A	Wetland Repetition B	Wetland Repetition C	All repetitions
1	50	5.66	2.01	1.19	2.96
	100	5.72	1.42	0.70	2.62
	150	4.04	1.00	0.51	1.85
	200	2.94	1.41	0.75	1.70
	250	2.51	1.29	0.61	1.47
	300	2.34	1.00	0.56	1.30
	400	0.43	0.50	0.46	0.47
	500	0.20	0.54	0.37	0.37
	600	0.28	0.49	0.29	0.36
	900	0.26	0.31	0.64	0.40
	1200	0.26	0.21	0.22	0.23
2	50	3.18	0.56	1.12	1.62
	100	2.23	0.23	0.67	1.05
	150	1.46	0.31	0.58	0.78
	200	1.56	0.28	0.58	0.81
	250	1.10	0.71	0.47	0.76
	300	0.71	0.41	0.34	0.48
	400	0.53	0.35	0.25	0.38
	500	0.36	0.48	0.23	0.36
	600	0.32	0.42	0.18	0.31
	900	0.30	0.32	0.62	0.41
	1200	0.26	0.28	0.04	0.19
3	50	1.25	0.56	0.70	0.84
	100	0.66	0.75	0.39	0.60
	150	0.80	0.37	0.44	0.53
	200	0.56	0.29	0.54	0.46
	250	0.53	0.25	0.46	0.41
	300	0.44	0.30	0.49	0.41
	400	0.41	0.27	0.41	0.36
	500	0.28	0.23	0.37	0.29
	600	0.24	0.26	0.36	0.29
	900	0.20	0.20	0.32	0.24
	1200	0.10	0.16	0.25	0.17

Appendix 3: Groundwater fluctuation data for the Northern Transect.

No	Elev	14Apr08	30Sept08	10Oct08	7Nov08	18Dec08	23Jan09	21Feb09	20Ma09	10Apr09	22Ma09	19Jul09	24Jul09	28Aug09	25Sept09	22Oct09	16Dec09	16Jun10	Wetland	Type	Purpose	Status	Descript
Z3	43.26	41.22	42.51	42.52	42.21	42.04	41.94	43.15	42.99	42.74	42.39	42.72	42.68	42.90	42.82	42.89	42.93	42.26	Y	well	human ,gar-den	Good	Well Muzi North
Z4	53.13	51.16	50.98	50.87	50.89	50.79	50.70	51.42	51.74	51.42	50.97	50.79	50.54	50.55	50.50	50.41	50.62	49.90	Y	pan	cattle	Fair	Pan next to road
Z5	49.82	0.00	46.37	46.46	46.35	46.30	46.28	46.84	46.93	44.41	46.38	46.34	44.98	46.34	0.00	0.00	44.56	0.00	N	well	human	Dry	
Z6	0.00	0.00	49.79	49.89	49.91	50.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	N	bore-hole		Moist	Bore-hole (plat-form for water pump)
Z7	56.08	0.00	54.94	54.94	54.86	54.81	54.69	55.57	55.51	55.58	55.29	55.20	55.08	55.17	55.07	55.06	55.30	54.99	Y	bore-hole	human cattle	Good	T2684 7 (29 Jan 1970)
Z8	54.54	0.00	52.67	52.66	52.66	52.58	52.55	53.01	52.91	52.82	53.16	52.71	52.71	52.57	52.63	52.66	52.56	0.00	Y	well	human ,gar-den	Fair	Water level 1.22 below what it should be
Z9	61.81	0.00	58.54	58.54	58.78	58.52	58.50	58.92	58.92	58.93	58.70	58.65	58.52	58.66	58.60	58.62	61.81	58.57	Y	well	human cattle	Fair	Well
Z10	65.98	0.00	59.31	59.82	59.78	59.76	59.72	59.97	59.93	59.89	59.83	59.71	59.72	59.71	59.67	59.68	59.64	59.52	N	bore-hole	human	Fair	Phoh-lo Clover Prim-ary School
Z11	60.64	0.00	57.54	57.46	57.44	57.41	57.19	57.93	57.86	57.78	57.69	57.64	57.55	57.52	57.49	57.46	57.46	57.76	Y	well		Fair	
Z12	72.59	0.00	0.00	65.24	65.21	65.15	65.14	65.21	65.23	65.25	65.27	65.18	65.19	65.08	65.05	65.04	65.01	64.91	N	bore-hole	human		Mdluli-house
Z13	69.76	0.00	64.55	64.54	64.51	64.34	64.43	64.65	64.61	64.56	64.49	64.44	64.41	64.38	64.37	64.35	64.35	0.00	N	well	human	Fair	Deep well

Z31A	**Z30**	**Z28**	**Z27**	**Z26**	**Z25**	**Z24**	**Z23**	**Z22**	**Z20**	**Z18B**	**Z17B**	**Z16**
75.54	0.00	77.74	0.00	74.36	73.79	75.00	73.94	73.08	74.88	74.53	73.92	72.73
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
71.10	76.49	74.22	69.15	71.98	72.99	74.01	72.25	70.98	73.23	71.41	71.63	68.58
71.12	0.00	74.18	69.15	72.00	72.97	0.00	72.22	70.96	73.26	71.48	71.62	68.54
71.07	0.00	74.04	69.12	71.94	72.94	73.91	72.17	70.93	73.17	71.54	71.59	68.54
71.00	0.00	73.97	69.10	71.89	72.87	73.83	72.09	70.86	73.13	71.52	71.55	68.52
71.04	0.00	73.93	69.05	71.82	72.82	73.62	72.06	70.75	73.05	71.43	71.50	68.35
71.23	0.00	74.47	0.00	0.00	73.32	74.41	72.75	71.56	73.67	72.01	73.76	68.83
71.23	0.00	74.44	0.00	73.26	73.37	74.44	72.75	71.39	73.57	72.01	0.00	68.77
71.21	0.00	74.46	0.00	72.30	73.28	74.23	72.57	71.34	73.44	71.96	0.00	68.96
71.07	0.00	74.32	0.00	0.00	72.85	74.06	72.50	71.25	73.77	71.90	0.00	68.79
71.01	0.00	74.26	0.00	0.00	73.19	74.04	72.42	71.18	73.34	71.84	0.00	68.71
71.12	0.00	74.19	0.00	0.00	73.05	73.94	72.35	71.04	73.25	71.75	0.00	68.65
70.86	0.00	74.17	0.00	72.00	73.19	74.04	72.46	71.15	73.25	71.61	0.00	68.62
70.92	0.00	74.10	0.00	72.01	73.00	74.03	72.65	71.07	73.24	0.00	0.00	68.50
70.77	0.00	77.74	0.00	71.98	73.01	74.00	72.35	71.05	73.28	0.00	0.00	68.50
70.68	0.00	77.74	0.00	72.07	73.15	74.20	72.49	71.19	73.45	0.00	0.00	68.82
70.57	0.00	74.02	0.00	0.00	72.97	73.62	0.00	0.00	73.15	0.00	71.69	68.83
N	N	N	Y	Y	Y	Y	Y	Y	Y	N	Y	N
bore-hole	bore-hole	bore-hole	well	well	well	pan	well	well	well	well	well	well
human	no use	human	human gar-den	no use	human gar-den	cattle gar-den	human gar-den	human gar-den	human gar-den	human	human	human
Excell-ent	Bad	Good	Good	Bad	Good	Good	Good	Fair	Good	Fair	Good	Bad
Bore-hole along side the fence of a beaut-iful house (Own-er: Mr. Justus Nste-le)	Well out-side house	Bore-hole at home of Mr. John Ndlo-vu	Well in gar-den	Well next to the road	Wet-land with gar-dens and wells (grid)	Pan: Cattle drink-ing area	Well in wet-land behind beaut-iful house	Well out-side gar-den. (Coll-apsed in March, dig again and plant-ed a pipe)	Well in gar-den	Nurse Home	17-Khofi Clover School / 17A-W ind-pump across the road	Mr. Boyi Man-zini

Z43	Z42	Z41	Z40A	Z39	Z38	Z37A	Z36B	Z36A	Z35	Z34A	Z33	Z32
20.80	24.54	65.16	45.18	37.63	33.12	36.70	0.00	46.99	63.40	71.64	73.31	72.95
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20.66	24.20	41.00	45.03	37.55	32.87	33.90	0.00	43.79	60.14	67.50	67.12	68.84
20.62	24.17	41.00	45.02	37.57	32.85	33.82	0.00	43.78	60.12	67.31	67.12	68.84
20.65	24.01	40.96	45.02	37.49	32.90	33.74	46.08	43.91	60.15	67.28	67.05	68.76
20.49	23.79	40.92	45.07	37.50	32.93	35.19	46.08	43.91	60.09	0.00	66.97	68.67
20.25	24.09	40.84	44.99	37.50	32.86	34.74	46.07	43.90	59.99	0.00	66.89	68.58
20.56	24.24	40.87	45.13	37.54	32.92	34.45	46.37	0.00	60.15	0.00	66.93	68.81
20.66	24.21	40.87	45.07	37.52	32.90	35.74	46.27	0.00	60.11	0.00	66.89	68.74
20.76	23.97	0.00	45.03	37.45	32.85	35.60	46.23	0.00	60.03	67.07	66.85	68.72
20.71	23.85	0.00	45.05	37.46	32.86	35.47	46.17	0.00	0.00	66.43	66.77	68.57
20.58	23.87	0.00	45.06	37.47	32.84	35.41	46.16	0.00	0.00	66.37	66.75	68.41
20.49	24.07	0.00	45.03	37.45	32.82	35.35	46.11	0.00	0.00	66.32	66.65	68.36
20.68	24.17	40.94	45.11	37.51	32.84	35.38	46.16	0.00	0.00	66.28	66.63	68.37
20.65	24.09	40.75	45.03	37.49	32.83	35.16	46.07	0.00	0.00	0.00	66.57	68.30
20.55	24.13	40.77	45.02	37.51	32.86	35.15	46.09	0.00	0.00	0.00	66.53	68.28
20.66	24.21	40.70	45.03	37.54	32.98	35.43	46.09	0.00	0.00	0.00	66.44	68.20
20.48	23.75	40.32	0.00	37.57	32.92	34.91	0.00	42.97	0.00	0.00	66.17	0.00
Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y
drain	lake	bore-hole	river	foun-tain	sur-face	well	well	well	well	well	well	bore-hole
gar-den	all	human	gar-den	human gar-den	gar-den	human gar-den	human	human	human gar-den	no use	human	human
Good	Excell-ent	Excell-ent	Excell-ent	Good	Fair	Fair	Fair	Fair	Good	Bad	Fair	Good
Wet-land with bridge across	Lake Shel-eza	Miss-ionary Stat-ion	Bridge across river	Foun-tain (Hand pump in road)	Zizam-ele Comm-unity Gar-den	Clay bar-rier, green sticky	On the road to the air field	On the road to the air field	Well in gar-den	Well near broken hand pump	Well near hand pump	Old wind mill

Z57	Z56	Z54	Z53	Z52	Z51	Z50	Z49	Z48	Z47	Z46	Z45	Z44
64.64	61.70	1.45	2.23	1.87	19.07	24.20	26.88	28.19	39.97	39.23	13.48	25.42
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.77	1.82	1.28	17.84	19.15	23.51	26.50	38.58	34.83	13.22	24.61
0.00	0.00	0.95	1.88	1.27	17.84	19.10	23.57	26.50	38.56	34.78	13.18	25.17
0.00	0.00	0.93	1.89	1.20	17.79	19.08	23.58	28.19	38.46	34.71	13.02	25.18
0.00	0.00	0.92	2.14	1.19	17.69	19.01	23.27	0.00	38.34	34.60	13.01	24.87
0.00	0.00	0.93	2.10	1.12	17.58	18.94	23.34	0.00	0.00	0.00	12.96	24.79
0.00	0.00	1.00	2.06	1.41	17.80	19.16	23.80	0.00	38.93	34.76	13.14	25.26
0.00	0.00	0.92	2.21	1.38	17.75	19.21	23.89	0.00	38.74	34.72	13.14	25.17
60.50	57.65	0.86	2.11	1.33	17.64	19.16	23.82	0.00	38.69	34.71	13.08	25.17
60.15	57.25	0.87	1.95	1.25	17.53	19.06	23.64	0.00	38.64	34.55	13.11	25.16
59.94	57.45	0.91	1.98	1.23	17.54	18.96	23.40	0.00	38.42	34.38	13.04	25.13
59.77	57.29	0.88	1.91	1.13	17.45	18.92	23.56	0.00	38.34	34.48	12.94	0.00
59.79	57.41	1.01	2.18	1.30	17.42	18.90	23.33	0.00	38.41	34.48	13.03	25.19
59.70	57.41	0.89	2.01	1.20	17.54	18.82	23.16	0.00	38.62	34.63	13.04	24.96
59.65	57.40	0.90	1.97	1.25	17.48	18.83	24.32	0.00	38.53	0.00	12.92	24.97
59.56	57.69	0.92	1.96	1.25	17.26	18.73	24.29	0.00	38.63	34.56	13.06	24.95
59.25	56.65	0.89	1.95	1.21	0.00	18.80	22.97	0.00	38.37	0.00	12.95	24.97
Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y
well	well	estu-ary	wet-land	lake	well	well	well	wet-land	well	well	lake	wet-land
human gar-den	human gar-den	no use	no use	all	human gar-den	human gar-den	human gar-den	gar-den	human	human gar-den	gar-den	gar-den
		Excell-ent	Excell-ent	Excell-ent	Fair	Fair	Fair	Good	Fair	Fair	Excell-ent	Good
Mloli-area (Indun a Joel) Well	Well with gar-dens	Low water bridge at Kosi Bay	Small wet-land at Kosi Bay	Forth Lake	Wet-land well in gar-den near homes	Well in gar-den near homes	Well in wet-land Area Induna : Nico-demus Ngo-bani	Wet-land across Blue gum stand	Well near blue gum stand	Well	Lake near Kosi Bay Lodge	Tob-eka board next to road

Z67	Z66	Z65	Z64	Z63	Z62	Z61	Z59	Z58
50.06	63.41	81.72	14.72	9.68	44.80	43.70	41.08	52.79
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
49.09	48.90	79.06	13.38	7.02	43.34	40.47	39.30	52.29
48.96	49.03	80.67	13.31	8.00	44.28	40.40	38.99	51.42
49.05	49.15	80.67	13.31	7.47	43.73	40.34	38.92	51.78
49.05	49.52	80.54	13.30	6.96	43.67	40.33	38.80	51.76
49.07	49.60	80.58	13.35	7.03	44.48	40.55	38.82	51.81
49.07	49.57	80.55	13.31	6.95	42.16	40.43	38.82	0.00
49.04	49.53	80.34	13.30	6.98	0.00	40.50	38.78	0.00
49.06	49.37	0.00	13.35	7.00	0.00	40.52	38.52	51.70
49.00	44.43	79.81	13.31	6.75	0.00	40.01	38.75	0.00
Y	N	Y	Y	Y	Y	Y	N	Y
bridge	bore-hole	lake	bridge	bridge	pan	bore-hole	well	bridge
human gar-den cattle	human	human gar-den cattle	human gar-den	human gar-den	eleph-ants and game	no use	human gar-den	human gar-den
Mvela busha (Mpa-ya river brid-ge)	House with pump	Lake Manza mhlo-phe.	Mqom -bo River bridge	Mili-tary Bridge	Kwam somi Pan (Tem-be Eleph-ant Park)	Kwam -somi Bore-hole (Tem-be Eleph-ant Park)	Coca Cola Store Well	Swa-mp Forest with bridge

Appendix 4: Soil organic carbon data for the Southern Transect.

Wetland 1		
Zone No	**Bottom depth (mm)**	**Carbon content (%)**
1	50	3.897
	100	3.144
	150	2.263
	200	1.7
	250	1.316
	300	0.903
	400	0.82
	500	0.632
	800	0.859
2	50	0.814
	100	1.673
	150	1.409
	200	1.281
	250	1.495
	300	0.781
	350	0.484
	400	0.253
	500	0.183
	600	0.142
	900	0.187
3	50	2.429
	100	0.876
	150	0.525
	200	0.45
	250	0.506
	300	0.418
	400	0.391
	500	0.304
	800	0.192
	1100	0.137
4	50	1.484
	100	1.089
	200	0.097
	300	0.332
	400	0.035
	500	0.042
	600	0.029
	700	0.028
	800	0.017
	1100	0.015
	1400	0.016
	1700	0.013

Wetland 2		
Zone No	**Bottom depth (mm)**	**Carbon content (%)**
1	50	6.802
	100	6.617
	150	5.183
	200	4.406
	250	3.109
	280	2.482
	380	1.816
	480	1.487
	580	1.241
	680	0.837
	780	0.559
	1080	0.223
	1350	0.147
	1550	0.13
2	50	0.965
	100	1.378
	150	1.707
	200	1.131
	250	1.289
	300	1.069
	400	1.039
	500	0.809
	600	0.715
	700	0.536
	800	0.322
	1100	0.274
	1400	0.19
	1700	0.099
3	50	2.226
	100	1.242
	150	1.532
	200	1.669
	250	1.246
	300	1.197
	400	1.041
	500	1.161
	600	0.907
	700	0.862
	800	0.917
	900	1.014
	1000	0.564
	1100	0.403
	1200	0.191
	1500	0.111
	1800	0.066

Wetland 3		
Zone No	**Bottom depth (mm)**	**Carbon content (%)**
1	50	25.412
	100	17.53
	150	10.908
	200	10.385
	250	6.34
	300	4.526
	350	4.87
	400	4.867
	450	4.531
	500	4.824
	550	2.404
	600	1.59
	700	0.94
2	50	3.023
	100	3.155
	150	3.086
	200	3.029
	250	2.036
	300	1.243
	400	1.507
	500	0.779
	700	0.256
	900	0.473
	1100	1.859
3	50	1.57
	100	1.588
	150	1.677
	200	1.234
	250	0.939
	300	1.017
	350	1.043
	400	1.311
	450	1.118
	500	1.156
	650	0.723
	950	0.632
	1250	0.4
	1550	0.212
	1850	0.127
4	50	0.684
	100	0.517
	150	0.031
	200	0.028
	250	0.034
	300	0.03
	400	0.023
	500	0.023
	600	0.023
	700	0.021
	950	0.012
	1300	0.008
	1600	0.051

Wetland 4		
Zone No	Bottom depth (mm)	Carbon content (%)
1	50	12.353
	100	4.466
	150	3.348
	200	1.643
	250	2.156
	300	1.551
	400	1.13
	500	0.818
	600	0.326
2	50	10.198
	100	4.586
	150	2.997
	200	2.096
	250	1.653
	300	1.466
3	50	4.607
	100	2.612
	150	1.542
	200	1.552
	250	1.578
	300	1.597
	400	1.651
	500	1.501
4	50	1.597
	100	1.216
	150	1.299
	200	1.241
	250	1.091
	300	0.946
	350	1.108
	450	0.775
	550	0.866
	750	0.886

Wetland 5		
Zone No	Bottom depth (mm)	Carbon content (%)
1	20	28.793
	40	40.091
	60	19.933
	80	10.33
	100	6.777
	120	5.967
	140	6.403
	155	4.898
2	20	1.677
	40	1.955
	60	1.836
	80	1.862
	100	1.841
	120	1.671

Wetland 6		
Zone No	Bottom depth (mm)	Carbon content (%)
1	50	11.846
	100	8.501
	150	6.365
	200	5.156
	250	4.697
	300	3.434
	400	2.018
	500	1.328
	600	0.774
2	50	6.963
	100	4.686
	150	3.425
	200	3.15
	250	2.695
	300	2.094
	400	1.618
3	50	2.301
	100	2.041
	150	2.324
	200	2.35
	250	1.723
	300	2.25
	350	2.306
	450	1.727
	650	1.138
	950	0.878
4	50	1.482
	100	1.343
	150	0.909
	200	0.674
	250	0.659
	300	0.502
	400	0.547
	500	0.532
	600	0.468
	950	0.449
	1130	0.177
	1480	0.085

Appendix 5: Groundwater fluctuation data for the Southern Transect.

Wetland No	No	Elevation (m a.s.l.)	23-Jun-10	2-Jul-10	16-Jul-10	5-Aug-10	17-Aug-10	27-Aug-10	6-Sep-10	17-Sep-10	27-Sep-10	7-Oct-10	15-Oct-10	21-Oct-10	4-Nov-10	15-Nov-10	23-Nov-10	8-Dec-10	17-Dec-10	23-Dec-10	4-Jan-11	11-Jan-11	24-Jan-11	Max Ground water depth	Min Ground water depth
1	**1/AA**	12.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	**2/BB**	10.55	-	5.99	5.99	5.94	5.90	5.87	5.89	5.90	5.88	5.85	5.92	5.96	5.92	5.95	5.95	5.88	5.90	5.85	6.14	6.40	6.58	6.58	5.85
1	**3/A**	9.31	-	6.12	6.11	6.03	5.99	5.97	5.96	5.97	5.94	5.94	6.02	6.06	6.03	6.01	6.02	5.94	5.97	5.90	6.16	6.48	6.63	6.63	5.94
1	**4/CC**	8.75	6.23	6.18	6.17	6.12	6.10	6.09	6.10	6.12	6.11	6.10	6.17	6.21	6.18	6.14	6.09	5.98	6.02	5.97	6.34	6.61	6.68	6.68	5.97
1	**5/B**	8.10	6.23	6.19	6.19	6.12	6.08	6.06	6.08	6.09	6.07	6.05	6.12	6.15	6.11	6.09	6.10	6.02	6.05	5.99	6.27	6.59	6.70	6.70	5.99
1	**6/C**	7.45	6.25	6.22	6.22	6.14	6.11	6.10	6.09	6.11	6.09	6.08	6.16	6.20	6.16	6.14	6.14	6.04	6.08	6.03	6.26	6.63	6.78	6.78	6.04
2	**7/DD**	9.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.87	5.92	5.94	5.90	5.94	5.90	6.15	6.56	6.68	6.68	5.87
2	**8/D**	8.85	-	6.08	6.07	5.97	5.94	5.92	5.92	5.95	5.92	5.90	5.95	5.98	6.01	6.02	6.02	5.95	5.92	5.88	6.14	6.58	6.74	6.74	5.90
2	**9/E**	8.39	6.17	6.12	6.11	6.02	6.00	5.98	5.97	5.98	5.97	5.96	6.02	6.05	6.07	6.06	6.05	5.98	6.05	6.00	6.22	6.60	6.79	6.79	5.96
2	**10/F**	7.82	6.21	6.15	6.14	6.04	5.99	5.97	5.99	6.03	6.00	5.99	6.05	6.08	6.10	6.10	6.09	6.03	6.02	5.98	6.16	6.62	6.75	6.75	5.97
3	**11/EE**	13.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.01	6.16
3	**12/FF**	9.57	-	6.51	6.49	6.43	6.40	6.39	6.37	6.37	6.35	6.34	6.39	6.42	6.47	6.50	6.52	6.37	6.43	6.37	6.64	7.09	7.26	7.26	6.34
3	**13/G**	8.81	6.63	6.52	6.51	6.47	6.45	6.44	6.42	6.40	6.38	6.37	6.43	6.47	6.50	6.52	6.53	6.40	6.45	6.40	6.68	7.09	7.22	7.22	6.37
3	**14/H**	8.07	6.55	6.55	6.55	6.43	6.40	6.38	6.38	6.39	6.38	6.37	6.42	6.45	6.48	6.50	6.52	6.39	6.44	6.40	6.68	7.10	7.19	7.19	6.37
3	**15/I**	7.40	6.63	6.59	6.58	6.50	6.47	6.46	6.46	6.45	6.43	6.42	6.51	6.54	6.57	6.60	6.59	6.45	6.51	6.48	6.73	7.32	7.53	7.53	6.42
3	**16/GG**	8.87	6.64	6.81	6.80	6.53	6.47	6.45	6.46	6.50	6.47	6.45	6.49	6.51	6.57	6.61	6.65	6.50	6.57	6.54	6.70	7.33	7.41	7.41	6.45
Y	**17/HH**	7.83	6.74	6.74	6.73	6.63	6.59	6.58	6.57	6.63	6.60	6.59	6.65	6.68	6.71	6.73	6.71	6.63	6.65	6.61	6.84	7.34	7.70	7.70	6.57
Y	**18/II**	8.43	6.70	0.00	0.00	6.61	6.57	6.55	6.57	6.59	6.57	6.57	6.60	6.63	6.69	6.74	6.82	6.59	6.62	6.58	6.84	7.49	7.59	7.59	6.55
4	**19/J**	7.96	6.57	6.65	6.64	6.53	6.50	6.49	6.49	6.52	6.51	6.50	6.56	6.59	6.67	6.71	6.74	6.52	6.55	6.50	6.79	7.39	7.55	7.55	6.49
4	**20/K**	7.63	6.65	6.65	6.65	6.52	6.46	6.44	6.48	6.52	6.50	6.49	6.55	6.57	6.64	6.69	6.72	6.52	6.55	6.51	6.90	7.43	7.62	7.62	6.44
4	**21/L**	7.27	6.69	6.66	6.66	6.52	6.47	6.46	6.47	6.51	6.48	6.47	6.52	6.56	6.62	6.66	6.69	6.51	6.53	6.50	6.86	7.14	7.38	7.38	6.46
4	**22/M**	7.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.51	4.83
N	**23/N**	3.45	3.37	3.30	3.29	3.25	3.22	3.21	3.21	3.25	3.23	3.24	3.33	3.36	3.30	3.26	3.24	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.21
5	**24/JJ**	8.65	7.94	7.96	7.95	7.86	7.81	7.80	7.81	7.83	7.82	7.81	7.89	7.91	7.95	7.97	7.98	8.30	8.35	8.32	8.54	8.74	8.71	8.74	7.91
6	**26/P**	9.77	8.80	8.81	8.80	8.65	8.62	8.61	8.59	8.61	8.60	8.59	8.65	8.68	8.70	8.73	8.72	7.61	7.91	7.89	8.23	9.79	9.90	9.90	8.59
6	**25/O**	9.53	8.66	8.68	8.68	8.39	8.33	8.31	8.38	8.46	8.44	8.43	8.48	8.51	8.56	8.59	8.60	8.46	8.75	8.72	9.03	9.56	9.64	9.64	8.31
6	**27/Q**	10.48	8.83	8.82	8.81	8.74	8.69	8.68	8.67	8.69	8.67	8.66	8.71	8.72	8.78	8.82	8.85	8.69	8.88	8.85	9.13	9.71	9.87	9.87	8.66
6	**28/R**	11.22	8.88	8.85	8.84	8.78	8.74	8.73	8.73	8.72	8.70	8.69	8.72	8.76	8.81	8.85	8.88	8.72	8.82	8.78	9.21	10.67	10.80	10.80	8.69
6	**KK**	11.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00