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

by

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AUTHOR’S DECLARATION

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Althea Theresa Grundling
University of Waterloo
May 2014

STATEMENT OF CONTRIBUTIONS

Exceptions to sole authorship:

I hereby declare that I was responsible to write the proposal for the research project (2009 – 2013) and was the project leader/main investigator for the research project that formed the basis of this PhD thesis and included an MSc study (Pretorius, 2011) and contributing to a PhD (Pretorius, *in progress*). The research project was funded by both the South African Water Research Commission and the Agricultural Research Council – Institute for Soil, Climate and Water. Because of the multidisciplinary nature of the research, expert input was received for remote sensing and GIS, terrain analysis, soil and vegetation studies (Pretorius, 2011), statistical analysis and hydrology modelling: Prof. Bruce (B.E) Kelbe who led the Hydrology Model Paper (Appendix 3). The relation between Soil Organic Carbon and hydroperiod (Appendix 5) complement the interpretation of permanent and temporary wetland types.

The Thesis is written in manuscript format. Some minor editorial differences may exist between the published version and the version that appears in Chapter 2 of the thesis.

Chapter 2 is published as:
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.

I was the lead author on this paper and did the main work of conceptualizing, analysing, writing, submitting, editing and addressing comments from the reviewers. Both co-authors contributed to the published manuscript: Ms. E.C. van den Berg helped with the land-cover classifications and accuracy assessments, field work and writing, especially the technical detail in the methodology section. Prof. J.S. Price acted as advisor, offering suggestions as well as editorial changes.

Chapter 3 to be submitted as:
Grundling, A.T., Price, J.S., Grundling, P. and Van den Berg E.C. Landscape processes controlling the dynamics of wetland type, extent and distribution in north-eastern KwaZulu-Natal, South Africa.

I did the main work of conceptualizing, analysing, writing; I wrote the majority of the text, was responsible for illustrating the conceptual model and classifying wetland types. Prof. J.S. Price gave help and suggestions with the landscape setting and wetland classification as well as editorial changes. Mr. P. Grundling offered suggestions and insight, verifying sites and help with extensive field work identifying and monitoring water-table levels. Ms. E.C. van den Berg contribution was related to the comparison of percentage clay content with wetland areas.

Chapter 4 to be submitted as:
Grundling, A.T., Weepener, H.L. and Price, J.S. Applying hydrogeomorphic wetland classification on the Maputaland Coastal Plain, north-eastern KwaZulu-Natal, South Africa.

I devised the approach and wrote the majority of the text, did the hydrogeomorphic classification, accuracy assessment and analysis of hydrogeomorphic type functioning in the landscape. Mr. Weepener assisted with the GIS steps to select the hydrogeomorphic classes and gave technical clarification in the methodology section. Prof. J.S. Price gave comments and offered suggestions as well as editorial changes.

Appendix 3: Hydrology Model Paper to be submitted as
Kelbe, B.E., Grundling, A.T. and Price, J.S. Modelling water-table depth in a primary aquifer to identify potential wetland hydrogeomorphic settings on the, northern Maputaland Coastal Plain, KwaZulu-Natal, South Africa.

Prof. Bruce Kelbe was the lead author on this paper and did the main hydrological modelling (setting the parameters and calibration) as well as the initial framework and main text. I provided water-table data collected and wetland and land-cover maps created as part of my PhD and sourced other data sets that include rainfall, evaporation values, Leaf Area Index values for Land-Cover classes and 5 m contours. Prof. J.S. Price and I contributed to the writing and editing of the paper.

Appendix 5: Soil Organic Carbon and Hydropgeriod

Grundling, A.T., Pretorius, M.L. and Grundling P. Association between Soil Organic Carbon and Hydroperiod in wetlands, Lake St. Lucia's Eastern Shores, KwaZulu-Natal, South Africa.

I was the project leader for the study, did the fieldwork and wrote the majority of the text and analysis. Ms. M.L. Pretorius helped with extensive field work, data analysis and text. Mr. P. Grundling offered suggestions and insight, helped with installing water-table monitoring wells. Both co-authors contributed to the writing and editing of the paper.

ABSTRACT

The Maputaland Coastal Plain is situated in north-eastern KwaZulu-Natal Province, South Africa. The Maputaland Coastal Plain and underlying aquifer are two separate but inter-linked entities. This area with high permeable cover sands, low relief and regional geology that slopes towards the Indian Ocean, hosts a variety of important wetlands in South Africa (e.g. 66% of the recorded peatlands). The wetlands overlie and in some cases also connect to the underlying regional water-table. The apparent distribution of wetlands varies in response to periods of water surplus or drought, and over the long-term has been reduced by resource (e.g. agriculture, forestry) and infrastructure (e.g. urbanisation) development. Accurate wetland mapping and delineation in this environment is problematic due to the ephemeral nature of wetlands and extensive land-use change. Furthermore the deep aeolian derived sandy soils often lacks soil wetness indicators in the soil profile. It is postulated that the aquifer is the source of water to rivers, springs, lakes and wetlands (and vice versa). However, the role of groundwater in the sustainability of hydro-ecological systems is unclear. Consequently this research attempted to determine spatial and temporal changes in the distribution of these wetlands, their susceptibility to human development, understand the landscape processes and characterise and classify the different wetland types. An underlying assumption of the hydrogeomorphic wetland classification concept in South Africa is that wetlands belonging to the same hydrogeomorphic unit share common features in terms of environmental drivers and processes. Given the above, the objectives of this thesis relating to the north-eastern corner of the Maputaland Coastal Plain are to: 1) Map the distribution of wetlands and their relation to other land-use; 2) Characterise the landscape processes shaping the dynamics of wetland type and their distribution; 3) Classify wetlands by applying hydrogeomorphic wetland classification system. This study used Landsat TM and ETM imagery acquired for 1992 and 2008 (dry) and Landsat ETM for 2000 (wet) along with ancillary data. Wetland type characteristics were described using terrain unit position in the landscape, SRTM DEM, land surveyor elevation measurements along with long-term rainfall records, *in situ* water-table levels with soil analysis and geology and vegetation descriptions. A conceptual model was used to account for the available data, and output from a hydrology model was used to support the interpretation of wetland distribution and function.

Wetlands in the study area include permanent wetlands (swamp forests and reed/sedge wetlands), but the majority of sedge/moist grassland wetlands are temporary systems. The wetland distribution reflects the rainfall distribution and groundwater discharge in lower lying areas. The weathering of the Kosi Bay Formation is a key factor in wetland formation. Because of an increase in clay content with depth, the pore-space and hydraulic conductivity are reduced which causes water to impede on this layer. The nature of the aquifer and regional geology that slope towards the east along with extreme rainfall events in wet and dry periods are contributing drivers of wetland and open water distribution. In 2008 (a dry year) the smaller wetland extent (7%) could primarily identify "permanent" groundwater-fed wetland systems, whereas for the wet year (2000) with larger wetland extent (18%) both "temporary" and "permanent" wetlands were indicated. Comparison between both dry years (1992 and 2008) indicates an 11% decrease in wetland (sedge/moist grassland) and a 7% increase in grassland distribution over time. Some areas that appear to be grassland in the dry years were actually temporary wetland, based on the larger wetland extent (16%) in 2000. The 2008 Landsat TM dataset classification for the entire Maputaland Coastal Plain gave an overall 80% mapping accuracy. Landscape settings identified on this coastal aquifer dominated by dune formations consist of 3 types: plain (upland and lowland), slope and valley floor. Although the wetland character is related to regional and local hydrogeology as well as climate affecting the temporal and spatial variability of the wetlands this research confirms that the patterns and wetland form and function are predominantly shaped by the hydrogeomorphic setting and not the rainfall distribution.

The following wetland types were identified: permanent wetlands such as peat swamp forests, peat reed and sedge fens; temporary wetland systems such as perched depressions, and sedge/moist grasslands. The Hydrogeomorphic wetland classification system was applied using a semi-automated method that was 81% accurate. The following hydrogeomorphic units could be identified: one floodplain, i.e., Siyadla River Floodplain, channelled valley-bottoms, unchannelled valley-bottoms, depressions on modal slope values <1%, seepage wetlands on modal slope values 1-2%. However, evaluation of the hydrogeomorphic classification application results suggests that the "flat" hydrogeomorphic class be revised. It did not fit meaningfully on the upland plain area. This research finding concludes wetland function does depend on landscape setting and wetland function is not truly captured by the hydrogeomorphic type classification. Not all depression on the coastal plain function the same way and three types of depressions occurs and function differently, i.e., perched depression with no link to the regional water-table vs. depressions that are linked with the regional water-table on plain, slope and valley floor landscape settings.

Overall, this research study made a useful contribution in characterising and classifying wetland type and distribution for a high priority wetland conservation area in South Africa. Applying similar methods to the broader Maputaland Coastal Plain will particularly benefit from the research findings. The importance of using imagery acquired in wet and dry periods as well as summer and winter for a more comprehensive wetland inventory of the study area, is stressed. To manage the effects of climate variability and development pressure, informed land-use planning and rehabilitation strategies are required based on landscape analysis and interpretation.

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Most of all, praise to my Saviour and Lord, Jesus Christ. "… *so that I might finish my course with joy, and the ministry, which I have received of the Lord Jesus*" (Acts 20:24).

For Renée and Amy

"With joy you will draw water from the wells of salvation" Isaiah 12:3

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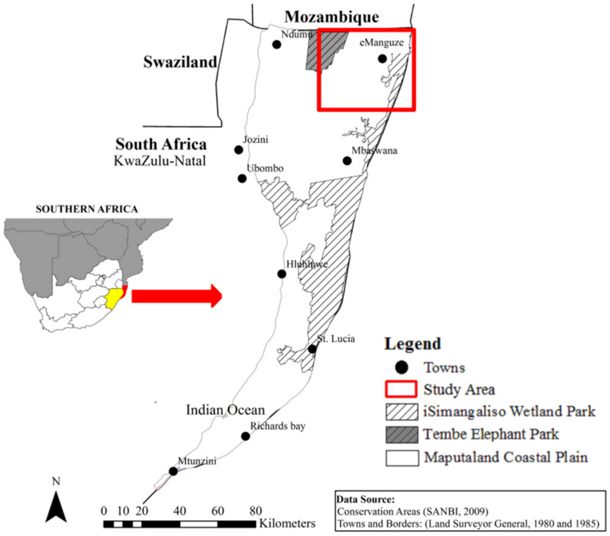
1. MAPUTALAND COASTAL PLAIN

1.1 INTRODUCTION

Wetlands are globally recognised as one of the support systems of humankind and important habitat for wildlife, 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 encroaching communities depend on the resources for their daily survival (Maltby and Barker, 2009). The Maputaland Coastal Plain 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). The Maputaland Coastal Plain is located in the KwaZulu-Natal Province, which hosts the highest percentage of wetland areas per province area in South Africa (SANBI, 2010). The Maputaland Coastal Plain is also home to South Africa's first World Heritage Site proclaimed to conserve and protect these unique wetlands. According to Le Maitre and Colvin (2008) and Colvin et al. (2007), it is likely that the baseflow derived from the Maputaland Coastal Aquifer is the most important source of water for most of these wetlands. The rivers, lakes and wetlands on the Maputaland Coastal Plain are predominantly groundwater driven (Kelbe and Germishuyse, 2010). As a consequence these wetlands are vulnerable to an aquifer draw-down through drought and water abstraction arising from land-use activities such as agriculture, forestry and urbanisation (Schapers, 2012). The area 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 for water extraction from wells, lakes, streams and springs (Grundling et al., 1998; Grundling, 2013), for building and making crafts, for fishing and for cultivating crops on the organic soils in the wetlands (Louw, 1984; Taylor, 1988).

1.2 STUDY AREA

The Maputaland Coastal Plain is situated in north-eastern KwaZulu-Natal province, South Africa between 32 – 33 degrees East and 27 – 28 degrees South. The Maputaland Coastal Plain lies within the Maputaland Centre of Endemism, an extremely biodiverse region (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 and overlap with species from the subtropical southern regions at the northern limit of their range (Smith and Leader-Williams, 2006). The Maputaland Coastal Plain stretches from the town of Mtunzini in the south and continues north towards the town Cabo Santa Maria in Mozambique (Momade et al., 2004). The linear north-south Lebombo Mountain range consists of the basalts and rhyolites of the Jurassic Jozini Formation that forms the Maputaland Coastal Plain border in the west, while the barrier dune complex of the Maputaland Group forms the border between the Indian Ocean and the Maputaland Coastal Plain in the east (Figure 1.2).



Data Source:
Conservation Areas (SANBI, 2009)
Towns and Borders: (Land Surveyor General, 1980 and 1985)

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

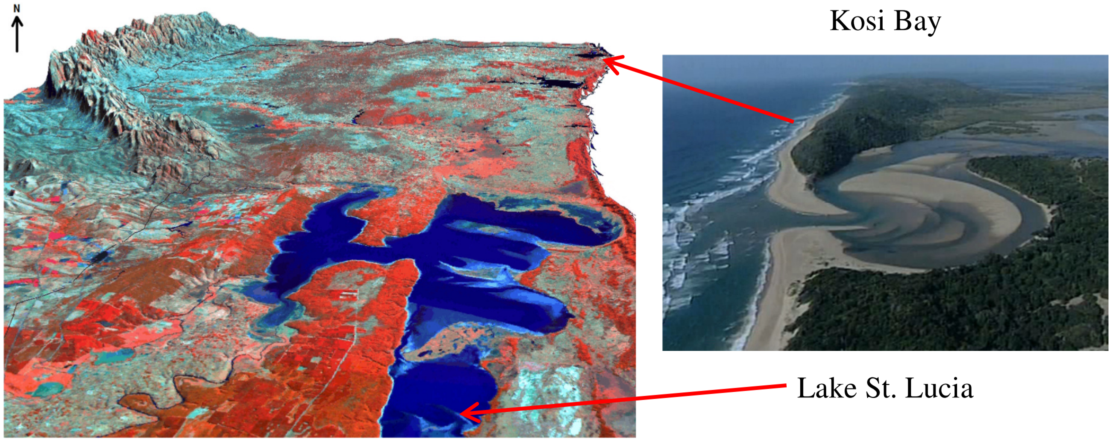


Figure 1.2: The southern end of the Maputaland Coastal Plain indicated with a false colour Landsat image draped over a 20 m DEM (Grundling and Beukes, 2011). Note the Lebombo Mountain on the left and the low relief of the coastal plain. Lake St Lucia to the south and Kosi Bay in the north.

The coastal plain consists of a flat to undulating dune topography at 45 – 70 m above sea-level and is 70 km wide in places. The Maputaland Coastal Plain is renowned for its biodiversity, conservation areas, and world heritage site status. A variety of wetlands including peatlands, swamp forest, saline reed swamp, salt marsh, submerged macrophyte beds, mangroves and riverine woodlands (Taylor, 1991) characterise the aquifer-dependent ecosystems (ADE) of the Maputaland Coastal Plain (Colvin et al., 2007; Taylor et al, 2006). According to Taylor (1991) and Taylor et al. (2006), rainwater is caught by the coastal dunes and percolates downwards, flowing out at the base of the landward dunes; indicating the strong interaction between surface precipitation and the local aquifer (Maputaland Coastal Aquifer). Many interdune or topographic depressions are inundated or saturated. The Maputaland Coastal Plain falls within the tropical/subtropical climate zone of Africa due to the warming influence of the Agulhas current. Summers tend to be very hot and winters mild (Taylor, 1991). Relative humidity is high. A rainfall gradient exist from east to west with the mean annual precipitation decreasing from 1200 mm/annum at the eastern coastal barrier dunes (100 to 180 m high) to 600 mm in the west at the 650m high Lebombo mountains) (Taylor et al., 2006). The vegetation groups (Maputaland Coastal Belt with Maputaland wooded grassland) present the different vegetation types defined in the vegetation map for South Africa (SANBI, 2005) namely: subtropical freshwater wetlands, North coastal forest, subtropical seashore vegetation and swamp forest found in low-lying saturated areas.

This thesis focused on the north-eastern part of the Maputaland Coastal Plain (Figure 1.1). 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 areas that include the iSimangaliso Wetland Park in the east and the Tembe Elephant Park in the west. Land-use activities in this rural area include forestry, subsistence agriculture, conservation and tourism. The study area on the Maputaland Coastal Plain falls within the Umhlabayalingana Local Municipality with the towns eManguze and Mbazwana, two major centres within the municipality area. Other significant places include the Tembe Elephant Park, Phelendaba and KwaNgwanase. In this rural setting the settlements (homesteads) tend to be scattered as part of the traditional "sense of place" and much of the population access water from shallow wells (Grundling, 2013).

1.3 CONTEXTUALIZATION

Maputaland has been a focus of interest for geologists studying the evolution of coastal plains (Botha and Porat, 2007; Grundling et al., 1998), vegetation ecologists investigating the vegetation diversity reflecting the soil and hydrology patterns (Goge, 2003; Venter 2003; Wejden, 2003; Kelbe and Taylor, 2011; Kelbe et al., 2013) and for hydrologists who study the coastal aquifer (Rawlings and Kelbe, 1998; Meyer et al., 2001; Kelbe et al., 2001; Kelbe and Germishuyse, 2000, 2001, 2010). Wetlands occur at the interface between terrestrial and aquatic systems and are the product of a diverse range of processes (Ellery et al., 2009b). Hydrological processes are key in determining wetland characteristics (Maltby and Barker, 2009). However, these hydrological processes are taking place in a system where evapotranspiration often exceeds precipitation (Tyson, 1987); i.e., precipitation is not the only key determinant of wetland occurrence in the Maputaland Coastal Plain. Wetlands in these drier areas are often dependent on groundwater and consequently, geology plays an important role in the wetlands' hydro-period and pattern of saturation (Været, 2008). Furthermore, geological and geomorphologic processes have a fundamental effect on the hydro-geomorphic position of the wetlands. It is evident that if precipitation is not the main source of water, the groundwater characteristics of wetlands will be more strongly linked to the geomorphic setting in the landscape, the alternative sources of water, and the flow pattern through the wetland (Kotze et al., 2009).

Groundwater flow is governed not only by topography but also geology and the storage and transmission properties of the geological materials and soils (Dingman, 2002; Freeze and Cherry, 1979). Topography can contribute to complex patterns of groundwater flow where a landscape with prominent or high relief will develop local flow systems compared to relatively simpler regional flow systems in a flatter landscape (Freeze and Cherry, 1979). Geological controls on groundwater movement include structural geology and lithostratigraphy (properties and age) of rock strata and unconsolidated sedimentary deposits. Preferential flow will typically take place in or along permeable layers, contact-, faulting- and folding zones (Dingman, 2002; Freeze and Cherry, 1979). Particle-size distribution, particle-shape characteristics and mineral composition are the main factors in lithology that control groundwater movement, as these characteristics affect the storage and transmission properties of aquifers (Dingman, 2002). It is important to understand the underlying geology that controls groundwater flow to wetlands in general and to saturated systems such as peatlands in particular, where sustained flow is vital for the survival of obligate species, and for anaerobic humification and organic accumulation processes. The Maputaland Coastal Plain, which at present hosts a variety of wetlands in different landscapes, is a product of processes beginning with the opening of the Mozambique Channel during the break-up of Gondwanaland 135 million years ago (Ellery et al, 2009b). With time the sediments that eroded from the interior were deposited on the continental shelf (McCarthy and Rubidge, 2005). According to McCarthy and Rubidge (2005) episodes of uplift 20 million and 5 million years ago resulted in increased erosion of the interior with more sediment accumulating on the continental shelf. This, at present, forms the lithology of the coastal plain.

1.4 RESEARCH GAPS

1.4.1 Contributing Environmental Factors

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 above mean sea level (Grundling, 2001; Turner and Plater, 2004). Peatlands formed where the clay-enriched Kosi Bay Formation weathering profiles are exposed, forming impeding layers as in the catchment areas of Lake Sibaya and the Kosi lakes (Botha and Porat, 2007), or calcimorphic clays are dominant in systems such as the Muzi wetland system (Watkeys et al, 1993). Grundling et al. (1998) and Marneweck, et al. (2001) suggest that there could be a strong relation between the spatial distribution of wetlands and geological formations, topography, elevation above sea level, rainfall distribution and depth to groundwater and/or groundwater fluctuation. However, no extant research has provided evidence linking the wetland types and dynamics to specific environmental factors such as rainfall, water-table, elevation, vegetation and soil with landscape processes such as weathering and peat-forming present on the Maputaland Coastal Plain. *Landform, hydrological characteristics and hydrodynamics* factors affect the geomorphological processes acting within the wetland such as erosion and sediment deposition and biogeochemical processes. Prolonged periods of drought have reduced the availability of groundwater (Rawlins and Kelbe, 1998), which can alter the distribution of wetlands in these groundwater-dependent ecosystems (Colvin et al., 2007). Drought is part of the dynamics of the area and part of the natural processes. However, the specific consequences of drought and how they affect wetlands are unknown. Mucina and Rutherford

(2006) identified the need for research focusing on temporal change in wetland patterns and function, and the processes that underlie them.

1.4.2 Aquifer Dependent Ecosystems

The information available on wetlands in South Africa, and specifically the Maputaland Coastal Plain, typically does not indicate the source of water for each wetland (Ewart-Smith et al., 2006). According to Colvin et al. (2007), research on South African aquifer dependent ecosystems (ADEs) is at an early stage. It is postulated that the aquifer is the source of water to rivers, springs, lakes and wetlands (and vice versa) (Taylor et al., 2006; Colvin et al., 2007; Le Maitre and Colvin, 2008; Kelbe and Germishuyse, 2010). Therefore, wetlands near the aquifer discharge zone need to be investigated to determine the relation between the wetland and the aquifer, i.e. is the wetland a source or sink of groundwater and/or surface water (Colvin et al., 2007). Begg (1989) emphasized this research need, stating that the groundwater recharge and discharge function of wetlands is not clear, while Taylor et al. (2006) suggested that there is good evidence that many wetlands serve as groundwater discharge areas. The degree to which swamp forest depends on groundwater is unknown but is predicted to be high for all wetlands that do not have a high proportion of surface-water in their catchment (Colvin et al., 2007). Further research is needed to qualify and quantify the nature and extent of these linkages, and to determine the type of ecosystem dependency. For example, what are the different vegetation community types that develop under various conditions, especially where it is in hydraulic contact with the water-table (Kelbe and Germishuyse, 2010). The water courses, estuaries and aquifers have been defined in the National Water Act of 1998, but not the interaction between them. This is primarily due to the gaps in the available data.

1.4.3 Hydrological Modelling

Kelbe and Germishuyse, (2010) reported that the estimations using models determining the vertical flux through the surface leading to infiltration, percolation and evaporation are available, yet there is a lack of information regarding methods and models describing a) the *interaction* between aquifers and b) their discharge *boundaries* (i.e. rivers, lakes and wetlands). The difficulty lies firstly, in delimiting distinct boundaries for these natural resources (i.e. rivers, lakes and wetlands) as they are seen as extensions of the groundwater system for which no clear boundary can be established; and secondly, establishing the recharge and discharge areas. Catchments are considered as both recharge zones and discharge zones, the latter typically along streams and stream banks where the water-table intersects the topography (Van der Griend and Engman, 1985). Prevailing moist conditions at discharge zones can make these areas also sources of surface runoff during precipitation. Recharge areas may be any area where the soils are highly permeable (normally higher areas) (Van der Griend and Engman, 1985). Germishuyse and Kelbe (1999) report that it was necessary to identify specific rainfall events (e.g. cyclonic systems) which had a significant effect on the groundwater levels and to evaluate the groundwater response. If recharge is a function of the rainfall distribution and the rainfall was uniformly distributed across the study area, then what secondary factors must play a role in wetland type and distribution in the landscape? The consequence of this lack of research on the role of groundwater in the sustainability of hydro-ecological systems (interaction between surface and groundwater) is hindering much-needed Groundwater Reserve Determination Methodologies (GWRDM) (Dennis and Dennis, 2009).

1.4.4 Wetland Delineation

Wetland delineation is problematic in sandy coastal aquifers with deep, aeolian-derived, sandy soils, often with grey profile colours and with no sign 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. 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) (Figure 1.3).

A recent MSc study (Pretorius, 2011) focusing on the vegetation composition of wetland zones in different wetland systems on the north-eastern Maputaland Coastal Plain has provided a valuable contribution to our knowledge on the main drivers of plant communities to aid wetland delineation in the Maputaland Coastal Plain. The results from the study indicated 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.

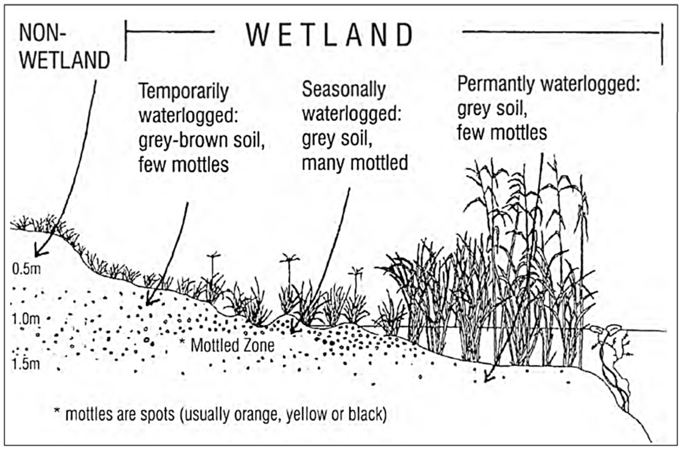


Figure 1.3: Cross section through a wetland (Kotze and Marneweck, 1999)

1.4.5 Wetland Mapping and Impacts

Various wetland mapping initiatives exist, ranging from international, national and provincial. Remote sensing (RS) has been applied in these mapping initiatives to provide information on wetland extent and distribution (or pattern). Landsat imagery has been applied in the following: international mapping studies for South Africa and Mozambique (Smith and Leader-Williams, 2006), the National Wetland Inventory for South Africa (NLC2000 Management Committee, 2005; SANBI, 2007a and 2007b;) and to map and identify swamp forests on the Maputaland Coastal Plain (Walsh, 2004). Various wetland mapping initiatives for KwaZulu-Natal (KZN) province have been created using different mapping methods and scales, including the KZN Wetland layer (Scott-Shaw and Escott, 2011), KZN Land-Cover 2005 and 2008 (GeoTerraImage, 2006; Ezemvelo KZN Wildlife, 2011). However, accurate wetland mapping is difficult. For example, there are some wetlands that have dried up, but old abandoned raised gardens indicate a period of wetter conditions once existed. MacDevette (1989) stated that wetlands on the Maputaland Coastal Plain are adapted to the prevailing weather and climate conditions but are threatened because of changing land-use. Agriculture, forestry and urbanization with prolonged periods of drought have resulted in land degradation and groundwater depletion (Rawlins and Kelbe, 1998) that could also affect the distribution and extend of wetlands. Therefore, Landsat Thematic Mapper (TM) (Zhang et al., 2011) and Landsat Enhanced Thematic Mapper (ETM+) (Baker et al., 2006) imagery along with ancillary data, such as a digital elevation model, vegetation and soil maps, etc., (Brooks et al., 2004; Jensen, 2005; Baker et al., 2006; Nagabhatla et al., 2012), could be used to map the wetlands in wet and dry years.

1.4.6 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. 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 shape and location of the wetland with respect to the surrounding terrain in terms of topography and lithology, which control its *Hydrological characteristics,* i.e., 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, an underlying assumption of the hydrogeomorphic wetland classification concept is that aquatic ecosystems function slightly differently in different landscape settings e.g. slope or valley floor; and that wetlands belonging to the same hydrogeomorphic unit, e.g., depression or channelled valley-bottom 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.

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 in order to generate a national wetland type map. The National Freshwater Ecosystem Priority Areas (NFEPA) project classified a wetland type layer for South Africa based on the hydrogeomorphic classification using an automated approach (Nel et al., 2011). No accuracy assessment has been done on the NFEPA wetland type layer. SANBI (2009b) recommended further testing and investigation into automation of the classification system, based on the availability of information required to distinguish one wetland type from another.

1.5 PROBLEM STATEMENT

Currently, the distribution and inter-annual variability of Maputaland Coastal Plain 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 drought, land-use change and environmental degradation is unknown. Monitoring of 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. An understanding of environmental factors and processes controlling the delineation and distribution of different wetland types is required before human-induced changes can be evaluated. It requires that wetlands be described and classified according to a set of biophysical characteristics and functional attributes to not only classify them accurately but also manage these systems and implement conservation practices (Ewart-Smith et al., 2006; Mucina and Rutherford, 2006). Consequently there is a need to a) determine spatial and temporal changes in the distribution of these wetlands, b) their susceptibility to human development, c) understand and characterise the landscape and/or aquifer processes, d) classify the different wetland types and apply the hydrogeomorphic wetland classification system proposed for South Africa. As stated above, the 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, have yet to be tested. It is important, when describing the typical characteristics of different wetland types found on the Maputaland Coastal Plain, to use a combination of remote-sensing classification, a classification specifically developed for the study area based on biophysical characteristics and functional attributes and adapting a geomorphic classification approach (Semeniuk and Semeniuk 1995) and a hydrogeomorphic classification in order to capture differences that have implications for the development of management and conservation strategies.

1.6 RESEARCH OBJECTIVES

The objectives of this thesis relating to the north-eastern part of the Maputaland Coastal Plain (study area) are to:

1) *Map* the distribution of wetlands within the study area and their relation to other land-use; Chapter 2
2) *Classify* wetlands types within the study area on the basis of their structure and function *and, on this basis, Characterise* the landscape processes shaping the dynamics of the wetland types and their distribution, Chapter 3
3) *Apply the Hydrogeomorphic Wetland Classification system* to the study area and determine if wetlands are dependent on landscape setting and if wetlands that belong to the same hydrogeomorphic unit share common properties and functions; Chapter 4
4) *Make recommendations* and identify priorities for wetland management in the study area: Chapter 5

1.6.1 Specific Objectives

1.6.1.1 Chapter 2: Map

To use Landsat TM and ETM imagery along with ancillary data to

1. Identify and map "permanent" and "temporary" (inland) wetlands and open water of the study area based on their spatial extent and distribution during wet and dry years; and
2. Determine wetland loss from land-use changes due to cultivation, plantations and urbanisation between 1992 and 2008.

1.6.1.2 Chapter 3: Classify and Characterise Wetland Types

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.

1.6.1.3 Chapter 4: Apply Hydrogeomorphic Wetland Classification

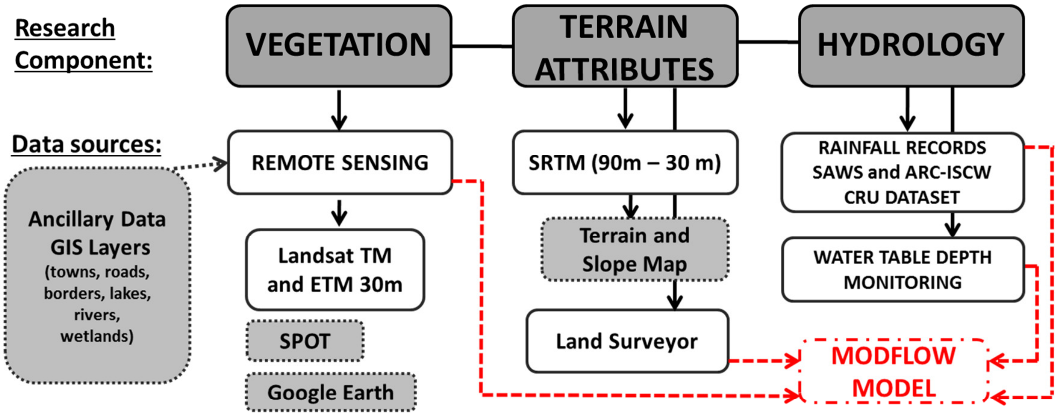
1. To identify the different hydrogeomorphic wetland units
2. To determine if wetlands that belong to the same hydrogeomorphic wetland unit share common features in terms of environmental drivers and processes by investigating the relation between landscape setting and local environmental factors such as water-table, rainfall, and elevation.

1.6.1.4 Chapter 5: Recommendation and Conclusion

1. To identify priorities for land-use management, especially plantations, subsistence agriculture and urban water abstraction under changing climate conditions.

1.7 RESEARCH APPROACH

Figure 1.4 illustrates the multi-disciplinary research approach to describe wetland types found within the north-eastern part of the Maputaland Coastal Plain (study area) and to try to understand the hydrogeomorphic drivers and the processes responsible for wetland occurrence. This method to identify, classify and monitor wetland distribution dynamics can also be applied on similar sandy coastal plains (e.g. south of the study area or north on the Mozambique Coastal Plain). Wetland classification forms a major part of the study using three main components: vegetation, terrain attributes and hydrology. Accuracy assessments were done for both the land-cover and hydrogeomorphic map produced.



Methods:

- Land-Cover and Land-Use Mapping, Accuracy Assessments
- Wetland Characterisation using: Long-term Rainfall, Water Table Monitoring, Soil Organic Carbon, Soil Fraction Analysis, Vegetation Descriptions, Geology, Conceptual and Hydrology Model
- Wetland Hydrogeomorphic Classification, Accuracy Assessment, Multivariate Discriminant Analysis

Outcomes:

① **TO UNDERSTAND THE HYDROGEOMORPHIC DRIVERS OF WETLAND TYPES ON THE MCP**

② **METHOD/TOOL TO IDENTIFY, CLASSIFY AND MONITOR WETLAND DISTRIBUTION DYNAMICS**

Figure 1.4: Flow chart illustrating the research approach producing a multi-disciplinary wetland information base.

In this thesis, 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 2, permanent and temporary wetlands and open water 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 (Figure 1.4). 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 (includes reeds)) were mapped spatially with the use of time-series Landsat TM and ETM imagery.

- In Chapter 3, the wetland type classification, specifically developed for the study area, was based on biophysical characteristics and functional attributes (landscape setting, water-table, vegetation and soil). A similar geomorphic classification approach to that used by Semeniuk and Semeniuk (1995) and the Classification System for wetlands and other aquatic ecosystems in South Africa (Ollis et al., 2013; SANBI, 2009b) that adapted the hydrogeomorphic classification system, was also applied. The wetland definition of the National Water Act, Act No 36 of 1998 (NWA, 1998) is used as a point of reference. Terrain unit position in the landscape, SRTM DEM, land surveyor elevation measurements along with long-term rainfall records, *in situ* water-table levels, soil analysis (Soil Organic Carbon and Soil Fraction Analysis) as well as geology and vegetation descriptions were used (Figure 1.4). A conceptual model shows wetland types and how they work in order to illustrate how landscape and aquifer properties affect the potential extent and distribution of wetlands, and how this could be influenced by drought, with reference to the Hydrology Model in the Appendix 3.

- In Chapter 4, the hydrogeomorphic wetland classification (adapted for South Africa) is applied and evaluated in terms of the relation between hydrogeomorphic wetland units and environmental factors using Multivariate Discriminant Analysis, and considers how well the hydrogeomorphic classification could be applied on the Maputaland Coastal Plain. In this chapter, 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 functions.

- The Hydrology Model manuscript (Kelbe et al., unpublished) in Appendix 3 aimed to populate the database of a single layer groundwater model (MODFLOW) (Harbaugh et al., 2000) to determine the water-table profile over a period with wet and dry years. The simulations are used to provide insight of how hydrogeomorphic setting and climate interact to produce persistent or transient high water-tables conducive to the evolution of wetland types in specific geomorphic settings. This study presents the MODFLOW (Harbaugh, 2005) results for a transient 10-year simulation period from January 2000 to December 2010. Contributions towards the manuscript include writing, editing, creating figures, providing data sets and expert knowledge. The Hydrological report (Dennis, 2014), using a combination of MODFLOW and MIKE SHE, was another parallel but separate investigation. In both (Dennis, 2014; Kelbe et al., unpublished, (Appendix 3)) the model parameters were configured and calibrated against measured *in situ* data acquired and used in this thesis (Grundling et al., 2014).

For the purpose of this thesis, it was decided to limit the investigation to the north-eastern part of the Maputaland Coastal Plain (study area). The study also focused on climatic, geomorphological and hydrological processes to improve the characterisation and understanding of wetland process within the landscape. It also focused on inland wetland systems (including peatlands) with no direct connection to the ocean. Not all the wetlands that occur on the coastal aquifer contain peat, and one therefore needs to distinguish between organic and mineral soil wetlands.

1.8 ORGANISATION OF THE WORK

This geographical approach investigates the distribution, characteristics and landscape processes of the wetlands on the Maputaland Coastal Plain, as well as changing land-use patterns from 1992 to 2008. Secondly, an application of hydrogeomorphic wetland classification for the Maputaland Coastal Plain is presented. The key themes of the thesis i.e. *mapping* of wetlands on the Maputaland Coastal Plain using Landsat TM and ETM imagery along with ancillary data; collection of environmental data for the *characterisation* of the different wetland types: rainfall data, elevation, water-table levels, soil surveys and, vegetation data as well as the *classification* of wetland on north-eastern part of the Maputaland Coastal Plain (study area) in hydrogeomorphic units are presented in a collection of three stand-alone manuscripts (Chapter 2, 3 and 4). Chapter 1 (Introduction) sets the context and background of the Maputaland Coastal Plain. Chapter 2 describes mapping the distribution of wetlands in wet and dry years and land-use change over time on the north-eastern part of the Maputaland Coastal Plain (study area) (published); Chapter 3, (manuscript form) discusses the landscape and aquifer processes characterising/determining the dynamics of wetland type extent and distribution (in which the groundwater modelling results are used) as well as classifying the wetland types (specifically developed in this PhD); Chapter 4 (manuscript form) applies and evaluates the hydrogeomorphic wetland classification for wetlands on the north-eastern part of the Maputaland Coastal Plain (study area) and shows the relation between hydrogeomorphic wetland units and environmental factors, and considers how well the hydrogeomorphic classification could be applied in the north-eastern part of the Maputaland Coastal Plain (study area); i.e., *do wetlands depend on landscape setting* and *do wetlands belonging to the same hydrogeomorphic unit share common features in terms of environmental drivers and processes*? These are tied together with a final Chapter 5: Recommendations and Conclusion. Appendices list the land-cover map metadada, water-table monitoring sites, hydrogeomorphic unit accuracy assessment results and give reference to a hydrological model and wetland study on a smaller scale on the Eastern Shores of Lake St. Lucia to indicate the relation between Soil Organic Carbon and hydroperiod; both were done as parallel studies and support the findings of the thesis.

2. DISTRIBUTION OF WETLANDS AND WATER

This chapter is published as:

Grundling, A.T., Van den Berg, E.C. and Price, J.S. (2013a) 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.

2.1 OVERVIEW

The Maputaland Coastal Plain (north-eastern KwaZulu-Natal) hosts an array of wetlands that provide valuable ecosystem services to an increasing population and tourism demand. The apparent distribution of wetlands varies in response to periods of water surplus or drought, and over the long-term has been reduced by resource (e.g. agriculture, forestry) and infrastructure (e.g. urbanisation) development. This study used Landsat TM and ETM imagery acquired for 1992 and 2008 (dry) and Landsat ETM for 2000 (wet) along with ancillary data to 1) identify and map permanent and temporary (inland) wetlands and open water based on their spatial extent and distribution during wet and dry years; and 2) determine wetland loss from land-use changes due to cultivation, plantation and urbanisation using imagery between 1992 and 2008. In 1992 (dry) the smaller wetland extent primarily identified “permanent” groundwater-fed wetland systems, whereas for the wet year (2000) both “temporary” and “permanent” wetlands were indicated. Comparison between both dry years (1992 and 2008) indicates an 11% decrease in wetland (sedge/moist grassland) and a 7% increase in grassland distribution over time. Some areas that appear to be grassland in the dry years are actually wetland, based on the larger wetland extent (16%) in 2000. Swamp forest wetlands were difficult to map and needed the support of ancillary data. Minor expansion of urban areas (0.87%) and the change in plantation and cropland distribution also replaced some wetlands. The 2008, Landsat TM dataset classification for the entire Maputaland Coastal Plain gave an overall 80% mapping accuracy.

2.2 INTRODUCTION

Land-use activities such as agriculture (croplands), forestry (plantations) and water supply schemes on the Maputaland Coastal Plain and prolonged periods of drought have reduced the availability of groundwater (Rawlins and Kelbe, 1998), which can alter the distribution of wetlands in these groundwater-dependent ecosystems (Colvin et al., 2007). The consequences are progressive landscape degradation, shrinkage and damage to remaining wetland ecosystems, increasing water scarcity and water access problems (Grundling, 2011) as well as a decrease in natural biodiversity on anthropogenically altered wetland sites (Grobler et al., 2004; Sliva, 2004).

The aeolian sands of the Maputaland Coastal Plain are leached and low in nutrients, resulting in low agricultural potential (Watkeys et al., 1993), so local communities rely heavily on wetlands for their daily livelihood, especially on peat-dominated wetlands such as swamp forests (Grundling, 2001; Sliva, 2004). However, significant land-use pressures occur from both cultivation and forest plantations (Grundling et al., 1998) that affect both permanent wetlands (including swamp forests) and the temporary sedge/moist grassland wetlands on the Maputaland Coastal Plain, while urbanisation impacts wetlands, for example, through infrastructure development (Cuperus et al., 1999).

Land-cover maps generated from remotely sensed imagery are used in numerous natural resource applications to assess, map and monitor the spatial distribution and pattern of land-cover classes such as open water and wetlands, as well as land-use classes like croplands, plantations or urban areas. The applications include the estimation of areal extent of various land-cover classes, land-cover change analysis and input layers for hydrological models (Stehman and Czaplewski, 1998). Wetland inventory and classification can provide information on wetland location, areal extent and wetland types within a landscape (Finlayson and van der Valk, 1995), whilst wetland assessment entails detailed evaluation of how a specific wetland or range of wetlands function by describing the ecological processes the wetland performs such as flood reduction or groundwater recharge (Smith et al., 1995; Kotze et al., 2009). Satellite sensors such as the Landsat Thematic Mapper (TM) (Zhang et al., 2011) and Landsat Enhanced Thematic Mapper (ETM+) (Baker et al., 2006) have been used in wetland vegetation mapping projects. Remote sensing methods include the use of Landsat imagery for application over regional scales because of the high cost of high resolution imagery (Jensen, 2005). However, wetlands are highly diverse ecosystems that have significant variability of physical properties. Seasonal wetlands or ephemeral features, marginal and degraded wetlands are often missed in wetland mapping procedures (Ramsey and Laine, 1997; Baker et al., 2006). However, remote sensing coupled with ancillary data sources such as a digital elevation model, vegetation and soil maps, etc., can be used to extract thematic information to characterise wetland type, extent, distribution and condition (Brooks et al., 2004; Jensen, 2005; Baker et al., 2006; Nagabhata et al., 2012).

The South African National Wetland Inventory (NWI) version 3 was incorporated in the National Freshwater Ecosystem Priority Area (NFEPA) wetland types layer (Nel et al., 2011), but some wetland areas in South Africa are still insufficiently mapped such as wetlands found in woodlands and savanna in lower altitude areas in KwaZulu-Natal, Limpopo and Mpumalanga provinces (NLC2000 Management Committee, 2008). Various wetland mapping initiatives for KwaZulu-Natal (KZN) have been created using different mapping methods and scales, including the KZN Wetland layer (Scott-Shaw and Escott, 2011), KZN Land-Cover 2005 and 2008 (GeoTerraImage, 2006; Ezemvelo KZN Wildlife, 2011). However, these datasets do not indicate whether wetland dynamics (extent and distribution) are related to seasonal and/or extreme rainfall events or whether they have well defined and relatively fixed boundaries. For example, Grundling et al. (2000) and Sliva (2004) described the nature of swamp forests on the Maputaland Coastal Plain as lower-lying interdune, valley bottom areas associated with drainage lines, underlain by low-permeability sediments, which receive sustained ground- or surface-water inflow. Groundwater seepage elevates the water-table sufficiently in the valley bottoms, which results in permanently wet conditions and the promotion of peat accumulation (Grobler et al., 2004; Grundling et al., 2012b). These can be described as “permanent wetlands”, and have a relatively fixed boundary. On the other hand, temporary sedge/moist grassland wetlands occur on the deep sandy soil in areas where the water-table fluctuations are greater; conditions which are not ideal for the development of peat. These can be referred to as “temporary wetlands”, whose boundaries may appear to grow or shrink in wet or dry periods, potentially causing their area to be underestimated in periods of water shortage. During very wet years, some areas including wetlands can be temporarily inundated with pools of open water for a short period. These can be described as “temporary open water”. In contrast, there are “permanent open water” areas including the Kosi Bay lake system and smaller lakes such as Lake Shengeza.

Currently, the distribution and inter-annual variability of Maputaland Coastal Plain 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 of 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, the aim of this paper was to use Landsat TM and ETM imagery along with ancillary data to 1) identify and map “permanent” and “temporary” (inland) wetlands and open water of the Maputaland Coastal Plain based on their spatial extent and distribution during wet and dry years; and 2) determine wetland loss from land-use changes due to cultivation, plantations and urbanisation between 1992 and 2008.

2.3 STUDY AREA

The Maputaland Coastal Plain is situated in north-eastern KwaZulu-Natal, South-Africa (Figure 2.1). The area covers ~943 000 ha and stretches from the Mozambique border in the north to the town of Mtunzini in the south and is bordered by the Indian Ocean on the east and the Lebombo Mountain range to the west. The Maputaland Coastal Plain is characterised by sandy soils and an undulating dune landscape on a low-lying coastal plain (Momade et al., 2004). The area has a subtropical climate with hot and humid summers and mild winters (Taylor, 1991). In summer (November to March), the mean monthly air temperatures exceed 21ºC and the area receives 60% of the annual rainfall (Mucina and Rutherford, 2006). The maximum potential evaporation is 1900 mm per annum (Mucina and Rutherford, 2006). The study area in the northern part of the Maputaland Coastal Plain is a combination of 79% unspecified or subsistence agriculture in the Tembe Tribal area (iSimangaliso Wetland Park, 2008a), while 21% is protected conservation area that includes the iSimangaliso Wetland Park in the east and the Tembe Elephant Park in the west (SANBI, 2009a) (Figure 2.1A).

The Maputaland Coastal Plain is characterised by cover sands with, north-south orientated parabolic dunes on the coastal plain (Whitmore et al., 2003) and drainage systems feeding the coastal lakes such as the Kosi Bay lake system (Porat and Botha, 2008). Surface water bodies include rivers, floodplains, estuaries, pans and coastal lakes (Botha and Porat, 2007). Wetlands include peatlands, swamp forests, reed swamps, and ephemeral interdune wetlands and hygrophilous grasslands (sedge/moist grasslands) (Taylor, 1991; Porat and Botha, 2008). Figure 2.1B indicates the subtropical freshwater wetland distribution in the study area based on the KZN Wetland layer (Scott-Shaw and Escott, 2011); Figure 2.1C indicates wetland types based on the NFEPA layer (Nel et al., 2011). Although the KZN Wetland layer and the

NFEPA wetland type layer show the extent and distribution of wetlands, they do not indicate whether the wetlands are permanent or temporary systems.

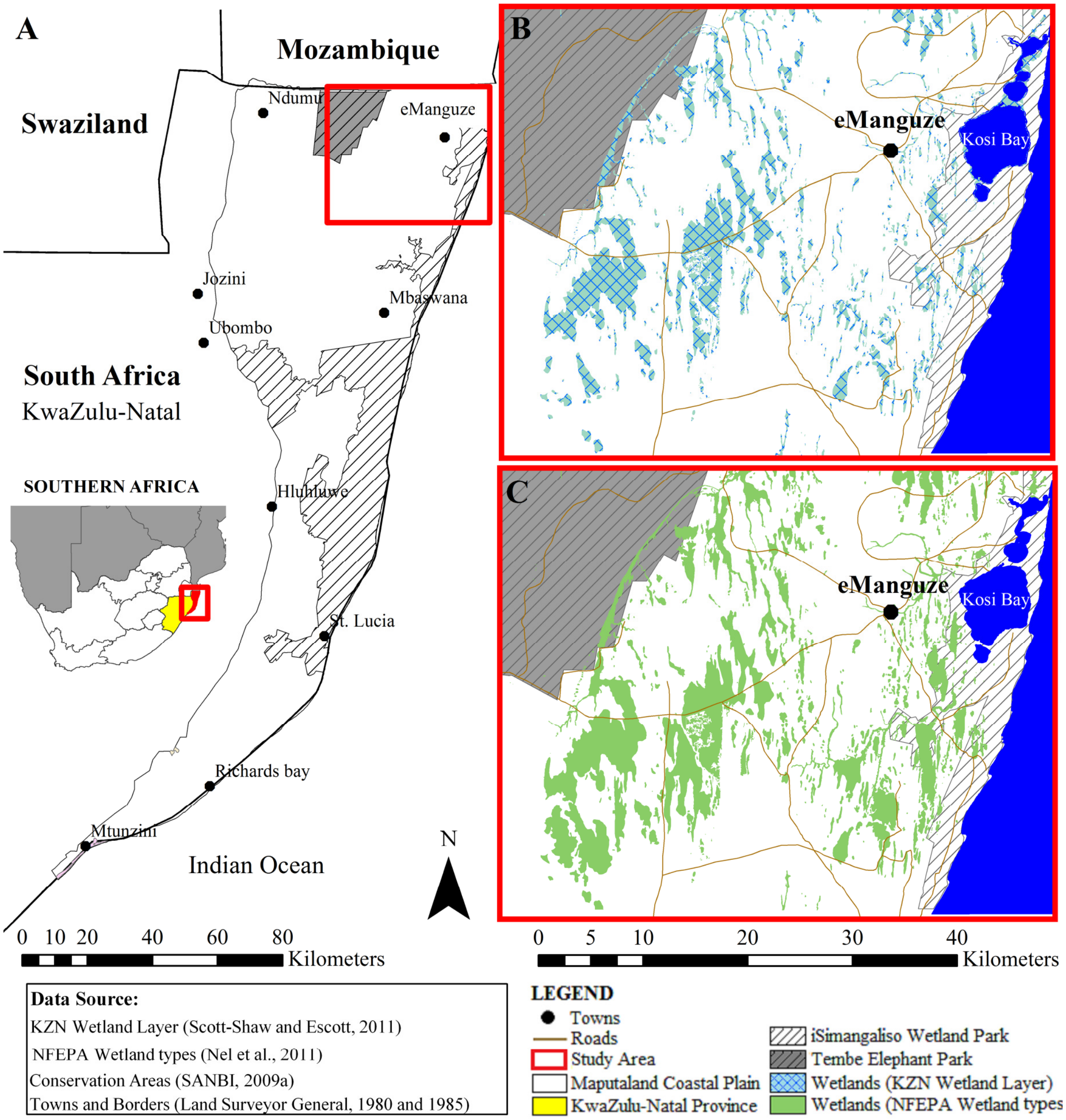


Figure 2.1: A) Regional map of the Maputaland Coastal Plain in South Africa and study area location. Study area indicating the KZN Wetland layer (B) and NFEPA Wetland Layer (C)

2.4 METHODOLOGY

2.4.1 Rainfall Data

The total monthly rainfall data for the northern study area was acquired from the ARC-ISCW (2011) for the period January 1989 to December 2011 (Figure 2.2). The long-term rainfall indicates high summer rainfall from October to March and lower winter rainfall from April to September with average rainfall 94 mm/month (summer period) and 30 mm/month (winter period). Rainfall data were grouped monthly and annually to determine dry and wet years to facilitate satellite imagery selection. Landsat TM imagery was acquired for both 1992 and 2008 (dry), and Landsat ETM for 2000 (wet) years. The selection of 2000 (wet) was made because it was the only distinctly wet year in the period of record (Figure 2.2). Less than average rainfall was received from 2002 to 2012, when the average annual rainfall (586 mm) was far below the long-term average rainfall of 753 mm (measured over the previous 23 years) (Figure 2.2).

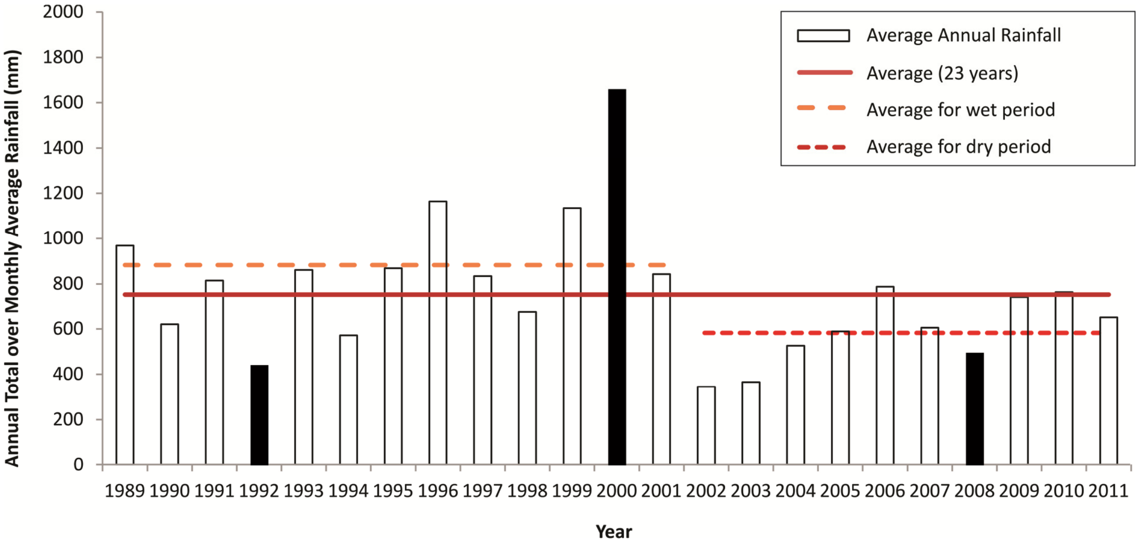


Figure 2.2: Average annual rainfall highlighting (in black) the wet year (2000) and dry years (1992 and 2008).

2.4.2 Wetland and Land-Use Mapping

2.4.2.1 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.

2.4.2.2 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 (2012). The land-cover maps created for the study follows 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 the 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 was 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 1) the knowledge gathered during the field reconnaissance to evaluate the first draft classification; and 2) interpretation and refinement based on the information from selected classes from existing ancillary datasets (Table 2.1). 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 2.2) is similar to that proposed by Thompson (1996) and GeoTerraImage (2006), with modifications of the wetlands (sedge/moist grasslands) and swamp forest classes, because their classifications 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 2.1: 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. These 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 of the forest classes (dune, sand, swamp and riverine classes)
KZN Land-Cover 2008	Ezemvelo KZN Wildlife (2011)	To familiarise with the distribution of wetland class

Table 2.2: 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

2.4.2.3 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: 1) Permanent wetland: these areas 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 wetland: this refers to seasonal wetlands characterised by saturation for three to ten 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). It 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 types (permanent or temporary) of wetlands and open water in the

Maputaland Coastal Plain. Firstly, an area comparison was made between the three years by overlaying the wetland and open water layers representing the different years. A script was used to calculate the sum value for the three years with each pixel value equal to one. 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 script in ERDAS to allocate class number to create a "wetness" map that distinguishes permanent and temporary wetlands and open water.

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 affected by land-use.

2.4.2.4 Accuracy Assessment

The accuracy assessment analyses were performed using two methods:

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) databases (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. 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. 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.

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 Microsoft 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.

2.5 RESULTS

2.5.1 Permanent and Temporary Wetlands and Open Water Areas

The nature of the aquifer, topography and rainfall distribution (hydrogeomorphic setting) are related to the wetland distribution and temporal character. The topography (Figure 2.3A) reflects the regional geological template that slopes towards the east, and is superimposed by more recent dune formations. There is also a precipitation (rainfall) gradient; the rainfall decreases from east (>820 mm) to west (680 mm) (ARC-ISCW, 2009) (Figure 2.3B).

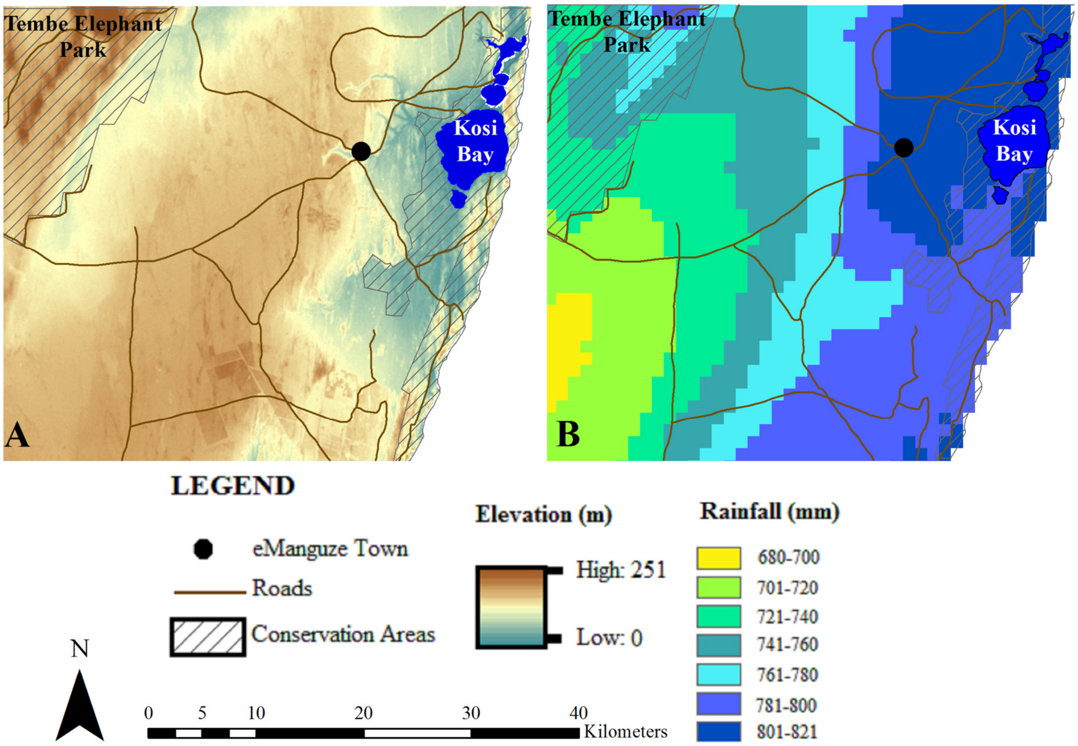


Figure 2.3: Elevation (A) and long-term rainfall distribution (B) of the study area.

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 2.4A-C) (Map Metadata in Appendix 1). 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 2.3). 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 2.4D). The sedge/moist grassland wetlands on the uplands 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 2.4 D).

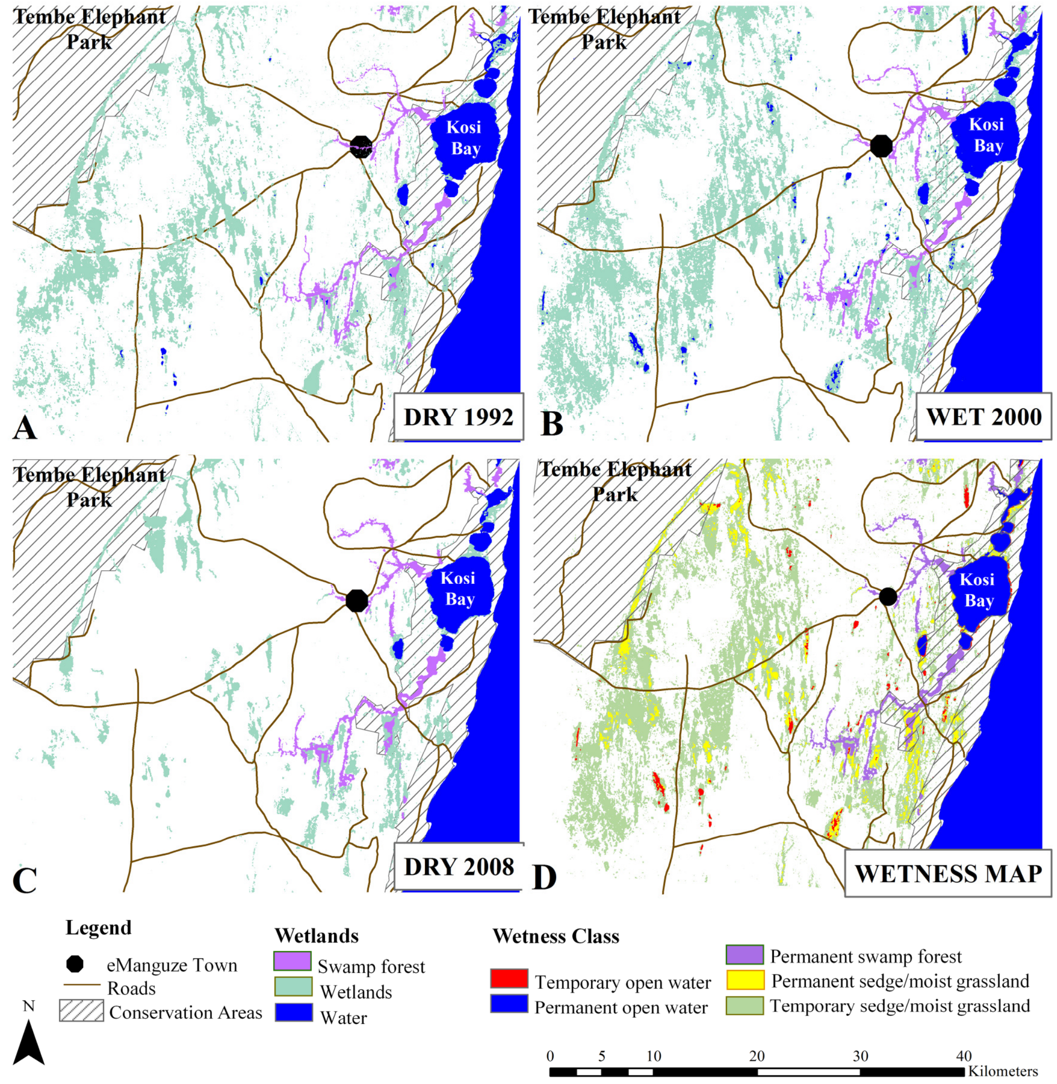


Figure 2.4: Wetland distribution in dry years (A and C), wet year (B) and wetness map with permanently-,temporary wetlands and open water areas (D)

Table 2.3: Selected land-cover class cover for 1992, 2000 and 2008 in percentage and hectares (ha)

Classes	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

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

Figure 2.5 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 Maputaland Coastal Plain (Map Metadata in Appendix 1). Table 2.3 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 2.3). However, the plantation area (south) (Figure 2.5) 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 2.3 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 2.3). 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 2.3). The results for the wet year (2000) (Figure 2.4B) indicate a larger wetland extent (16%) (Table 2.3). 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 2.3). Cultivation areas in 1992 were more (17%) than in 2000 (15%) and 2008 (11%) (Table 2.3). The cultivation, plantation and urban distribution pattern changed significantly from 1992 to 2008 (Figure 2.5A 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 2.5B).

Results from comparing the known permanent and temporary wetland and open water areas (Figure 2.4D) with 2008 land-cover classes (Figure 2.5B) 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 2.3), 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.

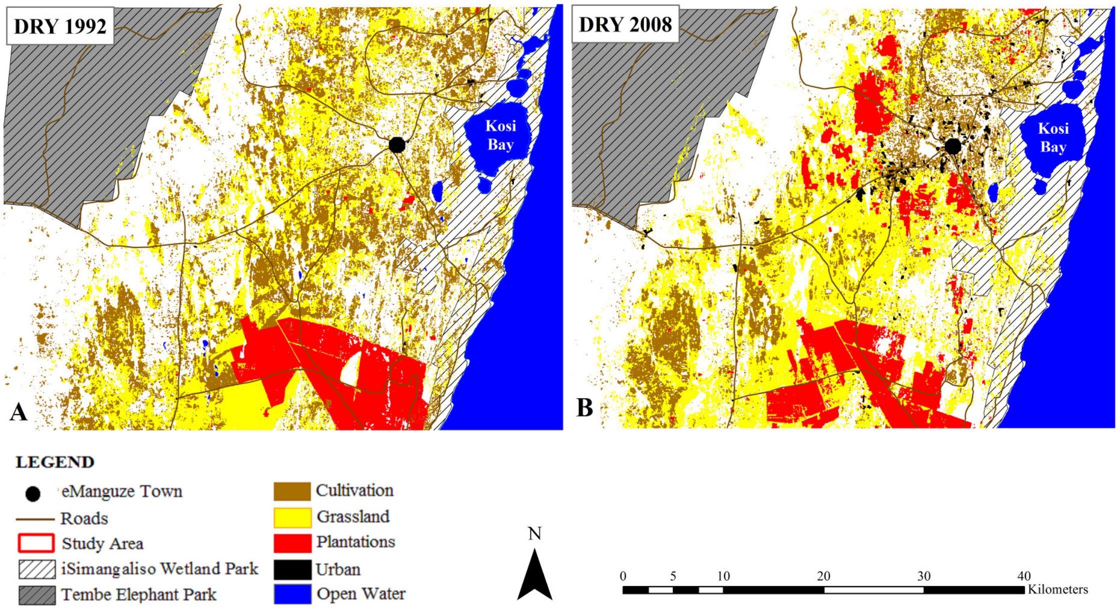


Figure 2.5: Comparing land-cover classification maps for the dry years 1992 (A) and 2008 (B).

2.6 DISCUSSION

2.6.1 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 Maputaland Coastal Plain. The upland (50-82 m.a.s.l.) has a greater proportion of temporary sedge/moist grassland wetlands; 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 2.4D). 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 total 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 the 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 (Grundling et al., 2012a), and hence may be undervalued habitat.

2.6.2 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 (+1353 ha) and plantation (+3147 ha) areas and decrease in cultivation practices by 10264 ha. The increase of tourism and entrepreneurial activities near the town 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 4212 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 (Grundling et al., 2012a) on wetland function and distribution is unknown and is therefore a major research need.

2.6.3 Accuracy Assessment

Accuracy assessment was performed using an error matrix (Table 2.4). 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 and calculate 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 2.4).

Table 2.4: Error matrix with verified points for land-cover classes (rows) versus 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% to 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 Maputaland Coastal Plain. 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 these classes were not of concern for the study. The 80% mapping accuracy for the 2008 Maputaland dataset compares well with the NLC2000 land-cover datasets (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 error occurred between cultivated and grassland classes (33% to 41%), between wetland and grassland classes (34%) and between bare soil and cultivation classes (26%). Ozesmi and Bauer (2002) indicated 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 that grassland areas were classed as cultivation because of the low grass cover in a dry year, similar to dry cultivated lands. Mapping of swamp forest and sedge/moist grassland wetland types indicate that Landsat classification did well in mapping the sedge/moist grassland wetland types. However, the swamp forest wetland type proved to be difficult. The resolution of the Landsat imagery (30 m) is not the 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 the 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 indicate 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 2.2) is that one would be likely to overestimate the coverage of permanent wetlands, while in extreme 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 on 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.

2.7 CONCLUSIONS

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 its 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; temporary 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 map 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 show land-use activities and drought have reduced wetland extent and distribution by 11%. Wetland 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 Maputaland Coastal Plain in Mozambique, supporting future research.

2.8 ACKNOWLEDGEMENTS

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3. LANDSCAPE PROCESSES

This chapter to be submitted as:

Grundling, A.T., Price, J.S., Grundling, P. and Van den Berg E.C. Landscape processes controlling the dynamics of wetland type, extent and distribution in north-eastern KwaZulu-Natal, South Africa.

3.1 OVERVIEW

This study focused on investigating the climatic, geomorphological and hydrological processes to classify wetlands types of north-eastern KwaZulu-Natal province, South Africa, and to improve the understanding of wetland processes within the landscape. The process driver on the Maputaland Coastal Plain is rainfall and evaporation coupled with the geological and geomorphological template of the area. Groundwater model results (from parallel but separate investigations) confirm that the wetlands' extent and distribution are directly linked to spatial and temporal variation of the water-table. For example, the temporary wetlands on the upland plain (≥50 m.a.s.l.) that occur in areas with mineral soils having low clay content, have water-table depths ≤ 2 m during the wet period, signifying they are linked to the regional water-table. The regional water-table rises to the surface following significant rainfall events during relatively wet periods, and with their permeable soils and topographic position these areas act as recharge zones. Temporary systems exhibit large water-table decline during dry seasons and within an 11-year drought period (2002-2013). Some temporary wetlands on the central upland occur where the regional water-table is >2m depth, as a result of illuviated horizons with higher clay content, buried ferricrete or paleo-peat layers that reduce hydraulic conductivity, promoting perched or partially perched water-tables that contribute to a prolonged hydroperiod (essential for wetland development). In the lowland areas (<50 m.a.s.l.), the groundwater model results confirmed the presence of groundwater discharge zones. These areas support more permanent wetlands with dominantly peat or high organic soil substrates, including swamp forest and most of the permanent open water bodies. This study indicates the landscape hydrological drivers are more important than the east-west rainfall distribution. The types of wetland that occur on the Maputaland Coastal Plain are dictated by a combination of water permanence (permanent and temporary wetlands and open water) controlled by the landscape settings (i.e. plain (upland and lowland), slope and valley floor). The wetland types identified include permanent or temporary channelled valley-bottom, unchannelled valley-bottom, depression (mostly interdune), and seep. One floodplain (the Siyadla River Floodplain) was identified.

3.2 INTRODUCTION

Freshwater ecosystems are amongst the most endangered ecosystems in the world (Dudgeon et al., 2006) and wetlands were recently identified as the most threatened ecosystem in South Africa (Driver et al., 2012). The sub-tropical freshwater wetlands found on the Maputaland Coastal Plain in north-eastern KwaZulu-Natal 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 (Low, 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 (Chapter 2) (Grundling et al., 2013a) have rendered these wetlands vulnerable, not only to natural stressors such as fire, but also to exploitation. Schmera and Baur (2011) emphasise 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 Maputaland Coastal Plain, namely north to south and east to west. Wetlands on the Maputaland Coastal Plain include *permanent* wetlands (peatlands, swamp forests and reed/sedge wetlands) and sedge/moist grasslands that are mostly *temporary* wetlands (Chapter 2) (Grundling et al., 2013a). Their distribution reflects their hydrogeomorphic characteristics as governed by the climate within a particular geomorphic setting, as described below.

The distribution of wetlands is related to the spatial patterns of rainfall. Eastern South Africa receives more rainfall that 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) have 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). On the other hand, prolonged periods of drought reduced the availability of groundwater (Rawlins and Kelbe, 1998), which can affect 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. Water losses by evapotranspiration represent the other significant climatic driver. In the Maputaland Coastal Plain, potential evapotranspiration exceeds average annual rainfall, leading to periods of moisture deficit in most years (Mucina and Rutherford, 2006). This results in wetlands being more reliant on groundwater to sustain the requisite level of wetness.

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 and influences the ecological patterns and processes. It is postulated that the aquifer is the major source of water that supports rivers, springs, lakes and wetlands during dry periods, and it is recharged by these systems during wet periods (Taylor et al., 2006; Colvin et al., 2007; Le Maitre and Colvin, 2008; Kelbe and Germishuyse, 2010). Grundling et al. (1998) and Marneweck et al. (2001) suggested that there could be a strong relation between the spatial distribution of wetlands and the regional or sub-regional hydrology and geology.

Van Wyk (1991) and Matthews (2007) reported on the *interrelated effects* of topography, water-table and soil type as the main ecological driving factors on the Maputaland Coastal Plain. 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 above-noted theory of general drivers, Maltby and Baker (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 includes carbon, phosphorus and nitrogen cycling (Barnes et al., 2002). This in turn influences the structure of the wetland ecosystem and mediates the accumulation of organic matter (Maltby and Baker, 2009). On the Maputaland Coastal Plain, topographic and hydraulic characteristics of the aquifer, the regional geology formations that slope eastward towards the coast, and rainfall distribution (diminishing away from the coast) are the main drivers of spatial and temporal variability in wetland and open water distribution (Grundling et al., 2013a). However, these drivers and landscape processes have not yet been sufficiently characterised to explain a) the extent and distribution of permanent and temporary wetlands and b) the formation of certain wetland types on a sub-regional scale for the Maputaland Coastal Plain.

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, which has a dry climate and a limited range of basic landscape units (settings or landforms) that host temporary wetlands, similar to the Maputaland Coastal Plain. However, temporary wetlands are ephemeral and transitional, and thus difficult to characterise. Nevertheless, characterising their extent and distribution is just as important as it is for permanent wetlands, in order to provide a basis for better landscape management (Lopez et al., 2013). 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 the seven primary names used in the Classification System for wetlands and other aquatic ecosystems in South Africa (Ollis et al., 2013; SANBI, 2009b), which adapted the hydrogeomorphic (HGM) classification system. The National Water Act (NWA), Act No 36 of 1998 (NWA, 1998) of South Africa defines wetlands as:

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

In the Maputaland Coastal Plain there is a need to identify and categorize the different wetland *types*, their biophysical characteristics and where are they located in the landscape. Furthermore, to better manage these wetlands it is essential to understand the landscape and aquifer *processes* shaping the wetland's presence, dynamics and character. Therefore, the objectives of this research were 1) to classify wetlands types within the study area on the basis of their structure and function; and on this basis 2) to characterise the landscape processes shaping the dynamics and distribution of the wetland types.

3.3 STUDY AREA

The study area extends from the Tembe Elephant Park in the west to the Kosi Bay lake system near the Indian Ocean in the east (Figure 3.1). The study area (~250 000 ha) is part of the Tembe Tribal area in the northern Maputaland Coastal Plain situated in north-eastern KwaZulu-Natal, South-Africa (Figure 3.1). Protected conservation areas (21% of the study area) include the iSimangaliso Wetland Park in the east and the Tembe Elephant Park in the west (SANBI, 2009a). The rest of the land-use is a combination of unspecified or subsistence agriculture (iSimangaliso Wetland Park, 2008a), forestry plantations and an urban area at the town eManguze near the Mozambique border post. The change in spatial land-use distribution from 1992 to 2008 exhibited a slight increase in urban (+1353 ha) and plantation (+3147 ha) areas and decrease in cultivation practices by 10264 ha, as a result of the 11-year drought period (Chapter 2) (Grundling et al., 2013a). The wetlands of the study area are used for cattle grazing and croplands (Grundling et al., 1998), and the wetland vegetation is harvested for crafts and building material (Tarr et al., 2004). The presence of previous agricultural land-use on wetlands was evident in the study area where abandoned gardens on temporary wetlands have become covered by grassland because of drier conditions (Chapter 2) (Grundling et al., 2013a). Macfarlane et al. (2012) noted the impact of reed harvesting on the vegetation structure and composition in the Muzi swamp (reed/sedge wetland inTembe Elephant Park); reeds are fewer, thinner and shorter than they were in the past (Hannekom, 2011).

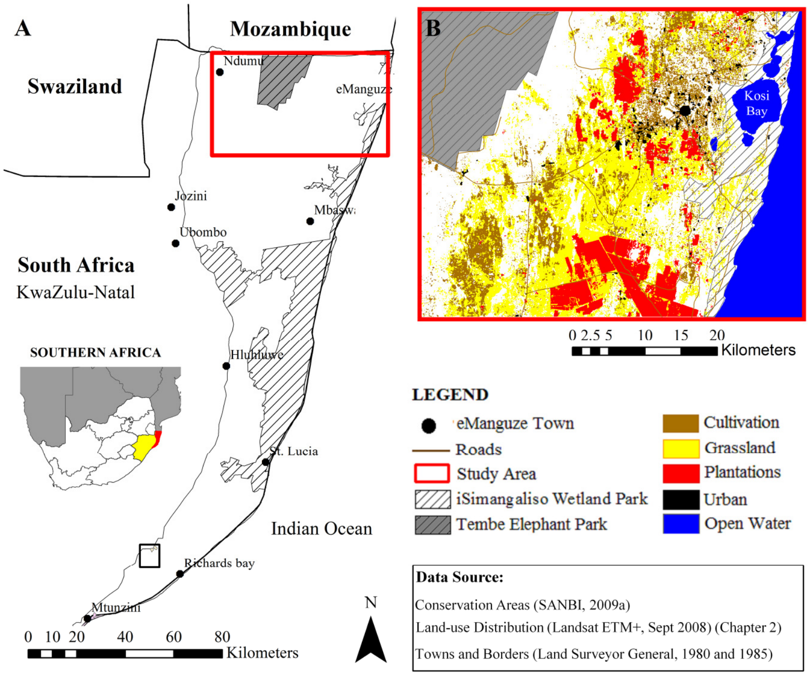


Figure 3.1: Regional map of the Maputaland Coastal Plain in South Africa and study area (left); land-use distribution from Landsat Enhanced Thematic Mapper (ETM+) imagery, September 2008 (Chapter 2) (Grundling et al., 2013a) (right).

3.3.1 Climate

Several global and macro-regional factors such as hot, wet summers (tropical) with high humidity and mild slightly drier winters (subtropical) are responsible for the tropical/subtropical character of the Maputaland Coastal Plain (Taylor, 1991; Mucina and Rutherford, 2006). These factors include the 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 et al., 2008). Tropical cyclones can cause major climatic and hydrological forcing e.g. 'cyclone Claude' in 1969 and 'cyclone Demoina' in 1984 (MacDevette, 1989). Bruton and Cooper (1980) reported on the events in early 1976 when Maputaland experienced 700 mm rainfall in only 3 days. Tropical storm Irina occurred during the research period in March, 2012. Cyclones originate over the Indian Ocean and approach the Maputaland Coastal Plain from the northeast. The 1901-2009 Climate Research Unit Global Climate Data records for a location in the study area (Lat: -27.1, Long: 32.5) indicates the total average rainfall is 908 mm per year, and alternating wet and dry periods ranging from 9-13 years (CRU, 2013). Wet periods (where the moving average rainfall over 10 years is more than the total average of 908 mm calculated from 1901-2009) occurred in 1909-1922; 1954-1967; 1971-1984 and 1989-2000. Mucina and Rutherford (2006) reported that 60% of the rainfall on the Maputaland Coastal Plain occurs during the summer months (November to March) and 40% during the winter months (April to October), and the mean annual temperature is 21^{o}C. The evaporation rates on the Maputaland Coastal Plain are the highest in the winter and early spring (Van Wyk, 1994; Van Wyk and Smith, 2001). Annual evaporation rates were measured in 2009 and 2010 on the Eastern Shores area adjacent to Lake St. Lucia was 900 mm for the Mfabeni mire and 478 mm for the coastal dunes (Clulow et al., 2012).

3.3.2 Geology and Hydrology

Table 3.1 lists the geology of the Maputaland Coastal Plain. It 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 formations and include alluvium, fine-grained aeolian redistributed sands, clayey sand, dune and beach sands, washout-fan gravels and small outcrops of diatomaceous earth (du Preez and Wolmerans, 1986; Van Wyk and Smith, 2001).

Table 3.1: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, but see Figure 3.2.

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)

3.3.3 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 Maputaland Coastal Plain 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:

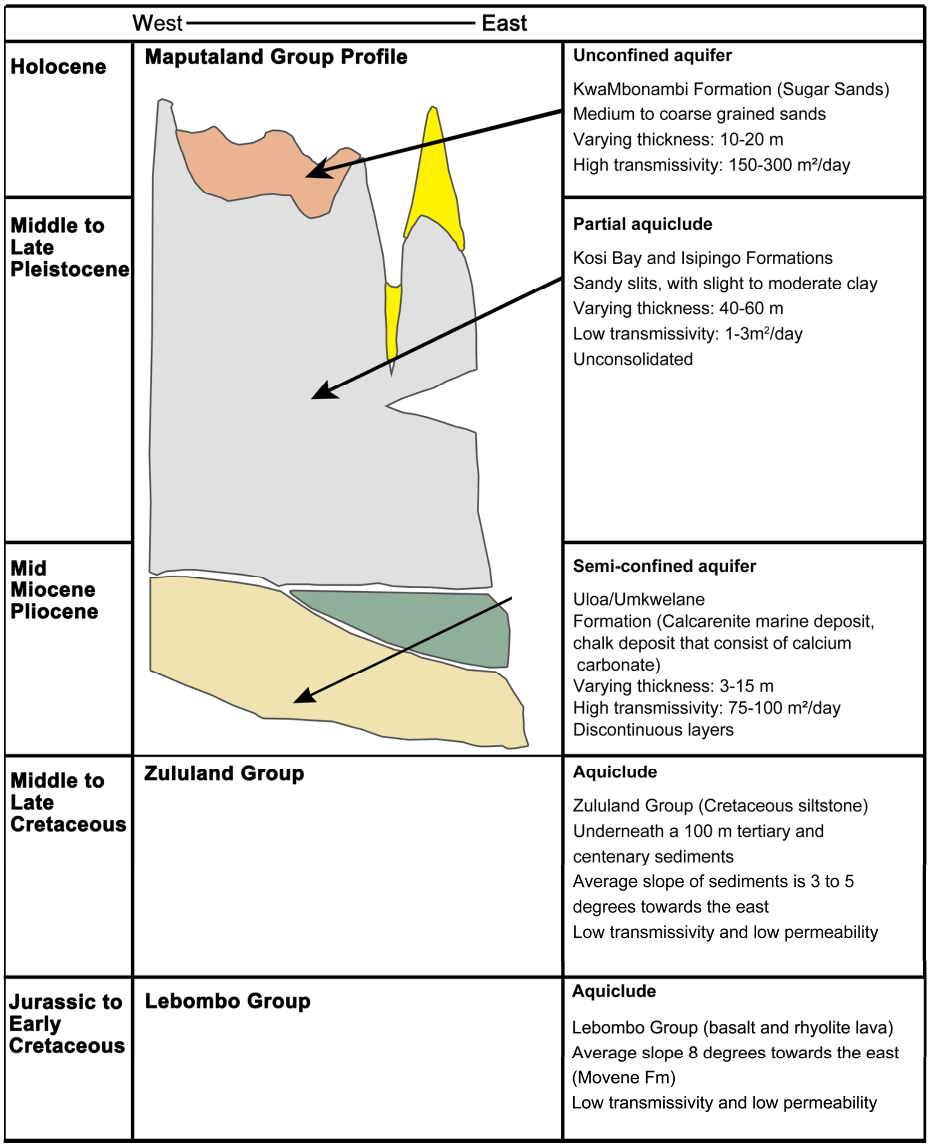
i) The hummocky dune systems comprise the KwaMbonambi Formation, representing sand mobilization, alluvium and peat deposits that occurred during the last glacial cycle. These make up the shallow, unconfined aquifer known as the Maputaland Coastal Aquifer (Colvin et al., 2007). The sandy sediments of the Late Pleistocene and Holocene (cover sands) are well sorted, highly porous and permeable (typical hydraulic conductivity values ~1.006e-04 m/s compared to the Port Durnford lacustrine mud values ~1.006e-10 m/s) (Grundling and Grundling, 2010). However, the sandy sediments do not occur everywhere. There are some localized occurrences of relatively low permeability substrate 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 where it emerges 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 m.b.g.l.), 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 uncertain (Maud 1998; Kelbe, 2010; Roux, 2011; Schapers, 2012).

The hydrogeological characteristics of the Maputaland Group, Zululand Group and Lebombo Group's lithostratigraphy within the immediate study area at eManguze (location shown in Figure 3.1) is shown in Figure 3.2. 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 with high transmissivity rates (75-100 m^2/day). The Uloa Formation contains a sequence of calcified marine

coquina, shelly and boulder/cobble conglomerate with sandstone and siltstone deposits in which gastropods, brachiopods, coralline algae and corals are present (Roberts et al., 2006). The Umkwelane Formation overlies the karst-weathered surface of the Uloa Formation and consists of cross-bedded aeolianite, decalcified and rubified in the upper surface forming the Berea-type red sand. Relatively high clay content in the Berea-type red sand is from weathering of the feldspar and mafic minerals (Roberts et al., 2006), forming the confining layer above the Uloa Formation (Meyer et al, 2001).



	West —— East	
Holocene	**Maputaland Group Profile**	**Unconfined aquifer** KwaMbonambi Formation (Sugar Sands) Medium to coarse grained sands Varying thickness: 10-20 m High transmissivity: 150-300 m^2/day
Middle to Late Pleistocene		**Partial aquiclude** Kosi Bay and Isipingo Formations Sandy slits, with slight to moderate clay Varying thickness: 40-60 m Low transmissivity: 1-3m^2/day Unconsolidated
Mid Miocene Pliocene		**Semi-confined aquifer** Uloa/Umkwelane Formation (Calcarenite marine deposit, chalk deposit that consist of calcium carbonate) Varying thickness: 3-15 m High transmissivity: 75-100 m^2/day Discontinuous layers
Middle to Late Cretaceous	**Zululand Group**	**Aquiclude** Zululand Group (Cretaceous siltstone) Underneath a 100 m tertiary and centenary sediments Average slope of sediments is 3 to 5 degrees towards the east Low transmissivity and low permeability
Jurassic to Early Cretaceous	**Lebombo Group**	**Aquiclude** Lebombo Group (basalt and rhyolite lava) Average slope 8 degrees towards the east (Movene Fm) Low transmissivity and low permeability

Figure 3.2: Interpreted geohydrological characteristics of the Maputaland Group lithostratigraphic layers at the eManguze area (Modified after Porat and Botha (2008) and Schapers (2012)).

3.3.4 Landscape Setting (Topographical Position)

Kruger, (1983) described the Maputaland Coastal Plain as the Coast Forelands characterised by plains (>80% of area with slopes less than 5%), low relief (0-130 m), presence of pans (i.e. depressions), low to medium drainage density and stream frequency. DLP (1992) described the geomorphology of the area as a broad low-lying coastal plain with a large dune cordon parallel to the coastline developed through bidirectional parabolic dunes. North-south orientated dune ridges (Botha and Porat, 2007) with dune troughs that occur as linear interdune depressions between the dune ridges (DLP, 1992) are characteristic of the area. The inland facing dune slopes are relatively gentle with slopes 3-7 degrees (DLP, 1992).

Although the study area is situated on a coastal plain, distinct landscape units do occur that detain or retain water necessary to form a wetland. Semeniuk and Semeniuk (1995) described such landscape settings as highlands/hills, slopes, flats, channels and basins. The Classification System for wetlands and other aquatic ecosystems in South Africa (Ollis et al., 2013) make a distinction between four landscape settings (i.e. valley floors, benches, plains, and slopes). *Valley floors* occur at the base of a valley, situated between two side slopes with a river, stream or longitudinal wetland that sometimes extends along the valley. *Bench*es are mostly level or nearly level high ground (relative to the broad surroundings), typically being less than 50 ha in area. *Plains* are extensive areas of low relief characterised by gently undulating or uniformly sloping land with gentle gradient (<1:100). *Slopes* are an inclined stretch of ground that can include scarp-, mid- and foot-slopes. However, in this study area (coastal aquifer with sandy plain and dunes formations) the landscape settings are identified as consisting of 3 types: plain (upland and lowland), slope and valley floor. The *upland plain* (high ground relative to the broad surroundings) extends more than 50 ha in area and is >50 m.a.s.l., while the *lowland plain* occupies areas below 50 m.a.s.l. The 50 m.a.s.l line was selected based on previous literature (Grundling, 2001; Turner and Plater, 2004) who indicated peatlands of the Maputaland Coastal Plain generally occur only below this elevation. The *upland* separates lower-lying areas (*lowland*) to the west and to the east (Figure 3.3), where incised valleys form part of the drainage network representing *valley floors.* The transition from the upland to lowland is the *slope* areas, which have a topographic gradient of about 1-2% (Figure 3.3). The drainage systems include the northwards flowing river in the Muzi swamp (west), the northeast flowing Siyadla River to the south of the lake system and west-to-east flowing rivers feeding the Kosi Bay Lake (Lake KuHlange) at approximately right angles to the coast (Figure 3.3).

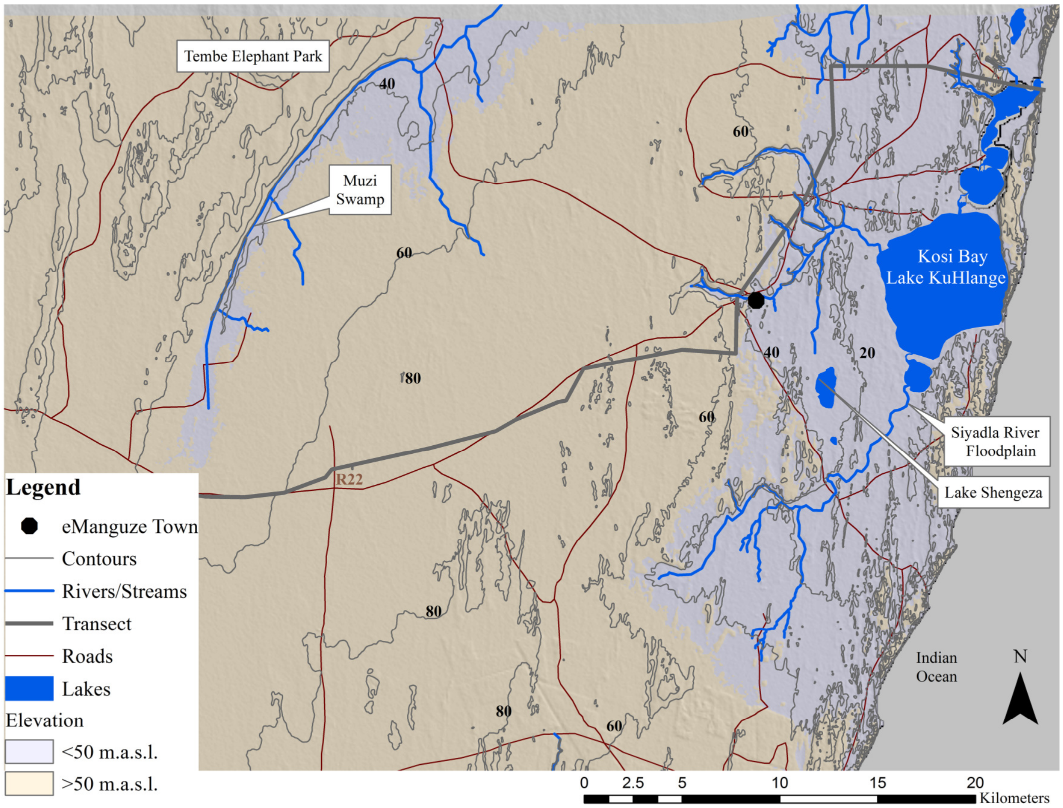


Figure 3.3: The location of the upland (≥50 m.a.s.l) region between the Muzi swamp and Kosi Bay (Lake KuHlange). The lowland (<50 m.a.s.l.) (*blue-grey shading*) to the west and to the east with drainage systems having incised *valley floors.*

3.3.5 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 Maputaland Coastal Plain 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).

3.3.6 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*), *Schoenoplectus corymbosus, Cyperus sphaerospermus, Leptochloa fusca, Fimbristylis ferruginea* in permanently waterlogged areas; sedge marsh (*Cyperus latifolius, Cladium mariscus, Centella asiatica)* in permanently to seasonally waterlogged areas; and *Imperata cylindrical, Dactyloctenium aegyptium* community wet grassland in temporarily waterlogged areas (Kotze, 1999; Pretorius, 2011). Dominant swamp forest species include *Raphia australis, Ficus trichopoda, Voacanga thouarsii* and *Barringtonia racemosa* (Grundling et al., 2000; Grobler, 2009).

3.4 METHODOLOGY

3.4.1 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.

3.4.2 Rainfall

To address the spatial-temporal variability of rainfall, total monthly rainfall data for the northern study area were acquired from the ARC-ISCW (2011) for the period January 1989 to December 2011. The locations of the automated and manual weather stations are shown in Figure 3.4. The rainfall measured during the Tropical Storm Irina (3-7 March 2012) was obtained at the Tembe Elephant Park office and the Mission Station at the town of eManguze.

3.4.3 Elevation and Landscape Setting

An elevation map highlighting valley floors, upland ($\geq$50 m.a.s.l.), lowland (<50 m.a.s.l.) and slope 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). SRTM data are 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). 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. The limitation with this dataset is the erroneous amalgamation of high vegetation (e.g. swamp forest and plantations) canopies as surface elevation. A land surveyor was contracted in June 2010 to measure the elevation at each of the 59 *in situ* water monitoring sites (accuracy 3-6 mm). The land surveyor readings for the 59 sites were compared to the 90 m and interpolated 30 m SRTM data (Van den Berg et al., 2009; Weepener et al., 2012). The results indicate a local average difference of 3 m higher and 1 m lower for sites without high tree cover and a local average of 6 m for sites in or near swamp forests and plantations (i.e. with tree cover). Work by Kelbe and Taylor (2011) comparing the SRTM data set with Lidar data for an area near St Lucia (50 km south of Kosi Bay) and found vertical errors at pixel resolutions (90 by 90 m) that can exceed 10 m but generally within 2 m for those areas with short vegetation or bare soil. Other datasets include the 1:50 000 5 m elevation contour data set (NGI, 2010) that was used in the Hydrology Model (Appendix 3)).

3.4.4 Hydrology (Water-table Monitoring)

During September 2008, 54 water-table monitoring sites were identified and in April 2009, 15 additional sites were added to obtain a total of 69. However, only data from 59 *in situ* sites are used in this analysis (Figure 3.4) as the other sites were compromised (dried up, damaged, collapsed or filled in with sand/gravel) and the correct water-table measurements could not be taken. From the 59 observation points, 40 sites included wetlands, 4 sites were lakes and 15 were non-wetland terrestrial sites. The monitoring sites included 11 boreholes (sunk for communal use), 29 wells (open wells dug for communal use in and outside wetlands), 3 depressions, 4 lakes, 6 stream crossings (low-water bridges), 1 spring, 3 wetlands and 2 drainage ditches in swamp forest wetlands. Lakes, spring and drains were assumed to represent the surface expression of the regional water-table. 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 shallow dug wells where the water levels dropped below the pit, additional PVC well-pipes were installed to access the water-table. The response of the water-table to Tropical Storm Irina was measured at 12 sites during 3-7 March, 2012. Groundwater electrical conductivity (EC) was measured at the Muzi wetland in the Tembe Elephant Park with the use of an electrical conductivity meter.

The sites were selected based on 1) their accessibility (clustered around the roads and rivers for easy access and 3 and 5 km apart), 2) permission from the community to measure the water levels and 3) 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 regional water-table distribution. The water-table monitoring sites were between 3 and 10 km apart. Appendix 2 lists the water-table monitoring points.

3.4.5 Hydrogeological Modelling

The use of a hydrological model to derive the best estimate of the regional water-table profile was examined as another way to aid in the delineation and characterisation of wetland types for comparison with wetlands mapped from Landsat (Chapter 2) (Grundling et al., 2013a). Groundwater model simulations (MODFLOW) provided by Kelbe et al. (unpublished) (Appendix 3) were used to estimate the regional water-table profile in the shallow unconfined aquifer systems over a period with wet and dry years. The hydrological model simulations are based on hydrogeological information and aquifer structure descriptions, calibrated with head data (water-table monitoring data) provided by this study. The hydrological model is not central to this research but formed part of a parallel but separate investigation. Groundwater simulations were done from January 2000 to December 2010. Another parallel but separate investigation (Dennis, 2014) used a combination of MODFLOW and MIKE SHE. In both modelling studies (Dennis, 2014; Kelbe et al., unpublished in Appendix 3) the model parameters were configured and calibrated using the actual water-table readings monitored between September 2008 and December 2009; also June 2010 to February 2011.

3.4.6 Soil and Vegetation

3.4.6.1 Soil and Vegetation Surveys

Soil and vegetation surveys were conducted at locations representative of the five different wetland systems along the 60-km transect based on preliminary field observation (Grundling et al., 2010; 2011) (Figure 3.4). These five different wetland systems include: 1) Interdune depressions and 2) swamp forests towards the east, 3) Muzi swamp, and 4) perched pans (depressions) towards the west; 5) upland wetland systems in the middle of the transect. Detailed soil and vegetation community and sub-community descriptions of the wetness zones found at 14 wetland sites provided a separate but comparable study to also confirm that the wetlands' extent and distribution are directly linked to spatial and temporal variation of the water-table (Pretorius, 2011). Two techniques were used to describe and sample the soil, either by soil/peat auguring or by describing a soil profile in an open pit. In June 2010, for each soil sample site, the data collected include elevation, groundwater level, soil form and family, and dominant vegetation type. The soil types were described using the procedure outlined by ARC-ISCW (Turner, 1991). Additional general soil observations and classifications (i.e. organic or mineral soil) were made at each of the 59 water-table 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. Laboratory analysis included % Soil Organic Carbon (SOC) (analysed with the Walkley-Black method), clay content (by determining the particle size) and pH (water and KCl solution method) (De Ligny and Rehbach, 1960).

3.4.6.2 Additional Soil Information

Additional soil information acquired includes 1) peatland surveys done by Grundling et al. (1998), acquired to help map locations where peat was documented (Figure 3.4); 2) a gravel pit location map indicating materials used for road building (Roux and Thomas, 1993); and 3) comparison of wetland distribution with clay soils occurrence. The latter was done by using the clay classes from a semi-detailed soil map created for KwaZulu-Natal by Van den Berg et al. (2009) with the wetland's class in the 2008 Landsat TM classification dataset (Chapter 2) (Grundling et al., 2013a). The comparison statistics were calculated using a confusion matrix usually applied for accuracy assessments (Chapter 2). The wetland class derived from the 2008 Landsat TM classification dataset was compared with clay classes (that indicate the weathered clay-enriched soil found in soil profiles) acquired from an independent data set (Van den Berg et al., 2009)). Area calculations were done for the wetland pixels that overlap clay and water classes.

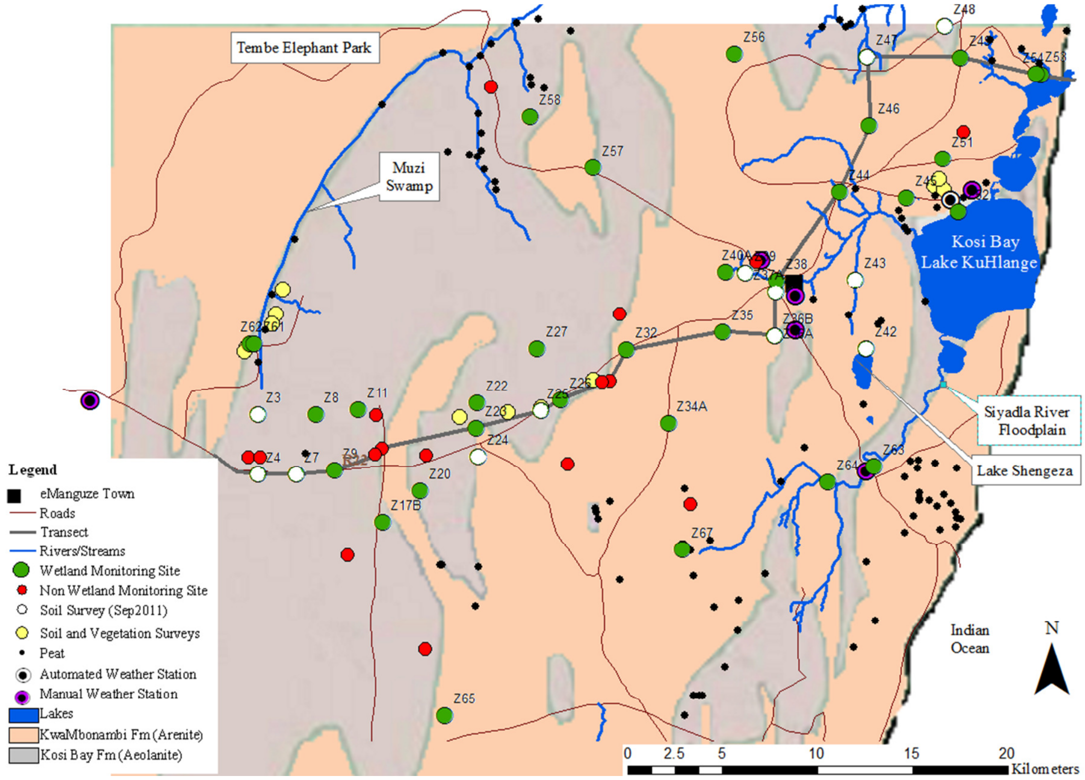


Figure 3.4: Water-table monitoring sites in wetland areas (green points) and non-wetland sites (red points). Soil surveys include 1) Survey in September 2011 to check for impermeable layer (white points), 2) detailed soil and vegetation descriptions at 14 sites (Pretorius, 2011) (yellow points) and 3) peat survey sites from Grundling et al. (1998) (black points). The locations of automated (1) and manual (6) weather stations in the study area are indicated by white and purple points (ARC-ISCW, 2011).

3.5 RESULTS

3.5.1 Long-term Rainfall

The long-term rainfall (1989-2012) for the study area indicates high summer rainfall from October to March and lower winter rainfall from April to September (Figure 3.5). Rainfall records indicate that less than average rainfall was received from 2002 to 2012. The average annual rainfall (586 mm from 2002 to 2012) for the study area was lower than the long-term average rainfall of 753 mm (measured over the past 23 years) (Figure 3.6) (Refer also to Figure 2.2).

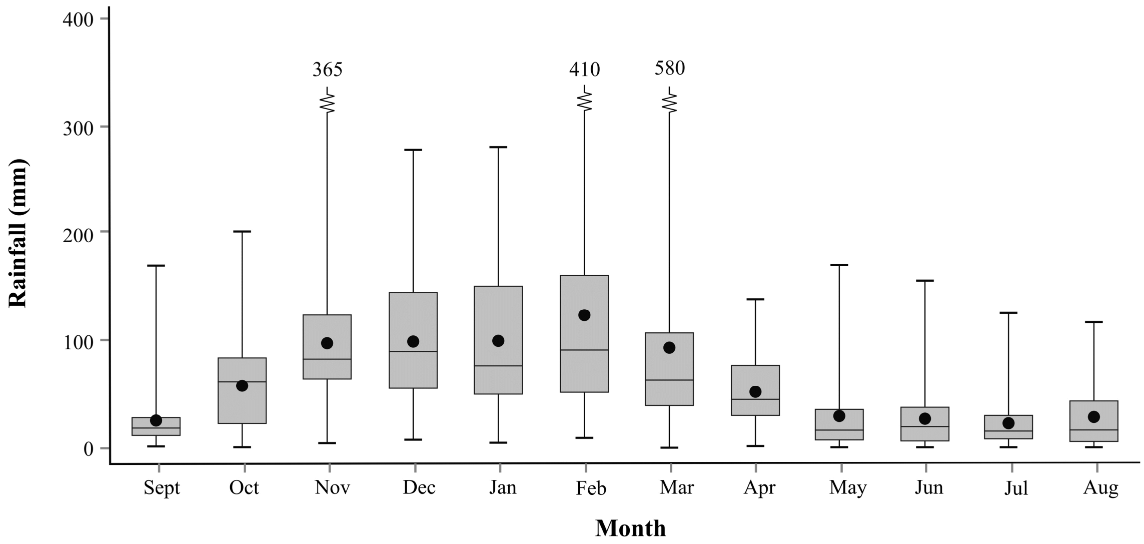


Figure 3.5: Box-and-whisker plots for rainfall over 23 years (Jan 1989 - March 2012) arranged according to the hydro-calendar (Sept-Aug) (ARC-ISCW, 2011). The box represents the lower and upper quartile, and includes the median (centre line), mean/average (dot) and upper quartile (top of box), while the whiskers are the minimum value and maximum values recorded.

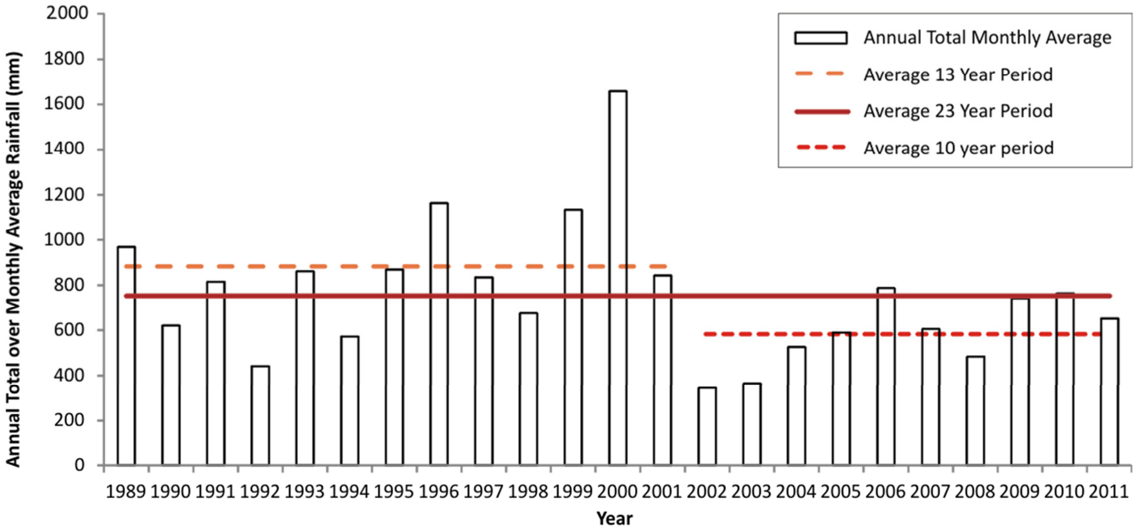


Figure 3.6: Average annual rainfall over 23 years arranged with average for wet period and average for dry period.

3.5.2 Wetland Occurrence in Relation to Hydrology

3.5.2.1 Simulated Water-table Depth

The simulated water-table profile for the entire study area was considered alongside previously identified temporary and permanent wetland and open-water areas (Chapter 2) (Grundling et al., 2013a) to provide a comprehensive understanding of the groundwater-dependent ecosystem. The mean depth to the water-table for the simulation period from January 2000 to December 2010 is shown in Figure 3.7A, and the standard deviation of depth to water-table is shown in Figure 3B (Kelbe et al., unpublished) (Appendix 3). Depth to the regional water-table for the wettest (Figure 3.7C) and driest (Figure 3.7D) conditions during the 11-year simulation period was determined and the 2 m depth to water-table contour was plotted, along with wetland distribution during the corresponding wet and dry periods (Chapter 2) (Grundling et al. 2013). Generally, areas within this 2 m contour during the dry period (e.g. 2008; Figure 3.7D) show close correspondence with permanent wetlands in the lowlands and valley floors (e.g. Muzi system along the Tembe Elephant Park boundary and to the south of Lake KuHlange (the larger of the Kosi Bay lakes). During the wet period (e.g. 2000; Figure 3.7C) there are many more wetlands areas indicated outside the 2 m water-table depth contour (i.e. where the water-table is greater than 2 m.b.g.s). These wetlands are characterised by large water-table fluctuations with standard deviation >1 m, implying changing water levels of >2 m during the simulation period (Kelbe et al., unpublished) (Appendix 3). Most of these correspond to temporary wetlands on the central upland plateau (plain). The temporary wetlands that fall within the 2 m water-table depth contour during the wet period (Figure 3.7C) are linked to the regional water-table, and have a smaller standard deviation in the water-table depth (Figure 3.7B).

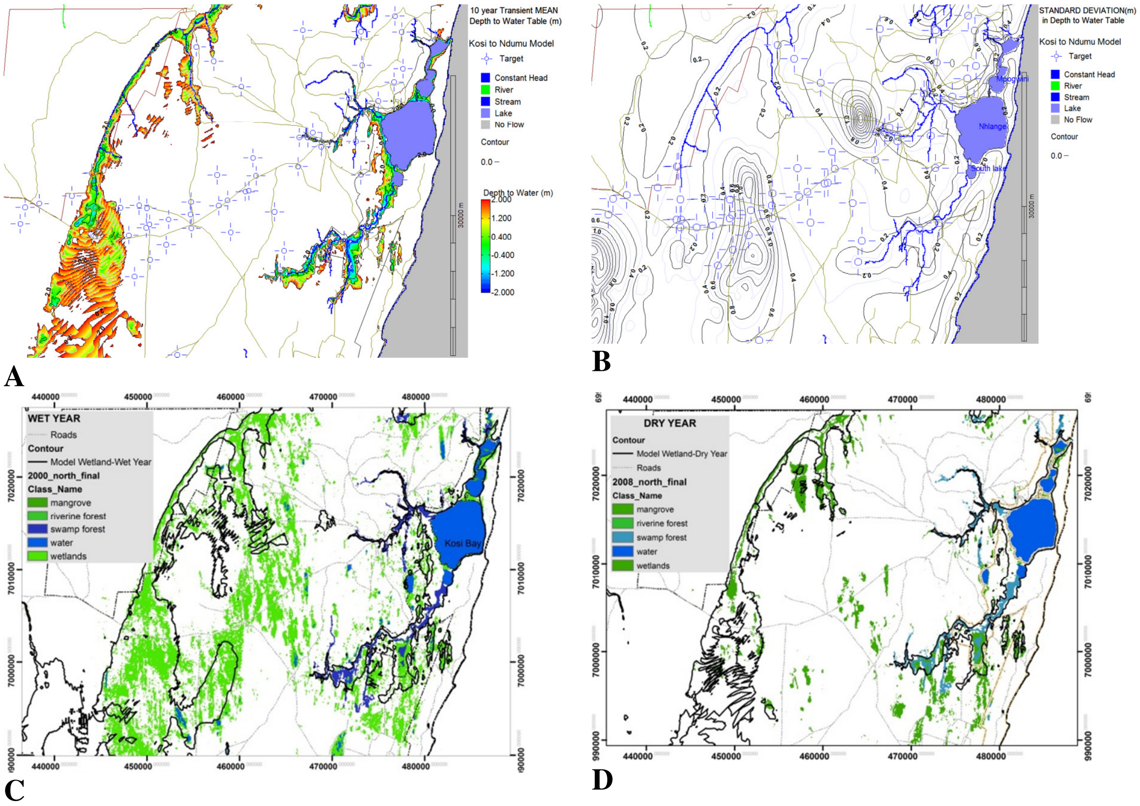


Figure 3.7: A) Predicted regional water-table level contours (meters below surface) for the 10 year transient mean simulated period. B) The Standard Deviation of the simulated depth to the water-table (mBGL), closely aligned to the derived hydraulic properties of the regional aquifer. The classified wetland distribution superimposed on the predicted 2 m depth to the water-table during corresponding C) wet conditions (2000) and D) dry conditions (2008). (Kelbe et al., unpublished) (Appendix 3).

3.5.3 Wetland Occurrence in Relation to Terrain Features and Clay Content

3.5.3.1 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 3.2 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 3.4 for locations). Sites Z7 and Z39 already had convincing evidence of an impeding layer (Table 3.2). Additional results for the Muzi wetland and perched pans (similar to Z62) were obtained from Pretorius (2011) (Grundling et al., 2014).

Table 3.2: Summary for 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 0-50 cm • > 32% clay 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 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	• Between 14-30% clay from 0-100 cm • Clay 8% 100-120 cm is lower • Water-table depth: 0.74 m
Z4	Pan with buried organic layer	Sand	420-480	10	• Between 0 to 4 % clay from 0-360 cm • Clay 10% 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	• A change in clay from 0 to 10% • A change in clay from 0 to 6% • Water-table depth: 4.90 m
Z37	Well near drainage line	Sand	196 235	16 22	• A change in clay from 0 to 16% • A change in clay from 16 to 22% • Water-table depth: 2.20 m
Z39	Spring near drainage line	Sand	520	-	• A change in grain size, texture and black colour • Buried paleo-peat layer • Water-table depth: 0.64 m

Analysis of why the wetlands mapped in Chapter 2 (Grundling et al., 2013a) are located in the study area show clear relation to the regional elevation profile (DEM) derived from SRTM data, the main geological units (Botha and Porat, 2007) and clay occurrence map (Van den Berg et al., 2009) (Figure 3.8). Figure 3.8A shows the surface elevation relative to mean sea level based on the SRTM DEM. Clay-enriched soil found in soil profiles (Figure 3.8A) corresponds well with the wetlands mapped in Chapter 2 (Grundling et al., 2013a) (Figure 3.8B). Results from the confusion matrix used for comparison statistics to calculate the clay occurrence with wetland distribution indicates that permanent wetlands (representing 15% of the total wetland and open water in in Figure 3.8A), occur mostly along drainage lines in valley floor (see Figure 3.3), commonly (~48 % of them) have > 16% clay content in the soil profile (Figure 3.8B. and Table 3.3). This is prevalent along the Muzi river valley swamps in the west and in the headwaters of the Siyadla River system that drains into the Kosi Bay lake system (Figure 3.8B) in the east. Temporary wetlands are more widespread (representing 75% of the total wetland and open water in Figure 3.8A), many of them occurring in the upland. Overall, temporary wetlands were less likely (24% of them) to have a high clay-content (>16%). However, many of these temporary wetlands, especially those occurring outside the 2 m depth to water-table during wet periods (Figure 3.7C) co-incide with mapped areas high in clay (see central upland in Figure 3.8B).

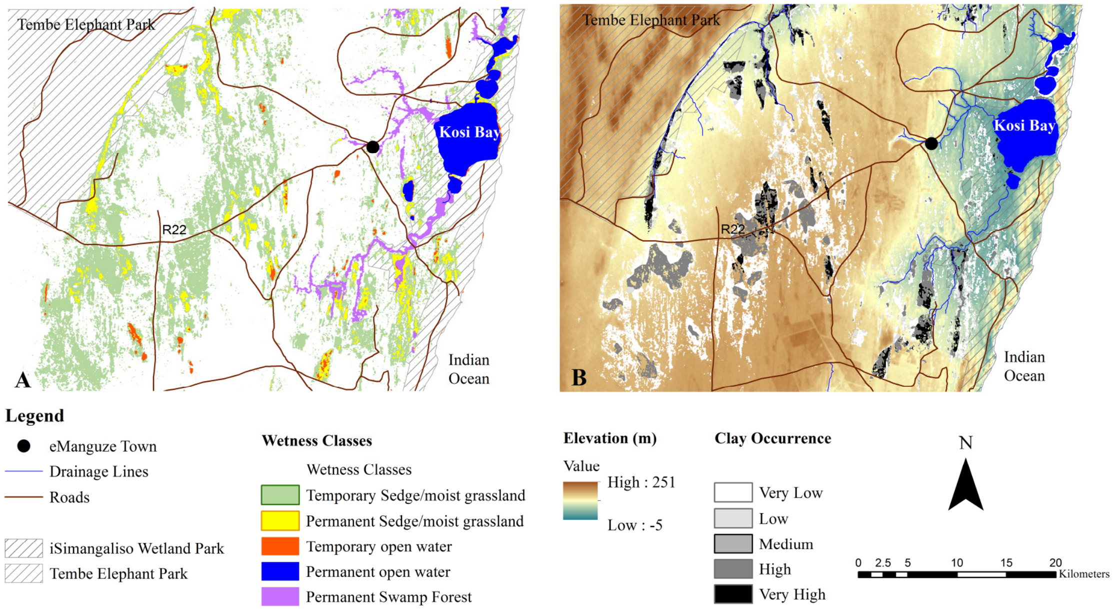


Figure 3.8: (A) clay content occurrence corresponds with (B) wetland distribution.

Table 3.3: Wetland overlap with clay content occurrence (%).

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

3.6 DISCUSSION

3.6.1 Wetland Classification

The wetland-type classification, specifically developed for the study area, was based on biophysical characteristics and functional attributes such as inundation period and saturation levels based on the landscape setting, water-table, vegetation and soil. Classification names used were similar to Classification System for wetlands and other aquatic ecosystems in South Africa (Ollis et al., 2013; SANBI, 2009b) that adapted the hydrogeomorphic (HGM) classification system.

3.6.1.1 Landscape Setting

The geomorphic approach takes into account the variability of wetland occurrence resulting from its geomorphic position (Brinson, 1993; Smith et al., 1995). Landscape settings identified for the study area include plain (upland and lowland), slope and valley floor (Figure 3.3).

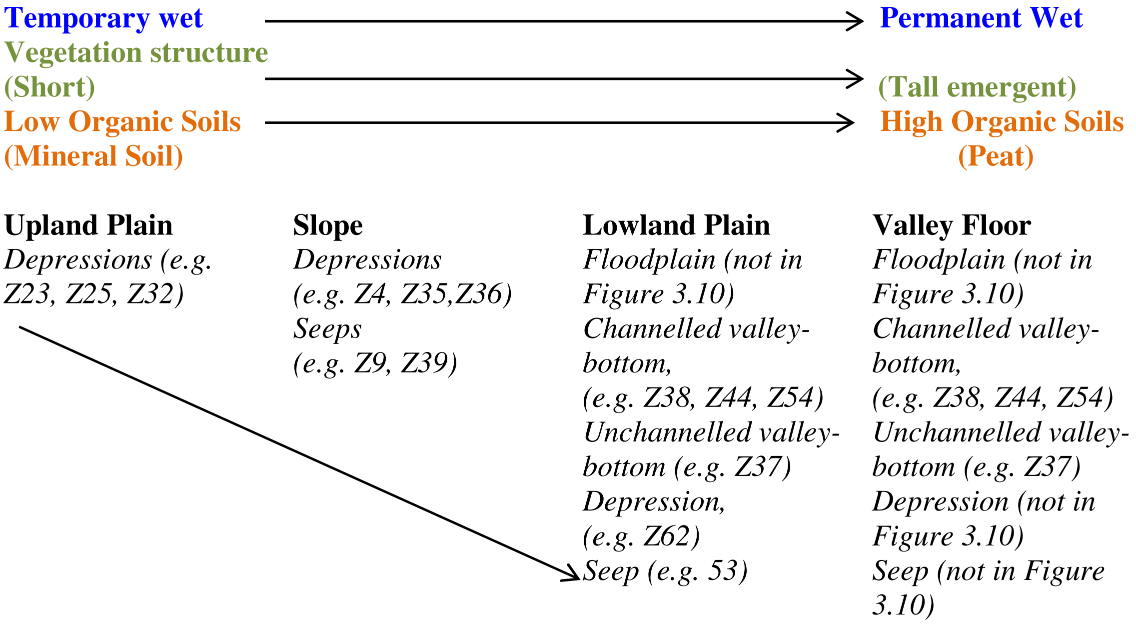
3.6.1.2 Water

In this study, four types of water permanence are distinguished based on previously established definitions for wetlands and open water (refer to Chapter 2) (Grundling et al., 2013a). These include: 1) *Permanent wetland*: these areas 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. Permanently waterlogged/saturated conditions promote the accumulation of organic matter in the soil. 2) *Temporary wetland*: this refers to seasonal wetlands characterised by saturation for three to ten months of the year, water-table 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). It 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). Temporary wetlands are not ideal for the development of organic matter. 3) *Permanent open water*: inland areas with open surface water such as lakes that exist in all years except the most extreme dry conditions. Permanent open water includes the Kosi Bay lake system and Lake Shengeza. 4) *Temporary open water*: areas where open surface water occurs only seasonally or in extremely wet years. During very wet years, some areas including wetlands can be temporarily inundated with pools of open water for a short period.

3.6.1.3 Wetland Type Classification

Ollis et al. (2013) listed seven possible primary hydrogeomorphic wetland types for inland systems: river, floodplain, channelled valley-bottom, unchannelled valley-bottom, depression, seep and wetland flat. Wetland flat areas are defined as "level or near-level wetland area that is not fed by water from a river/channel, and which is typically situated on a plain" (Ollis et al. 2013, p103). The primary water source for wetland flat is precipitation except on a coastal plain where groundwater may rise to, or near the surface (Ollis et al., 2013). However, in review of the hydrogeomorphic classification system, especially pertaining to this dune landscape, depressions (large, small, flat bottomed and round bottomed, elongated, linear, perched and through-flow) are the main local features in the landscape and they can occur on any landscape setting (plain, slope and valley floor). The character, ecological function and driving hydrological processes between "depressions" and "flats" are typically indistinct. This is because the defining feature, according to the hydrogeomorphic classification by Ollis et al. (2013) is whether or not the wetland area has enclosed elevation contours and in this sandy aquifer such subtle elevation features may not be important, hydrogeologically. For example large depressions (i.e. with closed contours can be sloping (with through-flow) and be indistinct from wetlands without closed contours. Confusion over the term "flat" is compounded because they are not necessarily flat, and can slope up to 0.3%, although more typically an order of magnitude less. However, the upland plains do not have typical wetland soil (problematic sandy soils), and only become wet in extreme wet years/events when the flow of water activates and connects with the larger drainage network, typifying through-flow wetlands. The depressions in the study area do not follow the classical definition of depression because they have no definite inward draining pattern. They do, however have closed (or near-closed) elevation contours that increases in depth from the perimeter to a central area of greatest depth, in which water typically accumulates. Consequently, since all these systems are wetlands because of water-table oscillation and/or through-flow of groundwater on gentle to moderate slopes, and are either fully or partially enclosed by elevation contours, we suggest that they be grouped as one wetland type, namely "depressions". These "depressions" can occur on all landscape settings.

Conceptual diagram (Figure 3.9) indicate the hydrogeomorphic wetland types found in the study area in relation to their water permanence and landscape setting with examples of wetland sites shown in the conceptual model (Figure 3.10). The diversity of hydrogeomorphic wetland types increase in relation to the increase of water permanence in the landscape affecting their structure and function (Figure 3.9). The different wetland types from the upland plain, slope, lowland plain and valley floor are described (Figure 3.10).



Temporary wet → **Permanent Wet**
Vegetation structure (Short) → **(Tall emergent)**
Low Organic Soils (Mineral Soil) → **High Organic Soils (Peat)**

Upland Plain	**Slope**	**Lowland Plain**	**Valley Floor**
Depressions (e.g. Z23, Z25, Z32)	*Depressions (e.g. Z4, Z35,Z36)* *Seeps (e.g. Z9, Z39)*	*Floodplain (not in Figure 3.10)* *Channelled valley-bottom, (e.g. Z38, Z44, Z54)* *Unchannelled valley-bottom (e.g. Z37)* *Depression, (e.g. Z62)* *Seep (e.g. 53)*	*Floodplain (not in Figure 3.10)* *Channelled valley-bottom, (e.g. Z38, Z44, Z54)* *Unchannelled valley-bottom (e.g. Z37)* *Depression (not in Figure 3.10)* *Seep (not in Figure 3.10)*

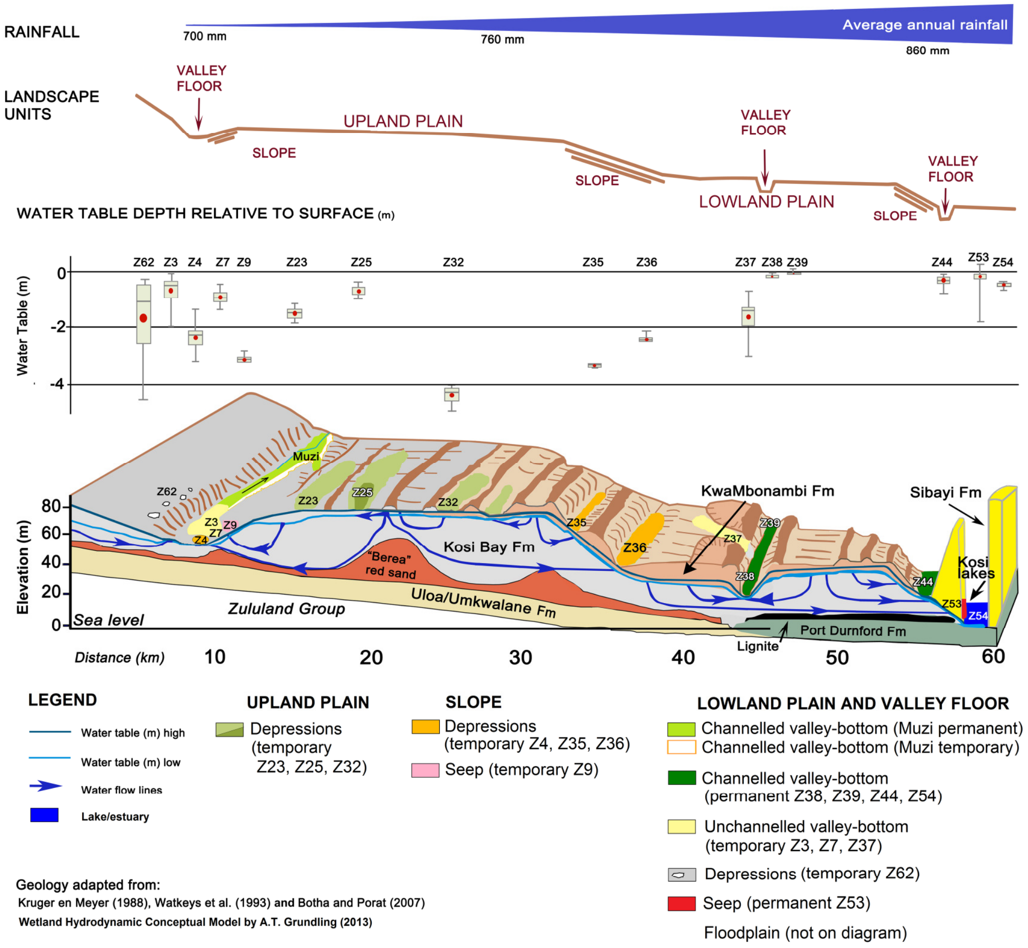
Figure 3.9*:* Conceptual diagram indicating wetland types found in relation to the different landscape settings and water permanence. Locations of the landscape settings are shown in Figure 3.3.

3.6.2 Conceptual Model

A conceptual model (Figure 3.9) illustrates the 1) rainfall gradient, 2) landscape setting, 3) underlying geological template and the high and low water-table position with interpreted water flow lines. Dennis (2014) defined the capture zones of the wetlands by means of particle tracking and it corresponds with the flow lines of the conceptual model. Water-table depth and variability at 16 selected representative *hydrogeomorphic wetland sites* 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 3.9) includes the Muzi wetland system, partially inside the Tembe Elephant Park, and follows Road no. 522-2S / R22, east-north-east from the headwaters of the Muzi wetland, through the town eManguze (not shown in Figure 3.9), to the Kosi Bay lake system in the east (see Figure 3.4 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). 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 widespread aeolian reworking of the inland dune sands during the Middle to Late Pleistocene deposited the Kosi Bay Formation on the coastal plain (Maud, 1998; Porat and Botha, 2008). The Kosi Bay Formation (40-60 m thick) is exposed, consisting of unconsolidated sandy silts with moderate to high clay content and low hydraulic conductivity (~1.006e-08 m/s) (Grundling and Grundling, 2010). Thus, acts as a partial aquiclude but still forms an important recharge system to the Uloa/Umkwelane Formations (Schapers, 2012) that underlie it. The KwaMbonambi (Sugar Sands) formation surfaces in the central and eastern parts of the transect as closely-spaced, northward, orientated parabolic dunes creating a hummocky dune system (Porat and Botha, 2008). The lithology description for the area is Arenite (blown sand) (DME, 1985) characterised by high infiltration rates, permeability and storage (hydraulic conductivity values ~1.006e-04 m/s) (Grundling and Grundling, 2010). The importance of deeper paleo-dune cordons (Berea-type red sands) becomes apparent as they have much lower transmissivity values and act as containment structures within the Kosi Bay and KwaMbonambi (Sugar Sands) formations (Botha, 1997; Schapers, 2012). Stabilization of the landscape occurred during the Holocene climatic optimum by rising groundwater levels and vegetation growth (Botha and Porat, 2008). Figure 3.9 show an abrupt difference with higher water-table on the Kosi Bay Formation compared to the upland plain area of the KwamBonambi Formation, then increasing in the KwamBonambi Formation towards the lowland plain and discharge systems. Except the Muzi wetland system, most wetland types in the west and central upland plain tend to be temporary or weak seasonal systems compared to the wetlands at discharge areas (e.g. Muzi wetland system), which are typically strong seasonal to permanently wet systems, including the swamp forests associated with drainage lines that occur from the Muzi wetland system eastwards. The upland plain area on the Kosi Bay Formation slopes from east to west and south to north with an average slope of ~0.03% (Macfarlane, et al., 2012). The calcimorphic clay from the Kosi Bay formation washes out/down and accumulates/deposits in the lower horizons of the soil profile forming impeding layers in the c*hannelled valley-*

bottom (Muzi wetland system) and the adjacent area (Watkeys et al, 1993), such as the small temporary *depressions* topographically elevated (~4 m) above the Muzi valley floor (e.g. Kwamsomi Pan, site Z62). The flow lines east of Z3 (headwaters of the Muzi wetland system, 43 m.a.s.l.) also suggest groundwater discharge at *unchannelled valley-bottom* (e.g Z3). Buried impeding layers of paleo-peat (*depressions* on slope, site Z4) ferricrete (*unchannelled valley-bottom*, site Z7), or clay restrict recharge (*seep* wetland on slope, site Z9) and are, thus, essential to wetland formation. Recharge occurs directly from the temporary wetlands of the Kosi Bay formation and from the wetlands and larger sand ridges of the KwaMbonambi formation. The *depressions* on the upland plain (Z23, Z25, Z32) in the central part of the transect receive an average annual rainfall of 720-780 mm. The depth to water-table is generally less than 1 m (i.e. Z25) (Figure 3.9). Here, localized illuviation of fine sediments causes perched, typically temporary wetlands to occur. Further east, *depressions* on upland plain (e.g. Z32) and *depressions* on slope (e.g. Z35, Z36) overlie the permeable KwaMbonambi formation (sugar sands), the water-tables are deeper (> 3 m) (Table 3.2 and Figure 3.9). In contrast, the water-table variability at Z35 and Z36 is relatively small suggesting it is associated with low to moderate discharge (e.g. Z36) because of groundwater through-flow driven by the locally steeper water-table to the west. Z35 recorded temporary open water during the wet year (2000) (Chapter 2) (Grundling, et al., 2013). Lowlands plains contribute to both groundwater recharge and discharge into the valley floor areas (lower elevations to the east) (Kelbe et al., unpublished) (Appendix 3). At the lowlands, the wetlands are most often permanent. Water input is derived from groundwater, while the surface water flow fluctuates according to wet and dry periods dominated by regional climate (Schapers, 2012). *Hydrogeomorphic wetland units* include *channelled valley-bottom* (Z38 and Z44) and one flowing to estuary (Z54), *unchannelled valley-bottom* (Z37) and *seep* (Z53), while *floodplain* and *depression* on lowland plain are not shown in Figure 3.9. Moderate discharge from adjacent upland plain occurs in *unchannelled valley-bottoms* (i.e. Z37), while *channelled valley-bottoms* (i.e. Z38, Z39 and Z44) receive groundwater discharge from the sides because of low-permeability sediments at their base (e.g. Z39) (Grundling et al., 2000; Sliva, 2004). These latter locations 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 (Grobler et al., 2004; Grundling et al., 2012; Grundling et al., 2013b). The lakes in the study area are considered an expression of the groundwater-table.



Geology adapted from:
Kruger en Meyer (1988), Watkeys et al. (1993) and Botha and Porat (2007)
Wetland Hydrodynamic Conceptual Model by A.T. Grundling (2013)

Figure 3.10: Wetland Hydrodynamic Conceptual Model. Schematic illustration of wetland types identified and their respective position in the landscape. The locations of these wetland types are indicated by their site numbers. Box and whiskers are as described in Figure 3.5.

3.7 CONCLUSIONS

Rainfall distribution, topography, hydraulic characteristics of the aquifer and the regional geology formations that slope towards the east are reported as the drivers of wetland and open water distribution. This research to classifying the wetlands and characterising the landscape processes confirms that the patterns and wetland form and function are predominately shaped by the hydrogeomorphic setting and not the rainfall distribution. The results confirmed that topography plays an important role on a sub-regional and local level to support wetland formation and the occurrence of peatlands <50 m.a.s.l., not only in the east with higher rainfall (>800 mm/year) but also in the west (e.g. Muzi wetland) where the rainfall is ~700 mm/year. The landscape settings found in the study area are mainly three types: plain (upland or lowland), slope and valley floor. Hydrogeomorphic wetland units identified include floodplain, channelled valley-bottom, unchannelled valley-bottom, depression and seep. Depressions can occur on any landscape setting (plain, slope and valley floor). The hydrogeomorphic types increase in relation to the increase of water permanence in the landscape affecting their structure and function. Temporary wetlands were mainly located on an elevated inland sandy plain (the water-tables vary from 1 to > 3 m), whereas permanent wetlands, such as peatlands (fall within the 2 m water-table profile during dry periods). The latter were more typically located in valley floor and lowland plain areas where the average water-table is <0.2 m deep and fluctuates within a small range. The externt and distribution of wetlands in wet years were much larger. Wetlands that fall outside the 2 m water-table depth contour during wet periods could be perched or partially perched due to buried low permeable, impeding layers of ferricrete, paleo-peat or clay that can prolong the hydroperiod.

3.8 ACKNOWLEDGEMENTS

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4. HYDROGEOMORPHIC WETLAND CLASSIFICATION

This chapter to be submitted as:
Grundling, A.T., Weepener, H.L. and Price, J.S. Applying hydrogeomorphic wetland classification on the Maputaland Coastal Plain, north-eastern KwaZulu-Natal, South Africa.

4.1 OVERVIEW

The main aim of this chapter is to determine if wetlands belonging to the same hydrogeomorphic unit share common features in terms of environmental drivers and processes, which led to an attempt to classify hydrogeomorphic wetland units for inland wetlands. The outcome was to evaluate if this hydrogeomorphic classification system can be applied. Different hydrogeomorphic units in the northeastern part of the Maputaland Coastal Plain, between the Tembe Elephant Park in the west and the Kosi Bay mouth in the east, were identified based on their position in the landscape with the use of a terrain map highlighting concave areas. Local environmental determinants (water-table, rainfall and elevation) were examined to show the link between these and the distribution of hydrogeomorphic units, for September 2008 – 2009, July 2010 and Feb 2011 with some additional readings in March 2012. Accuracy assessment was done by comparing these ground reference sites with the classified hydrogeomorphic wetland units for this study using a semi-automated approach, and was 81% accurate. The semi-automated approach could identify five of the seven hydrogeomorphic wetland units, namely: floodplain, channelled valley-bottom, unchannelled valley-bottom, depression and seep. The strengths and limitations (e.g. ambiguity between classes especially the proposed flat wetlands on sand coastal plains) are highlighted. Wetland occurrence is dependent on the hydraulic characteristics of the aquifer and localised topographical features, and the associated hydrological processes. We found that using broad hydrogeomorphic unit classifications with limited hydrological data could be problematic because not all wetlands belonging to the same hydrogeomorphic unit function the same, e.g. perched depressions (rainwater fed) and depressions linked to the regional water-table. Furthermore, the character, ecological function and hydrological processes between "depressions" and "flats" are typically indistinct. The upland plain are not necessarily flat, and can slope up to 0.3%, although more typically an order of magnitude less, characterised by through-flow systems and fluctuation of the regional water-table. 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.

4.2 INTRODUCTION

Wetlands are water-controlled ecosystems and the temporal and spatial distribution of water influence a wide range of ecological processes (c.f. Price et al., 2005; Cullum and Rodgers, 2010 and 2011). Wetland distribution and character is determined by variations in hydrogeomorphic setting, e.g., soil and topography (abiotic) as well as vegetation (biotic) factors (Mitsch and Gosslink, 1993). Mitsch and Gosselink (2000) stated that most wetland classification approaches consider differences in soils, vegetation and hydrological behaviour as the most appropriate criteria to distinguish wetland types. In contrast, the *hydrogeomorphic classification* developed by Brinson (1993) assigns wetland functioning based on the geomorphic setting, water source and hydrodynamics (pattern of water flow through the wetland). *Geomorphic setting* refers to the physical attributes and location of the wetland with respect to the surroundings in terms of topography and lithology, which control its *hydrological characteristics,* i.e. water sources including precipitation, surface flow and groundwater. *Hydrodynamics* refers to the direction and strength of water movement, and its variability, within the wetland (Brinson, 1993). An underlying assumption of the hydrogeomorphic wetland classification concept is that wetlands belonging to the same hydrogeomorphic unit share common environmental drivers and processes (Smith et al., 1995; Ollis et al., 2013). Although widely applied in South Africa, *this underlying assumption has yet to be tested.*

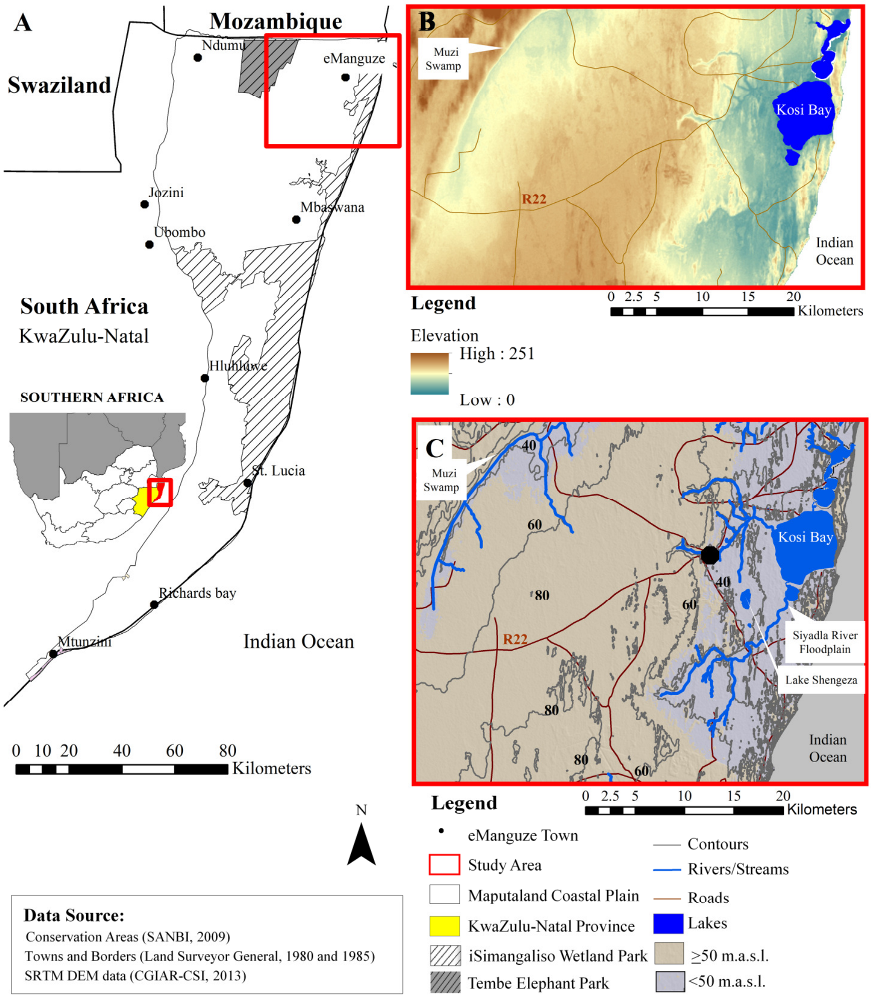
The Classification System for Wetlands and other aquatic ecosystems in South Africa adapted the hydrogeomorphic classification approach (Ollis et al., 2013; SANBI, 2009b). Ollis et al. (2013) listed seven possible primary hydrogeomorphic wetland types for inland systems: river, floodplain, channelled valley-bottom, unchannelled valley-bottom, depression, seep or wetland flat. The National Freshwater Ecosystem Priority Areas (NFEPA) project classified a wetland-type layer for South Africa based on the hydrogeomorphic classification using an automated approach (Mbona et al., 2010; Driver et al., 2011; Nel et al., 2011). No accuracy assessment has been done on the NFEPA wetland-type layer. SANBI (2009b) recommended further testing and investigation into automation of the classification system, based on the availability of information required to distinguish one wetland type from another. In this chapter, local environmental determinants of hydrogeomorphic units (e.g.

water-table, rainfall and elevation) were examined to show the link between these environmental attributes and the distribution of hydrogeomorphic units. Classification accuracy was determined by comparing these ground reference sites with the classified hydrogeomorphic wetland units for this study (using a semi-automated approach) and the NFEPA project wetland type layer.

Moreover, establishing the relation between wetland and its local water-table, and how this relates to rainfall and elevation will help to characterise the form and function of hydrogeomorphic wetland units and their hydrological processes (Ollis et al., 2013; SANBI, 2009b). Applying the hydrogeomorphic wetland classification for inland systems on sandy coastal plains will highlight the strengths and limitations of this approach, and the implications for management and conservation strategies. The objectives of this chapter were 1) to identify the different hydrogeomorphic wetland units in the study area; and 2) to determine if wetlands that belong to the same hydrogeomorphic wetland unit share common features in terms of environmental drivers and processes. This will be done by investigating the relation between landscape setting and local environmental factors namely water-table, rainfall, and elevation. Consequently, this evaluation of the hydrogeomorphic wetland classification will contribute to the understanding of the wetland types found on the Maputaland Coastal Plain and how well the hydrogeomorphic wetland classification can be applied.

4.3 STUDY AREA

The study area stretches from the Tembe Elephant Park in the west to the Kosi Bay lake system in the east (Figure 4.1A), part of the Maputaland Coastal Plain, situated in north-eastern KwaZulu-Natal province (Figure 4.1A). The Maputaland Coastal Plain is characterised by the relatively flat, low relief, undulating dune landscape of the coastal plain (Kruger, 1983; Scott-Shaw and Escott, 2011) bordering the Lebombo Mountain range in the west and the Indian Ocean in the east (Figure 4.1.B). The sandy sediments of the Late Pleistocene and Holocene (cover sands) are well sorted, highly porous and permeable, have relatively high hydraulic conductivity and drain rapidly (DLP, 1992). The study area located on the low-lying coastal plain is characterised by north-south orientated dune ridges (Botha and Porat, 2007) and linear interdune depressions between the dune ridges (DLP, 1992). The following three landscape settings have been identified in the study area: plain (upland and lowland), slope and valley floor (Chapter 3) (Figure 4.1.C). The *upland plain* (≥ 50 m.a.s.l.), *lowland plain* (< 50 m.a.s.l.) separation is based on previous literature (Grundling, 2001; Turner and Plater, 2004) that reported peatlands generally occur below the 50 m.a.s.l elevation on the Maputaland Coastal Plain. The lower-lying areas (*lowland*) to the west and to the east represent *valley floors.* Here incised valleys form part of the drainage network. The transition from the upland to lowland are the *slope* areas, which have a topographic gradient of about 1-2% (Figure 4.1.C) while the inland facing dune slopes are relatively gentle with slopes 3-7 degrees (DLP, 1992). The study area (~250 000 ha) was selected because it hosts a diverse set of wetlands (Chapter 3) and available supporting baseline data (Chapter 2 and 3) to assist in the hydrogeomorphic wetland classification process.



Data Source:
Conservation Areas (SANBI, 2009)
Towns and Borders (Land Surveyor General, 1980 and 1985)
SRTM DEM data (CGIAR-CSI, 2013)

Figure 4.1: A) Location of the Maputaland Coastal Plain and study area. B) Elevation map of the study area. C) Landscape setting of the study area.

4.4 METHODOLOGY

4.4.1 Environmental Determinants: Ground Reference Points

Forty-two sites (41 wetlands sites and Lake Shengeza) were used as hydrogeomorphic ground reference sites to measure environmental determinants (i.e. water-table, rainfall and elevation) as well as to compare with the mapped hydrogeomorphic wetland units and the NFEPA wetland ecosystem types as part of the accuracy assessment.

4.4.1.1 Water-table

Monthly readings were taken between September 2008 to October 2009, December 2009, as well as June 2010 and February 2011 with some additional readings in March 2012, with the use of a Solinst water-level meter, to measure variations in water levels at the 41 wetlands sites and Lake Shengeza (Figure 4.2). The Kosi Bay Lake system was not included in the hydrogeomorphic classification and analysis.

4.4.1.2 Rainfall

Total monthly rainfall data for the study area were acquired from the ARC-ISCW (2011) for the 18 month period September 2008 to October 2009, December 2009, June 2010, February 2011 and March 2012. The locations of the automated and manual weather stations are shown in Figure 4.2. Rainfall grids were interpolated from ARC automatic weather station point data and 10-day Rainfall Estimate (FEWS NET, 2001) 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.

4.4.1.3 Elevation and Landscape Setting

Elevation data from the 90 m Shuttle Radar Topographic Mission System (SRTM) (CGIAR-CSI, 2008) (Farr and Kobrick, 2000) was used to create an elevation map (Figure 4.1B). Figure 4.1C highlights the landscape settings namely plains on the upland (≥50 m.a.s.l.) and lowland (<50 m.a.s.l.), slope and valley floors. 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. The *absolute vertical accuracy* (this is m.a.s.l.) is significantly better than 16 m and is closer to +/- 10 m for the world. The *relative vertical accuracy* is much higher; up to 1 m. The limitation with this dataset is the erroneous amalgamation of high vegetation (e.g. swamp forest and plantations) canopies as surface elevation. A land surveyor was contracted in June 2010 to measure the elevation at each of the 42 *in situ* water monitoring sites (accuracy 3-6 mm). The land surveyor readings for the 42 sites were compared to the 90 m and interpolated 30 m SRTM data (Van den Berg and Weepener, 2009; Van den Berg et al., 2009; Weepener et al., 2012). The results indicate a local average difference of 3 m higher and 1 m lower for sites without high tree cover and a local average of 6 m for sites in or near swamp forests and plantations (i.e. with tree cover). Work by Kelbe and Taylor (2011) comparing the SRTM data set with Lidar data for an area near St Lucia (50 km south of Kosi Bay) found vertical errors at pixel resolutions (90 by 90 m) that can exceed 10 m but generally within 2 m for those areas with short vegetation or bare soil.

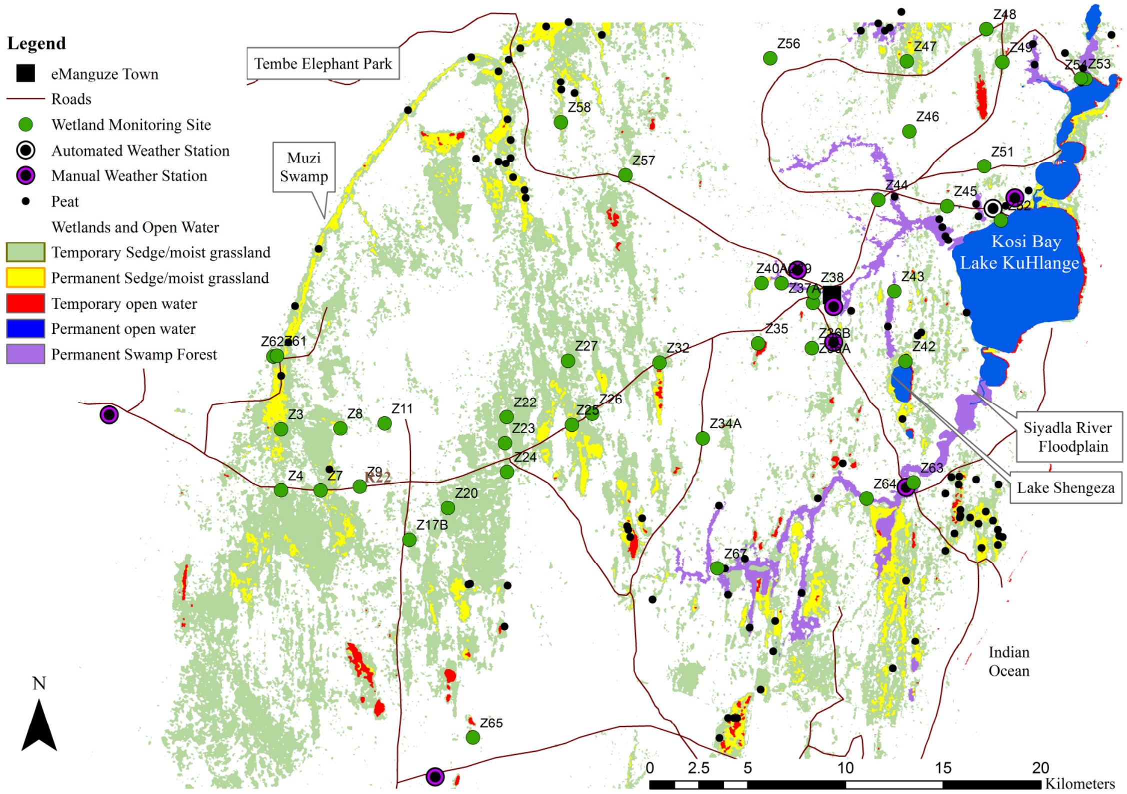


Figure 4.2: Wetland distribution (Grundling et al., 2013a) (Chapter 2) and water-level monitoring sites in wetland areas (green points). Peat survey sites from Grundling et al. (1998) (black points). The locations of automated (1) and manual (6) weather stations in the study area are indicated by white and purple points (ARC-ISCW, 2011).

4.4.1.4 Relations between Water-table Depth and Environmental Factors

Boxplots and descriptive statistics were used to explore the data and were created with SAS Institute, Inc., (1999) for the water-table depth readings at each site. However, the relation between water-table depth, total monthly rainfall and elevation for each of the 42 ground reference sites were determined for the 18-month period (dates for total monthly rainfall data correspond with the same months the water-table readings were done) using multivariate Agglomerative Hierarchical Clustering Analysis. XLSTAT 4.03 was used to run a multivariate Agglomerative Hierarchical Clustering Analysis using Ward's method and Euclidean distance dissimilarity to define groups using the ground reference sites and sorting them according to clusters based on the differences and similarities of variables (environmental factors) namely elevation, average and maximum water-table depth and average and maximum total monthly rainfall. According to this method groups are determined and represented in a dendrogram based on an algorithm created by Post and Sheperd (1974) and adapted by McCune and Mefford (2006). These groups were then subjected to a multivariate Discriminant Analysis (DA) to identify the variables that play a major role in separating the groups also using XLSTAT 4.03. Analysis was performed on a standardised matrix (so as to have a zero mean and unit variance) (Galpin, 1977) to better establish the contribution of the variables to each group because the variables were measured in different units. The scale of the variants (elevation, water-table depth and rainfall) was of different magnitudes and had an effect on highlighting the contribution of the variants to variations in the data set irrespective of scale. Therefore, for each of the variants (elevation, average and maximum water-table depth and average and maximum total monthly rainfall), the macro-reach was calculated under the normalised curve.

4.4.2 Hydrogeomorphic Wetland Classification

4.4.2.1 Data Preparation

Not only the landscape setting (plain (upland and lowland), slope and valley floor) (Figure 4.1C), but also careful consideration of the smaller topographical features such as swales and depressions that occur throughout the study area, are important factors locally, and should be considered in creating the hydrogeomorphic wetland unit map. Troughs and ridges form the geological template that expresses the major topography of the study area. Trough areas play an important role on a sub-regional and local level to support wetland formation (Chapter 3). Van den Berg et al. (2009) used curvature morphology (concave and convex areas) to define terrain units (Figure 4.3). This technique is used extensively to define the smaller topographic features in soil mapping (Van den Berg and Weepener, 2009), as topography consist of slopes having distinctive morphologic elements with different hydraulic characteristics (Richardson and Vepraskas, 2001).

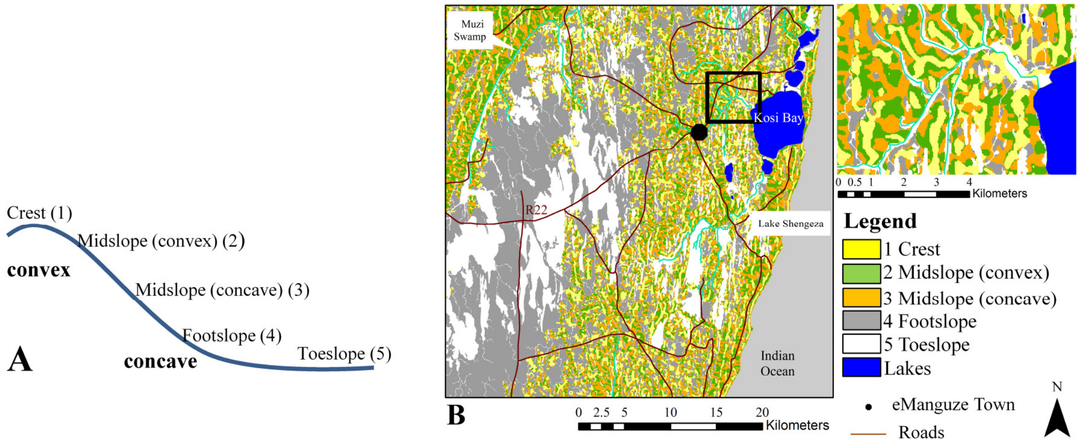


Figure 4.3: A: Profile of Terrain units- 1 represents a crest, 2 a midslope (convex), 3 a midslope (concave), 4 a footslope and 5 a toeslope. B: Map of the study area indicating the various terrain units (Van den Berg et al., 2009). Only terrain units 5 was considered to support wetland areas.

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). Given the study area's relatively flat, undulating dune landscape with deep sandy soils, Figure 4.3B shows more detailed terrain units or settings defined according to slope changes and surface profile shapes (concave and convex).

4.4.2.2 Data Processing

In order to apply the hydrogeomorphic wetland classification for inland systems, a semi-automated approach with the use of ancillary datasets such as a wetness map (Grundling et al, 2013a) (Chapter 2), terrain unit map (Van den Berg et al., 2009) and slope (Weepener et al. 2012) was used in this chapter. All input layers used as criteria for the hydrogeomorphic wetlands classification are listed in Table 4.1. The ancillary datasets were cut to cover the full extent of the study area. The terminology and definitions for the five primary hydrogeomorphic wetland types used for the hydrogeomorphic wetland classification in this study (Table 4.2) is a modified version of the proposed classification by Ollis et al., (2013).

Table 4.1: Ancillary datasets used in the hydrogeomorphic wetland classification.

Datasets	Reference	Purpose
Wetness layer (permanent and temporary wetlands and open water areas) (Chapter 2)	Grundling et al., (2013a)	To use as baseline dataset for the distribution of subtropical freshwater wetlands and swamp forests on the coastal lowlands
KwaZulu-Natal (KZN) province soil and terrain unit map derived from the SRTM DEM	Van den Berg et al. (2009)	To use the toeslope terrain unit. These are closely associated with wetlands occurrences
SPOT 2010 imagery	SANSA (2013)	To digitize the prominent channels
River lines	NGI (2012b)	To familiarise with the distribution of 1:50 000 rivers and streams
Inland wetland layer	NGI (2012a)	To use as baseline dataset for the distribution of depressions with closed (or near-closed) elevation contours.
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.
Slope	Weepener et al. (2012)	To use slope as percentage rise, derived from the improved gap-filled SRTM DEM. Modal values for slope, drainage pattern and flow direction were calculated for each wetland polygon in the wetness layer.

Table 4.2: Primary Hydrogeomorphic Wetland Unit Definitions (modified from Ollis et al., 2013)

Class No.	Class Name	Definitions (summarised)
1	Floodplain	Situated adjacent or close to distinct active channel of a river, located on a valley floor, with river-derived depositional features (e.g. levees) and water input from periodic (intermittent to seasonal) overtopping of the channel banks.
2	Channelled Valley-bottom	Situated adjacent or close to distinct active channel of a river, located on a valley floor, with no river-derived depositional features (e.g. levees) characteristic of a floodplain. Water input via (surface and subsurface) runoff from one or both of the adjacent valley side-slopes.
3	Unchannelled Valley-bottom	Located on a valley floor, without clearly discernable channel banks characterised by permanent or periodic, diffuse, unidirectional through-flow of water (often dominated by subsurface flow).
4	Depression	An area characterised by closed (or near-closed) elevation contours (well defined to indistinct) within which water typically accumulates. It includes areas not fed by water from a river channel, typically located on a lowland (plain) or a upland (plain), not necessarily completely flat, but can slope up to 0.3%, although more typically an order of magnitude less. Water movements include vertical (water-table oscillation) and horizontal (through-flow).
5	Seep	Not located on a valley floor and without clearly discernable channel banks. Characterised by permanent or periodic, diffuse, unidirectional through-flow of water (often dominated by subsurface flow).

4.4.2.3 Data Analysis

Since the focus of this study is the classification of hydrogeomorphic wetland units, the character of the study area need to be considered i.e. low relief (0-82 m). Kruger, (1983) reported >80% of area with slopes less than 5%), while 8% of slopes are ≥ 5 degrees (which is fairly flat) (DLP, 1992). The undulating dunes and sandy soils are characterised by high infiltration rates and a low water-holding capacity. Therefore, it is assumed that slope values for depressions are unlikely to have modal slope value of >2%. On the other hand, channelled valley-bottom wetlands have sections where the modal values for slope is on the order of 6%. 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 were <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.

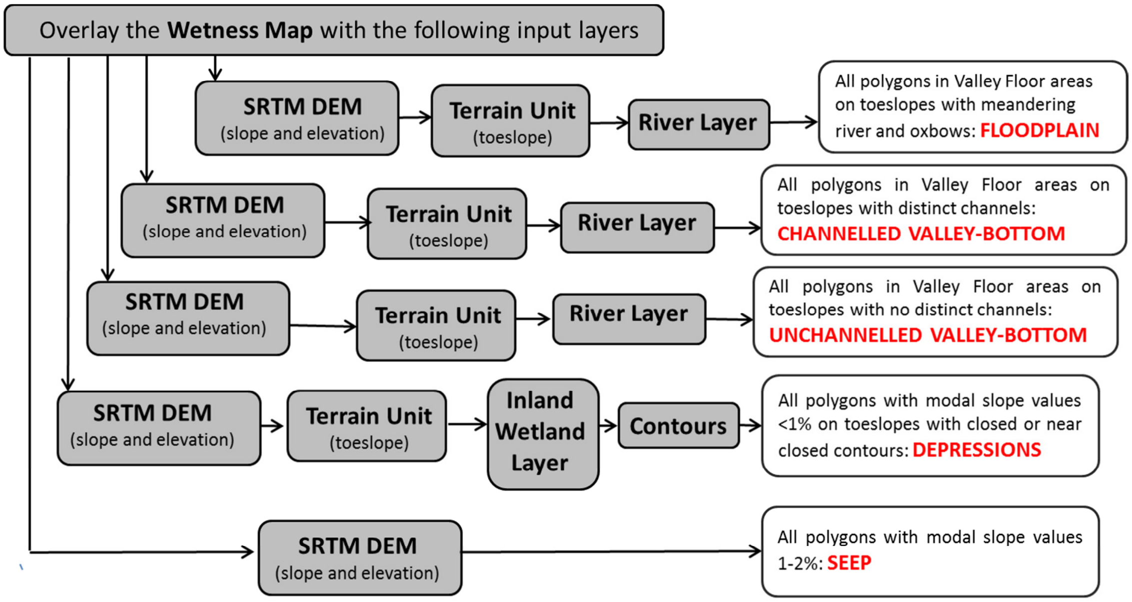


Figure 4.4: Diagram showing the elimination steps part of the hydrogeomorphic wetland classification process.

4.4.2.4 Accuracy Assessment

Accuracy assessment was performed using known hydrogeomorphic sites (ground reference points) to compare with both a) the classified hydrogeomorphic wetland unit map and with b) the National Freshwater Ecosystem Priority Areas (NFEPA) Project Wetland Ecosystem Type layer (Mbona et al., 2010; Driver et al., 2011; Nel et al., 2011). The hydrogeomorphic unit at each of the 42 ground reference sites were described during field visits (Chapter 3) and verified using the Google Earth Elevation Profile tool (Dolliver, 2012; Google Inc. (2013) (Appendix 4). No other independent data set is available.

4.5 RESULTS

4.5.1 Hydrogeomorphic Wetland Classification

The hydrogeomorphic wetland unit map for the study area was created using a semi-automated approach, with the use of ancillary datasets in the Geographic projection (Datum World Geodetic System 84). The following hydrogeomorphic wetland units were mapped (Figure 4.5): one *floodplain*, i.e., Siyadla River Floodplain (with evidence of a meandering river), *channelled valley-bottoms*, *unchannelled valley-bottoms*, *depressions* on <1% slope and *seepage* wetlands on 1-2% slope. Table 4.3 indicates the surface area (ha) of each hydrogeomorphic wetland unit as percentage of the total study area for wetlands from the wetness map (Chapter 2). The drainage networks include 11% *channelled valley-bottom wetlands*, 1% *floodplain*, whereas 36% were *unchannelled valley-bottoms* (Table 4.3). Depressions vary in size from < 5 ha to large upland depressions of 4900-5900 ha. Depressions comprise 35% of the total wetland area. *Seeps* on modal slope values of 1-2% comprise 8%. The Kosi Bay Lake system (total 3639 ha) with open water represent 9% of the total wetland area.

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

Class	**HYDROGEOMORPHIC (HGM) Unit**	**Occurrences of the HGM unit**	**Total Area**	**Percentage**
1	Floodplain	1	564	1
2	Channelled Valley-Bottom	57	4754	11
3	Unchannelled Valley-bottom	204	15422	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
		7454	**42373**	**100**

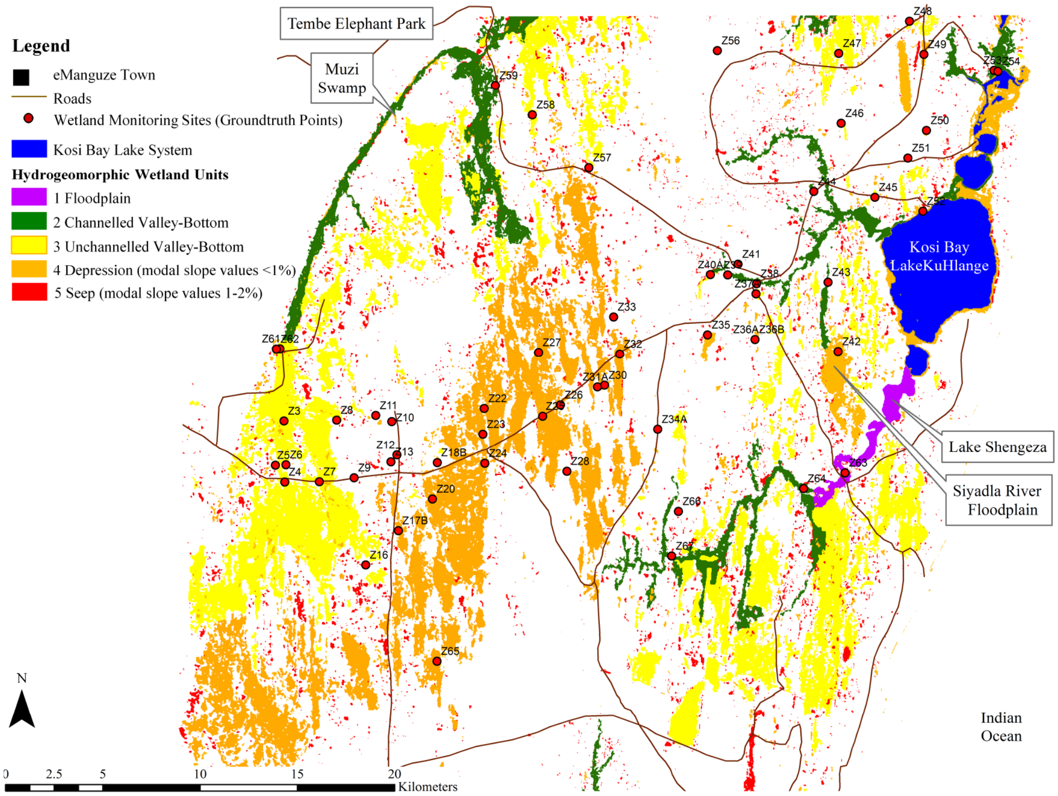


Figure 4.5: Hydrogeomorphic wetland units positioned in the landscape.

4.5.2 Accuracy Assessment

Using the 42 known hydrogeomorphic unit sites from field verification (ground reference points) against the classified hydrogeomorphic wetland units mapped, as well as with the NFEPA Wetland Ecosystem Type layer (Mbona et al., 2010; Driver et al., 2011; Nel et al., 2011) the mapping accuracy could be determined. The mapping accuracy for both the datasets are calculated and shown in Appendix 4. If a ground reference point was located <100 m from a wetland polygon, it was still considered, but if a ground reference point was located ≥100 m from a wetland polygon, it was considered not mapped. The overall hydrogeomorphic wetland unit map accuracy for the study area was 81%, while the NFEPA Wetland Ecosystem Type layer gave an overall 40% mapping accuracy (Appendix 4). High mapping confidence (88% to 100%) was obtained for hydrogeomorohic units in valley floor landscape settings (Table 4.4). Three wetland areas were not mapped in the hydrogeomorphic wetland unit map (Figure 4.5) compared to 9 of the NFEPA Wetland Ecosystem Type layer (Appendix 4).

Table 4.4: Hydrogeomorphic comparison results between ground reference classification and the semi-automated hydrogeomorphic classification in this study and the automated NFEPA classes.

HGM UNIT	HGM UNIT MAPPED	NFEPA	VERIFIED SITES	% ACCURACY HGM MAP	% ACCURACY NFEPA
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
Incorrect	5	16			
Not mapped	3	9			
	42	42	42		
OVERALL ACCURACY				**81**	**40**

4.5.3 Relation between Water-table Depth and Environmental Factors

4.5.3.1 Geomorphic Setting

The distribution of hydrogeomorphic wetland units are related to the hydrological and geomorphological drivers and processes on the Maputaland Coastal Plain, but the relation needs to be defined. An Agglomerative Hierarchical Clustering Analysis was used as part of this process to define the distribution of hydrogeomorphic wetland units in the landscape based on spatial similarities and, conversely, if there are distinct differences evident between groupings in relation to environmental factors (elevation, water-table and rainfall). Data for each site were collated and investigated for the 18-month period. A dendrogram shows the progressive grouping of the standardised data used and their location in the study area (Figure 4.6). Table 4.5 list the results for the 3 groups.

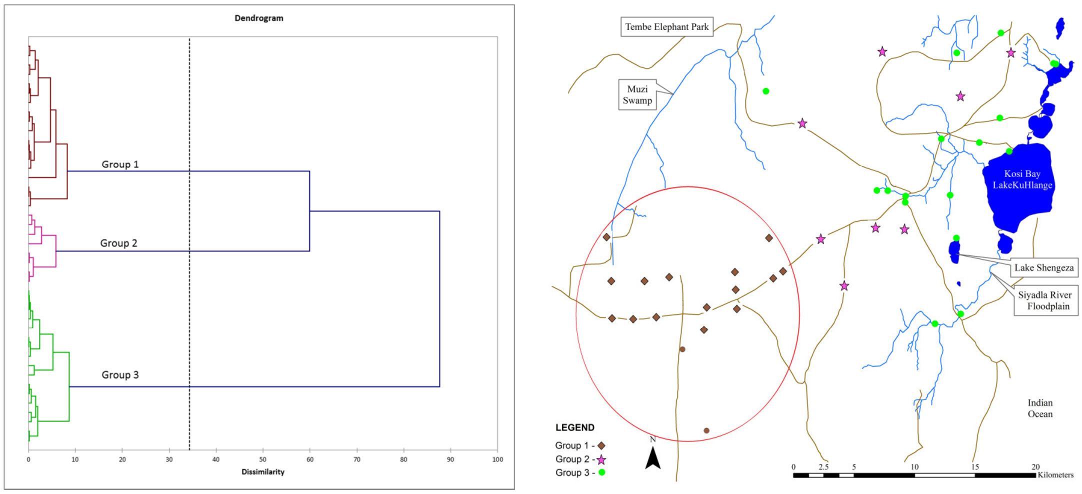


Figure 4.6: Dendrogram (left) indicating the three distinct groups using the Agglomerative Hierarchical Clustering Analysis and location of the three distinct groups in the study area (right).

Table 4.5: Results of the Agglomerative Hierarchical Clustering Analysis per group

GROUP	**1**	**2**	**3**
Objects	18	8	17
Within-class variance	2	2	2
Minimum distance to centroid	0	1	0
Average distance to centroid	1	1	1
Maximum distance to centroid	3	2	2
Ground reference sites	Z3, Z4, Z7, Z8, Z9, Z11, Z17, Z18, Z20, Z22, Z23, Z24, Z25, Z26, Z27, Z62, Z65, Z67	Z32, Z34, Z35, Z36, Z49, Z56, Z57, Z46	Z37, Z38, Z39, Z40, Z42, Z47, Z48, Z53, Z54, Z58, Z63, Z64, Z43, Z44, Z45, Z51, Z52.

Multivariate Discriminant Analysis (DA) was used to identify the variables that differ the most among the groups. Results of the Discriminant Analysis are listed in Table 4.6 (mean values of the variables) and the variable/factor correlations displayed in Table 4.7 and Figure 4.7. Table 4.7 shows the eigenvalues and the corresponding percentage of variance of the 5 variables. There are only two factors (F1 and F2): the maximum number of factors is equal to k-1, when n>p>k, where n is the number of observations, p the number of explanatory variables, and k the number of groups. Figure 4.7 shows how the initial variables are correlated with the two factors (F1 and F2) and represent the ground reference points on the factor axes. Size and shape of the oval/circle around the centroids (yellow point) represent the 95% confidence of the ground reference points on the factor axes. This confirms that the wetland groups are very well discriminated on the factor axes extracted from the explanatory variables. F1 (68%) means the variance is represented with the high percentage eigenvalues listed in the first factor (elevation and average and maximum total monthly rainfall), while F2 (32%) represented the high percentage eigenvalues listed in the second factor (average and maximum depth to water-table) (Table 4.7).

Table 4.6: Discriminant analysis variant mean per group.

Data used without the standardised matrix					
Group \ Variable	**Elevation**	**Average Water-table Depth**	**Maximum Water-table Depth**	**Average Total Monthly Rainfall**	**Maximum Total Monthly Rainfall**
1	66	-1.91	-1.38	60	236
2	35	-1.76	-1.29	69	302
3	20	-1.25	-0.84	73	345
Data used with the standardised matrix					
1	0.753	0.11	0.14	-1.02	-1.01
2	0.374	-1.59	-1.61	0.51	0.52
3	-0.973	0.64	0.61	0.84	0.83

Table 4.7: Percentage values of the variable correlation matrix

Eigenvalues	**F1**	**F2**
Elevation	**73**	-53
Average Water Table Depth	5	**96**
Maximum Water Table Depth	8	**96**
Average Total Monthly Rainfall	**-97**	8
Maximum Total Monthly Rainfall Rain	**-96**	7

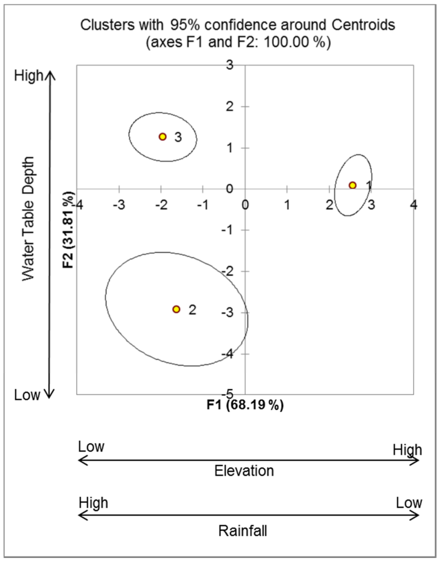


Figure 4.7: Variables correlated with the two factors representing the groups on the factor axes. High elevation and low rainfall distinguish group 1 in west from group 2 and 3 closer to the coast (low elevation and high rainfall. Water-table depth is low for group 2 and high for group 3.

Group 1 is situated southwest in the study area (headwaters of the Muzi swamp system and on the upland plain with low rainfall (700 – 760 mm average annual rainfall)) (Figure 2.3, Chapter 2). The mean elevation of the 18 sites clustered in group 1 is 66 m.a.s.l. Group 2 and 3 both occur towards the north-eastern side of the study area where average annual rainfall is 761-860 mm (Figure 2.3, Chapter 2), and mean elevations are 35 and 20 m.a.s.l., respectively. Group 3 is strongly associated with valley floors where the water-table of streams and lakes is persistent at or near the surface. The variable correlations (Figure 4.7) indicate that rainfall and elevation are the major factors influencing clustering between group 1 and groups 2 and 3 by 68% (F1), while water-table depth (F2) influences the clustering between group 2 and 3 by 32%. Caution must be used in ascribing attributes that discriminate between groupings, and causal mechanisms (i.e. the dependency of wetland occurrence/type on rainfall, elevation and water-table depth. Here, Group 1 (inland/higher elevation) and Groups 2 and 3 (coastal/lower elevation) are discriminated most strongly on the basis of rainfall and elevation (Table 4.7). This discrimination is likely related to the relatively consistent increase of elevation and decrease of rainfall over the 55 km distance inland. A weaker discrimination is made between groups 2 and 3 on the basis of water-table. The locations of the ground reference points for these groups are interspersed across a similar region (Figure 4.6) but with Group 3 being strongly associated with drainage network (high water-table) compared to Group 2 (away from drainage lines and so deeper water-table). Being interspersed across a wide region, the rainfall and elevation gradients are mixed and unable to discriminate between these groups. The weakness of water-table as a discriminating variable is likely due to its high variability, particularly in unchannelled valley-bottoms, depressions and seeps (Figure 4.8), which make up most of Group 2 and 3 wetlands. Thus, while we can discriminate between groups of wetlands most confidently with rainfall and elevation (because of their consistent gradients), it seems unlikely that these are casual mechanisms. The local hydrological setting (which is related to elevation) and hydraulic properties of the soils, have a much stronger effect on controlling the requisite saturation than the relatively small differences in precipitation.

For example the distribution of swamp forest in channelled valley-bottoms is strongly linked with elevation and groundwater discharge conditions, largely a product of the geomorphological history of the coastal plain governed by the interactions between local rainfall, groundwater flow characteristics and sea level (Sliva et al., 2004).

The lowland (<50 m.a.s.l.) areas host most of the hydrogeomorphic wetland types. *Floodplain* and *channelled valley-bottoms* wetlands (see Figure 4.5) are distinct fluvial features covering 5318 ha, most with swamp forest vegetation (Table 4.3). The largest proportion of wetlands are classified as *unchannelled valley-bottoms* wetlands (15422 ha) followed by *depressions* (14695 ha) (Table 4.3). The upland plain (≥50 m.a.s.l.) has the largest proportion of depressions, consisting mostly of large flat-bottomed features (11352 ha). *Depressions on the* lowlands (1399 ha) include Lake Shegeza and area surrounding the lakes but exclude the The Kosi Bay Lake system (total 3639 ha). Small depressions (< 5 ha in size) make up 1944 ha of the study area. Depressions (total 35%) are common features in this interdune landscape and can occur on all landscape settings: plain (upland or lowland), seep and valley floor, same as seep occurence but seeps in 1-2% slope represent only 8% of the total wetland area.

4.5.3.2 Hydrological Characteristics

The hydrological character of the hydrogeomorphic wetland unit typically reflects the landscape setting specifically as it controls relative water-table depth and fluctuation (Figure 4.8). For example channelled valley-bottoms have water levels sustained closer to the surface, followed by unchannelled-valley-bottoms. However, floodplains, depressions and seeps experience a much wider range of water levels, as a result of their periodic inundation with flooding events (Figure 4.8).

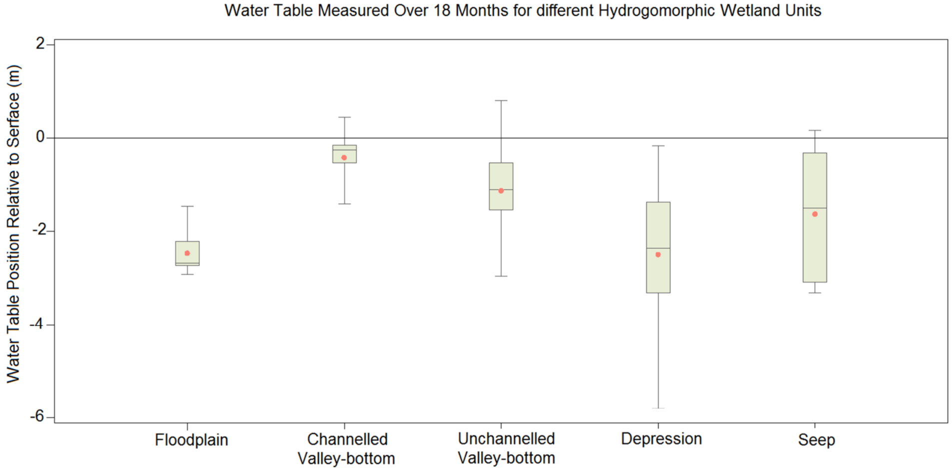


Figure 4.8: Average, minimum and maximum (boxplots) of water-table depth for different hydrogeomorphic wetland units over 18 month's period. Floodplain (n=1), channelled valley-bottomed (n=8), unchannelled valley-bottom (n=7), depressions (n=22) without perched depression (Z62) and seep (n=3) (Total n=41). The boxplots represent the1st and 3rd quartiles, the line is the median, the red dot is the average and the whiskers are max and min values. Note that all the time series points for each station have been included.

Evaluating the proposed hydrogeomorphic wetland unit classification types, the study found that the character, ecological function and driving hydrological processes between "depressions" and "flats" are typically indistinct. They are not necessarily flat, and can slope up to 0.3%, although more typically an order of magnitude less. They may be through-flow systems affected by fluctuation of the regional water-table, similar to how unchannelled valley-bottom and seeps function. Depression wetlands of various genres occur such as perched depressions (rainwater fed), or groundwater-fed depressions associated with through-flow of groundwater on all landscape settings. Figure 4.9 is a schematic representation of depression wetlands; all three genres have water inside the depression from a previous water-table rise. Figure 4.9A is a temporary *depression* (e.g. Kwamsomi Pan, site Z62) with high clay content (25%) at 0-20 cm in the soil profile, and with relatively large water-table fluctuations. The water-table of site Z62 perched pan is on average 0.59 m above the surface in the rainy season versus the regional water-table in the nearby Z61 borehole (187 m away) that is on average 3.31 m below surface. 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. For example, the uplands are flooded during large rainfall events (e.g. the floods in 2000) giving rise to the groundwater at or near the surface. Figure 4.9B and C are phreatic (phreato-genic, i.e., the genesis is related to the water-table) and can occur on plains (upland and lowland). The depressions on the upland plain (Z23, Z25, Z32) (Figure 4.9B) in the central part of the transect receive an average annual rainfall of 720-780 mm. The depth to water-table varies from less than 1 m (i.e. Z25) to much deeper (> 3 m, Z32). In contrast, the water-table variability at Z35 and Z36 is relatively small, being associated with low to moderate discharge because of groundwater through-flow driven by the topographical slope towards the east. Figure 4.9C represents a through-flow wetland with groundwater discharge into the one side of the wetland and with an outflow to the regional groundwater at the opposite bank.

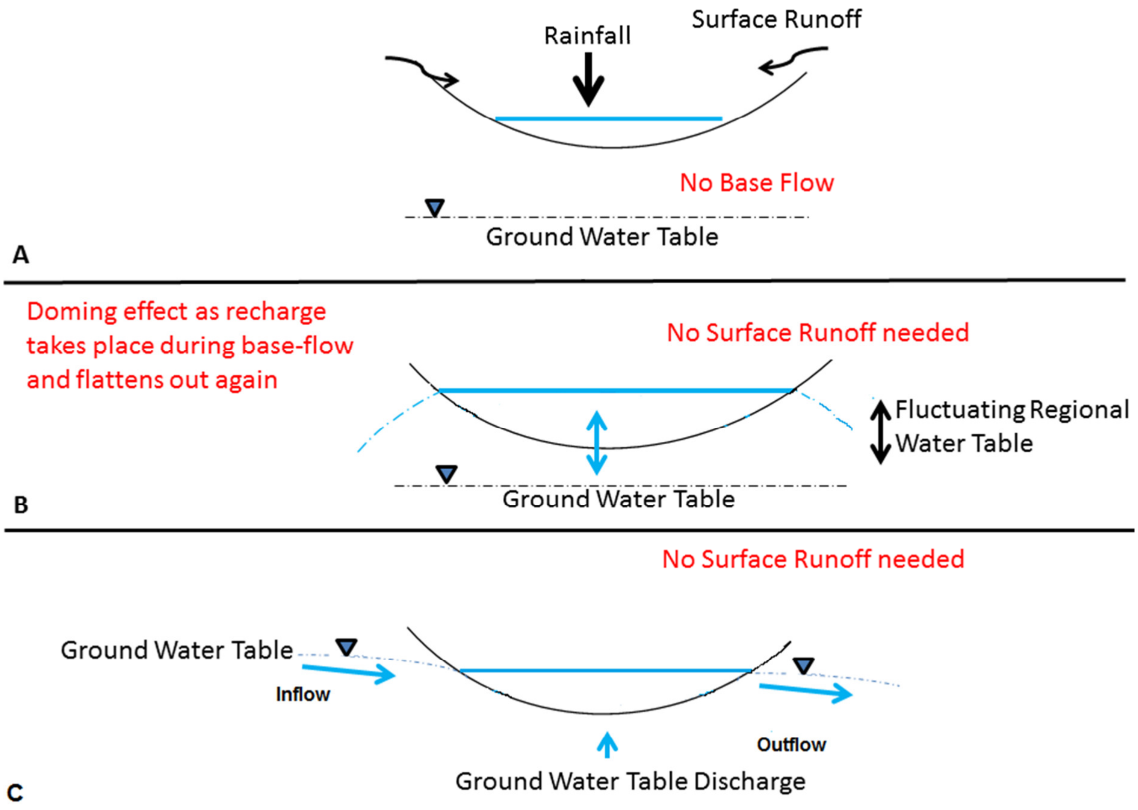


Figure 4.9: Depressions (hydrogeomorphic units) with different functioning processes. A) perched depression; B) upland depression, and C) depression on slope. Diagrams adapted from Semeniuk and Semeniuk, (1995) and U.S. EPA (2008).

4.6 DISCUSSION

Ambiguity occurred between some hydrogeomorphic units: *unchannelled valley-bottom* and *depression* (e.g. Z7); *seep* or *depression* (e.g. Z9), *seep* and *channelled valley-bottom* (e.g. Z39 is a spring (groundwater *seepage*) feeding a *channelled valley-bottom)* and *wetland flat* and *depression,* that were the most ambiguous of categories in the study area. The *wetland flat* as hydrogeomorphic type is defined by Ollis et al. (2013). Ollis et al. (2013) expressed concern that *wetland flat* should not be confused with floodplain flats which are connected to and fed by a river. The upland plain areas in the study area display large flat-bottomed relic features on <1% slope, denuded by wind and water. Some of these relic features are 10 km long with micro-topography (<1 m high dune remnants and smaller depressions with pools of standing water in wet years). Ollis et al. (2013, p103) indicated that *wetland flat* areas may have "small ponded areas that form digressional micro-features within an extensive *wetland flat*" area and is therefore considered as part of the wetland flat. These wetland types on the upland and lowland plain were classified as depressions and not "flats" because large depressions because they have closed contours that can slope (up to 0.3%), characterised by through-flow systems and fluctuation of the regional water-table. The micro-topography associated with these "flats" on up and lowlands (modal slope values <1%) were also considered to be individual depressions (Appendix 4).

Limitations in the use of automated and semi-automated approaches involve the quality of baseline wetland inventory layers and ancillary input layers, as these are overlaid to classify the hydrogeomorphic units. If these layers are not comprehensive and accurate it will affect the accuracy of the product. The wetland layers that were produced comparing wetland distribution in wet and dry years were fairly accurate in mapping wetland extent and distribution with only 3 areas not mapped. The NFEPA Wetland Ecosystem Type used the National Wetland Inventory VS 3 (SANBI, 2010) and 9 wetland sites were not mapped (Appendix 4). Another limitation could be use of inaccurate river/stream layers, consequently misclassifying the *channelled* and *unchannelled valley-bottom* wetlands. Furthermore, the number of independent ground reference points representing the different hydrogeomorphic wetland units was limited due to deep sandy soils, overgrown dirt roads and access entering conservation areas. This, too, had an implication on the accuracy of the classification. However, the 81% mapping accuracy for the study area compares well with the NFEPA Wetland Ecosystem Type dataset (average accuracy 40%) that used an automated approach (Mbona et al., 2010; Driver et al., 2011; Nel et al., 2011; Van Deventer et al., in press) but on a national scale. No accuracy assessment has been done for the NFEPA Wetland Ecosystem Type dataset and this study makes a significant contribution in assessing the classifications on sandy coastal plains.

4.7 CONCLUSIONS

Incomplete and inaccurate input layers (e.g. wetlands layer and river layer) and limited ground reference points with substantiated groundwater monitoring data are the major limitations in an automated and semi-automated approach for hydrogeomorphic wetland classification. The danger in using the broad hydrogeomorphic classification with limited criterion for future land-use planning and assessments is that it permits a direct judgement of a single wetland's value. For example, the hydrogeomorphic classification is based on the fundamental factors, namely: landscape setting, permanence of water (hydroperiod), source of water (rain or groundwater) as well as the sediment input and type (e.g. alluvial). It addresses aspects such as: 1) the origin of the landscape setting (e.g., interdunal or fluvial features like floodplains); 2) the importance of the landscape setting (e.g., upland recharge and lowland discharge areas); 3) the description of the water source (e.g., seepage of groundwater discharge or runoff or flow-through/interflow) and 4) if the wetland is permanent, seasonally or intermittently inundated (i.e., wetland distribution and extent mapped for wet and dry years). Additional detailed information can only be added to sub-classify the hydrogeomorphic units that are part of the hierarchical structure in which the hydrogeomorphic classification is applied, when and if the information becomes available. This study highlights that a classification is only useful if it can be reasonably applied. In this study area it was not easy to know the hydrological cause of depressions without long-term measurements. Not even a single site visit will help because some depressions on the moist/sedge grasslands look the same but function differently. Hydrological data of a wetland could indicate interaction with the regional water-table (either recharge or discharge function) and the ponding of rainwater (could indicate perched or partially perched conditions). Defining these relations and the ability to quantify aquifer dependency are much needed for biodiversity management or sustainable aquifer development. The supplementary ground reference data confirmed that not all wetlands belonging to the same hydrogeomorphic unit function the same, e.g. perched depressions (rainwater fed) and depressions linked to the regional water-table. Through-flow systems by regional fluctuation of the regional water-table in the deep sandy dune landscape are characteristic to more than one type of hydrogeomorphic unit e.g. “depressions” and “flats” and can also occur in unchannelled valley-bottom and seeps because of slope. This 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 contributes to further refining of the wetland classification work in South Africa and can be applied on similar sandy coastal plains.

4.8 ACKNOWLEDGEMENT

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5. CONCLUSION AND RECOMMENDATIONS

5.1 SANDY COASTAL PLAINS

Wetlands on sandy coastal areas have in common sand, wind and water as drivers of ecological processes that determine how a specific wetland or range of wetlands functions. Sea-level regression and transgression are characteristic to sandy coastal areas (Wright et al., 2000) in The Netherlands (Wadden Islands) (Grootjans, 2009), Australia (Fraser Island) (Sinclair, 1997) and Mozambique Coastal Plain (Momade and Achimo, 2004), resembling similar hydrogeomorphic settings. Characteristic of coastal plains are the undulating dune systems continuously shaped and formed by wind action resulting in recent dunes (mobile or partially mobile) close to the coast to reworked parabolic dunes in the interior that have a more hummocky aspect (Momade and Achimo, 2004). Local blowouts are common processes seen along the coast still today (Grootjans, 2009; Momade and Achimo, 2004; Sinclair, 1997). Coastal areas, known to host wetlands, are being utilized for a variety of land-use activities that range from developed areas to conservation areas where humans can enjoy recreational activities or where protection of sensitive habitats exclude or limit human access (Barker et al., 2009). Either way, human intervention in coastal areas has an ecological cost, especially in areas where human life and infrastructure are threatened (e.g. dikes to protect the coast and to reclaim land) (Grootjans, 2009). Internationally, the appreciation towards the importance of landscape analysis and interpretation is increasing, especially in solving ecological problems and resolving previous bias convictions and philosophies on wetland function in landscapes (Grootjans, 2008; Ellery et al., 2009a).

In South Africa, wetlands make up only 2.4 % of the country's area but are the most threatened ecosystem (Driver et al., 2012). The KwaZulu-Natal Province has the highest percentage of wetlands per province area (4%) (SANBI, 2010) but is also the province with the highest rate of natural habitat loss and wetland loss (Driver et al., 2012; Kotze et al., 1995). Estimated predictions indicate that there will be almost no natural habitat left outside protective areas by 2050 (Driver et al., 2012). Functional coastal landscapes are dependent on intact natural habitat and healthy ecosystems in the long-term to be resilient in different climatic conditions (Driver et al., 2012; Barnes et al., 2002). Therefore, the need has been expressed on various governmental levels in South Africa to incorporate multidisciplinary knowledge by supporting research on how wetlands and other inland aquatic ecosystems function in the landscape (WRC, 2011).

The Maputaland Coastal Plain has experienced a combination of expanded *Eucalyptus* plantations, development and less than average rainfall was received from 2002 to 2012, when the average annual rainfall (586 mm) was far below the long-term average rainfall of 753 mm (measured over the previous 23 years). This had an effect on the groundwater levels (Schapers 2012). The specific consequences of prolonged drought and how it affects wetlands are unknown. The importance of maps to guide decisions about where best to allow different land-use activities other than conservation areas is stressed (Taylor et al., 1995; Driver et al., 2012). Maltby and Barker (2009) view wetland occurrence from water supply, from one or more sources including discharge areas, yet wetland maps typically do not indicate the source of water for each wetland, i.e. groundwater recharge and discharge function of wetlands. Therefore, the science of mapping, characterising and classifying ecosystems is laying the foundation for meaningful assessments, planning and monitoring of ecosystems (Driver et al., 2012), especially for groundwater dependent ecosystems on the Maputaland Coastal Plain (Colvin et al., 2007). The primary aquifer is thought to be the principle source of water for rivers, lakes and wetlands (and vice versa) (Taylor et al., 2006; Le Maitre and Colvin, 2008; Kelbe and Germishuyse, 2010). The temporal and spatial variability of these wetlands make their identity and characterisation difficult not only because of the deep sandy soils with no signs of wetness (DWAF, 2005), but also because the vegetation composition varies between the different wetland types. For example, swamp forests 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 (Pretorius, 2011).

5.2 RESEARCH CONTRIBUTION

From the literature it was stated that the Maputaland Coastal Plain has a strong relation between the spatial distribution of wetlands and geological formations, topography, elevation above sea level, rainfall distribution and depth to groundwater and/or groundwater fluctuation (Grundling et al., 1998; Marneweck, et al., 2001). Although this statement on the *interrelated effects* of topography, water-table and soil type and vegetation composition and structure has already been demonstrated (Matthews, 2007; Taylor et al., 2006; Goge, 2003; Van Wyk,

1991) on local-scale studies, more work was needed to prove this on a sub-regional scale to link wetland types and dynamics to specific environmental factors (such as rainfall, water-table, elevation). Therefore, two hypotheses were tested with this research: 1) wetland function depends on landscape setting and 2) wetland function is rightly captured by the hydrogeomorphic type classification. In order to test the hypotheses the following methods were used: *mapping, characterising and classifying* hydrogeomorphic wetland types.

A combination of classification approaches were used to map the spatial and temporal character of these wetlands. Remote sensing classification, classification specifically developed for the study area based on biophysical characteristics and functional attributes and adapting a geomorphic classification approach (Semeniuk and Semeniuk 1995) and applying hydrogeomorphic classification (Ollis et al., 2013). Landsat images from dry periods (1992 and 2008) and a wet period (2000) were used along with data on soils, vegetation and a digital elevation model and terrain map. The regional water-table was defined on the basis of 59 *in situ* measurement points including drilled and dug wells, lakes, streams and springs, then modelled (MODFLOW) to characterise the regional water-table profile. A landscape perspective was needed to fully understand the interactions and to inform planning and management decisions. The conceptual model was used to interpret the rainfall gradient, landscape setting, and underlying geological template and the high and low water-table position. Both model parameters were configured and calibrated against measured *in situ* data. The extent and distribution of permanent and temporary wetlands and open water in dry and wet years assessed with remote sensing were used as a source of information for both models.

5.3 MAIN FINDINGS

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 a result of the hydrogeomorphic setting and not the rainfall distribution, although some wetland types such as peatlands do occur in areas where the rainfall exceeds 800 mm/year and at elevations between sea level and 50 m.a.s.l. Exceptions such as the Muzi "swamp" occur in the west of the study area at 700 mm/year. Landscape settings identified on this coastal aquifer were dominated by dune formations which consist of 3 types: plain (upland and lowland), slope and valley floor. The Wetland character is related to regional and local hydrogeology as well as climate affecting the temporal and spatial variability of the wetlands. Wetland types range from peat-forming swamp forests to moist sedge-grasslands, depending on their hydrogeomorphic setting. Wetlands with less than 2 m water-table fluctuation during dry periods were almost exclusively those we characterised as “permanent” wetlands, while the “temporary” wetlands were mapped with larger extent on an upland plain (Appendix 2). Assessment of the groundwater-surface water connectivity provides a holistic view of the abiotic template that sustains the biota. In this environment, where potential evapotranspiration greatly exceeds precipitation, external water sources such as surface or groundwater are critical to the hydroperiod and pattern of saturation and inundation. In locations where the surface intercepts the regional 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 delineation of wetland wetness zones as defined by the period of inundation (hydroperiod) is of importance in wetland management. Results from a separate research study site in the south on the Maputaland Coastal Plain (Appendix 5) found that soil organic carbon is a good indicator of hydroperiod and can be used to delineate and classify permanent and temporary wetlands on sandy coastal aquifers. The vegetation indicators in combination with the soil organic carbon content provide the best options to define different wetland systems and individual wetness zones.

Groundwater is an important driver in wetland distribution on the Maputaland Coastal Plain, 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 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. The impact of groundwater depletion on aquifer-dependent ecosystems depends on the wetland type and drop in water-table. It can vary from slight wetland loss to loss in wetland function and ultimately to ecosystem collapse. The permanent lowering of water-table below effective capillary action depth will result in wetlands drying out and replaced by terrestrial species as seen in temporary wetlands on the upland areas. Wetlands formed by groundwater discharge rely more heavily on shallow aquifer contributions. Therefore, wetlands differ in type, distribution and extent that emanate from hydrological response due to groundwater fluctuation and discharge across spatial and temporal scales.

The hydrogeomorphic classification brings into prominence the important underlying features of all wetlands, i.e. land (geomorphology) and water (hydrology). The results in the relation 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.

This research finding concludes on the two hypotheses:

Wetland function depends on landscape setting – Answer: Generally **YES**.

This research has demonstrated depressions on slope function differently than depressions on plain. Partially perched conditions in the upland plain have prolonged hydroperiods.

Wetland function is truly captured by the hydrogeomorphic type classification. Answer: **NO**. Not all depression on the coastal plain function the same way and three types of depressions occur and function differently, i.e., perched depressions with no link to the regional water-table vs. depressions that are linked with the regional water-table on plain, slope and valley floor landscape settings.

The semi-automated approach to map hydrogeomorphic units on the Maputaland Coastal Plain was 81% accurate compared to ground reference sites. Incomplete and inaccurate input layers (e.g. wetlands layer and river layer) and limited ground reference points with substantiated groundwater monitoring data are the major limitation in a semi-automatic approach for hydrogeomorphic wetland classification. Furthermore, the mapped or classified hydrogeomorphic units depend greatly on the data source. The 2008 Landsat TM dataset classification for the entire Maputaland Coastal Plain gave an overall 80% mapping accuracy. The combination of Landsat imagery with ancillary data show land-use activities and drought have reduced wetland extent and distribution in the north-eastern Maputaland Coastal Plain by 11% over 16 years (1992-2008). Wetland 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.

5.4 LAND-USE IMPACTS

The sedge/moist grassland wetlands that occur primarily on the uplands cover ~5% of the study area and are flooded during large rainfall events (e.g. the floods in 2000). As such, these wetlands are vulnerable to land-use activities such as forestry plantation that, on a large scale, can influence groundwater recharge (Walters et al., 2011) especially in potential recharge areas like the upland plains. There is evidence of an increase in afforestation from 2005 to 2008 (Macfarlane et al., 2012). Recent studies by Dennis (2014) reported on the negative effect that emerging plantation could have on water levels in lakes and wetlands in the area. However, the extent of the influence still needs to be quantified. Old, abandoned raised gardens indicate a period of wetter conditions once existed (Grundling et al., 1998). Wetlands and croplands <1 ha and cultivated fields in swamp forests are difficult to map using Landsat. The ambiguity between classifying: cultivation and grassland; temporal wetland and grassland; and bare soil and cultivation were highlighted using Landsat imagery. Road improvement from the towns Hluhluwe and Jozini through the town eManguze (26°59’15”S; 32°45’25”E) to the Mozambique border post resulted in the increase of development around eManguze and population density increase (Grundling et al. 2013a; Schapers, 2012). This caused increase in cultivation in wetlands near access roads to transport the crops to the markets and urban sprawl alongside the road networks. The two main regional sources of coastal aquifer contamination are land-use practices and sea-water intrusion (Meyer et al., 2001). Unconfined aquifers are most vulnerable to pollution both in the unsaturated zone and in the aquifer because the shallow water-table and the high permeability of the sediments allow a short travel time for pollutants (King, 2007). These pollutants use the same travel path to the aquifer as normal recharge. King (2007) stresses the importance that no pollution should take place in known areas of recharge. Worthington (1978) mentions bacterial and chemical contamination as the two types of localised pollution that threated the area. Land-use practices such as pit latrines and informal cemeteries are sources of bacteria and aquifers can be readily polluted by *E. Coli*, whereas the forestry, agriculture and unregulated industries pose the risk of chemical pollution. Water abstraction impacts in the KwaMbonambi Formation aquifer was measured by Schapers (2012) and analysis of critical drawdown depth in boreholes in the Airfield well field (south of the town eManguze) range in the order of 10 m per day while remaining boreholes have a variable and large drawdown range (25 to 40 m) and maximum 60 m per day. Groundwater is typically slow moving and, therefore, the need exists to take into account the lag time before impacts of groundwater abstraction on ecologically sensitive areas can be determined. Withdrawing water from shallow aquifers (abstracting or through rapid evapotranspiration) near surface water bodies (i.e., rivers, lakes and wetlands) can reduce the available surface water supply (Kelbe and Germishuyse, 2010; Schapers, 2012) through 1) capturing the groundwater flow that should be discharged into the surface water source (less discharge) or 2) inducing flow from the surface water source to the aquifer (less recharge) i.e. in the case of a water body being a source of water to the aquifer and water is reduced through abstraction or evapotranspiration.

5.5 RECOMMENDATIONS

1. Monitoring of the groundwater during this study and analyses clearly indicated that the Maputaland Coastal Plain has experienced a significant drought with less than average rainfall 2002 to 2012 this effect was both noted on groundwater levels and wetland distribution. However, the specific consequences of prolonged drought and how it affects wetlands are unknown and the combination of expanded *Eucalyptus* plantations could have a devastating impact on wetland function, related eco-services and socio-economic benefits of wetlands. Therefore the following recommendations are made:

   - Appropriate groundwater monitoring programmes, e.g. the South African Environmental Observation Network (SAEON), need to be implemented on the entire Maputaland Coastal Plain to account for aquifer vulnerability and volumes abstracted; thereby informing management decisions regarding water abstraction.
   - Socio-economic aspects impacting on wetlands and water security should be identified and monitored. Alternative land-use practices should be investigated and improper land-use of wetlands (such as draining) be regulated. Improved management should be promoted by all stakeholders with the aim to re-establish wetland functioning and to re-initiate peat-forming processes.

2. This research has clearly demonstrated that wetlands formed by groundwater discharge on primary aquifers depend on the shallow aquifer contributions as determined by its geological and hydrological characteristics (e.g., hydraulic conductivity). Furthermore, wetlands differ in type, distribution and extent that emanate from hydrological response due to groundwater fluctuation and discharge across spatial and temporal scales. Results of the thesis were incorporated into the modelling of wetlands of this region and successfully incorporate into the mapping of wetlands on a regional scale.

It is therefore recommended that a similar approach is followed to support management of wetlands on similar landscapes:

- Improved identification and classification of the lithology and geological significance of the shallow and deeper aquifer in primary aquifer regions.
- Further development of methods and models describing the interaction between aquifers and their discharge boundaries (i.e. rivers, lakes and wetlands).
- The impact of direct water abstraction and evapotranspiration by plantations on wetland function and distribution is unknown and need to be quantified.
- Improved inventory of wetlands and land use planning in primary aquifer regions

3. This thesis concluded that wetland function on the Maputaland Coastal Plain depends on landscape setting and that wetland function is not fully captured by the hydrogeomorphic type classification. Therefore, a review of the hydrogeomorphic classification system especially pertaining to sandy coastal aquifers is required

5.6 CONCLUSIONS

This thesis attempts to illustrate the use of a holistic approach to define the interaction of landscape processes maintaining the dynamics of wetland type, extent and distribution through the use of mapping, characterising with conceptual models supported by numerical models and classification. Various multidisciplinary studies have been conducted, but the challenge was to combine previous studies and current findings to indicate and understand the processes at work on the Maputaland Coastal Plain, north-eastern KwaZulu-Natal. An approach which integrates various assessment methodologies was required to understand the hydrological abiotic template that sustains ecosystems at various scales in the catchment. It was the quest of this research to present a conceptual framework of the connectivity of landscape processes across spatial and temporal scales in the selected study area on the Maputaland Coastal Plain. Up-scaling studies to the broader Maputaland Coastal Plain will particularly benefit from the research findings. Improvements to the remote sensing method used in this research can be applied to similar coastal areas, such as the Maputaland Coastal Plain 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). The importance of using imagery acquired in wet and dry periods as well as summer and winter for a more comprehensive wetland inventory of the study area, is stressed. The wetland inventory layer is a valuable asset for various applications (e.g. GIS analysis to type and classify wetlands and hydrology model input). The quality of the wetland inventory can have serious accuracy implications. Temporal differences also exist especially in semi-arid environments where distinct wet and dry periods are experienced, of which the study area is an example. This research initiative created a gateway for other research projects (The Alliance for Wetlands: Research and Restoration (AllWet RES)) to follow (Sliva et al., 2013) and documented methods and techniques that could be applied in the rest of the coastal plain or similar coastal plains in other parts of the world.

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APPENDICES

A1. APPENDIX 1: MAP METADATA

Title and Description			
Title of data set	Metadata for north-eastern Maputaland Land Cover 1992		
Description	Land-Cover map for north-eastern Maputaland, KZN province		
Supplemental Information	Coastal Plain, Dry year 2008		
Theme Keywords	Land-Cover		
Bounding Coordinates in Decimal degrees			
Upper left X	32.25 degrees		
Upper left Y	-26.86 degrees		
Lower right X	32.89 degrees		
Lower right Y	-27.24 degrees		
Place Keywords	Phongolo Floodplain, Tembe Elephant Park, eManguze, Mozambique border post (Farazel).		
Scale Denominator			
Scale	1:50 000	Pixel size	30m x 30m
History			
Originator	Agricultural Research Council (ARC) - Institute for Soil, Climate and Water		
Publication date (YYYYMMDD)	2012		
Publication Place	Pretoria		
Presentation Form	Digital raster data		
Online linkage	From Landsat TM 5 satellite images Scene ID 167079; Date 9 July 1992.		
Purpose	Done for the Water Research Commission (Project K5/1923)		
Access Details			
Conditions of use	To all non-profit organizations		
Access rights	Water Research Commission		
Contact details			
Contact Organization	Agricultural Research Council (ARC) - Institute for Soil, Climate and Water		
Contact Person	Althea Grundling		
Mailing address	Private Bag X79, Pretoria, 0001		
Phone no.	(012) 310-2500/2561		
Fax no.	(012) 323-1157		
E-mail	althea@arc.agric.za		
Native data set environment			
Full path name where data is stored			
Data stored on	Hard drive		
Size of data set	3.4 Mb		
Data Format	Erdas Imagine raster (.img)		
Time Period			
Date of data collection, publication etc (YYYYMMDD)	Data collected from satellite images of 2008. Land-Cover Data produced in 2012.		
To what does date refer, collection, publication, etc.	WRC Project (K5/1923) Final Report 12 Dec 2012 (publication only in 2013).		
Progress			
Progress of data	Complete		
Data set maintenance and update frequency	Irregular		

Data Quality	
Attribute Accuracy	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%
Positional Accuracy	The 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.
Other data quality issues	High mapping confidence (75% to 100%) was obtained for land-cover classes: open water, wetlands (sedge/moist grasslands), cultivation, plantation and bare soil. Classes difficult to map include: grassland and the overlap with cultivation practices and temporary wetlands; woodland, savanna and other forest classes (e.g. dune forest, sand forest) due to the similar spectral signatures; urban areas represent scattered homesteads with mixture of bare soil and croplands, and the swamp forest class that represent narrow linear features in drainage lines.
Spatial Data Organization Information	
Spatial data type	Raster
Spatial Reference Information	
Map projection name	Geographic, WGS84
Map Units	Decimal Degrees
Attribute Overview	
Attribute label and description	Land cover class: • water • wetlands • urban • grassland • closed savanna • open savanna • cultivation • plantations • bare soil • clouds and shadow • mangrove • sand forest • riverine forest • swamp forest • dune forest • dens coastal woodland • open coastal woodland
Distribution Information	
Distributor Organization	Agricultural Research Council (ARC) - Institute for Soil, Climate and Water
Distribution contact person	Althea Grundling
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Fax no.	(012) 323-1157
E-mail	althea@arc.agric.za
Liability	
Liability held by distributor	None

Title and Description			
Title of data set	Metadata for north-eastern Maputaland Land Cover 2000		
Description	Land-Cover map for north-eastern Maputaland, KZN province		
Supplemental Information	Coastal Plain, Dry year 2008		
Theme Keywords	Land-Cover		
Bounding Coordinates in Decimal degrees			
Upper left X	32.25431 degrees		
Upper left Y	-26.86 degrees		
Lower right X	32.89 degrees		
Lower right Y	-27.24 degrees		
Place Keywords	Phongolo Floodplain, Tembe Elephant Park, eManguze, Mozambique border post (Farazel).		
Scale Denominator			
Scale	1:50 000	Pixel size	30m x 30m
History			
Originator	Agricultural Research Council (ARC) - Institute for Soil, Climate and Water		
Publication date (YYYYMMDD)	2012		
Publication Place	Pretoria		
Presentation Form	Digital raster data		
Online linkage	From Landsat TM 5 satellite images Scene ID 167079; Date 17 September 2000.		
Purpose	Done for the Water Research Commission (Project K5/1923)		
Access Details			
Conditions of use	To all non-profit organizations		
Access rights	Water Research Commission		
Contact details			
Contact Organization	Agricultural Research Council (ARC) - Institute for Soil, Climate and Water		
Contact Person	Althea Grundling		
Mailing address	Private Bag X79, Pretoria, 0001		
Phone no.	(012) 310-2500/2561		
Fax no.	(012) 323-1157		
E-mail	althea@arc.agric.za		

Native data set environment	
Full path name where data is stored	
Data stored on	Hard drive
Size of data set	3.4 Mb
Data Format	Erdas Imagine raster (.img)
Time Period	
Date of data collection, publication etc (YYYYMMDD)	Data collected from satellite images of 2008. Land-Cover Data produced in 2012.
To what does date refer, collection, publication, etc.	WRC Project (K5/1923) Final Report 12 Dec 2012 (publication only in 2013).
Progress	
Progress of data	Complete
Data set maintenance and update frequency	Irregular

Data Quality	
Attribute Accuracy	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%
Positional Accuracy	The 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.
Other data quality issues	High mapping confidence (75% to 100%) was obtained for land-cover classes: open water, wetlands (sedge/moist grasslands), cultivation, plantation and bare soil. Classes difficult to map include: grassland and the overlap with cultivation practices and temporary wetlands; woodland, savanna and other forest classes (e.g. dune forest, sand forest) due to the similar spectral signatures; urban areas represent scattered homesteads with mixture of bare soil and croplands, and the swamp forest class that represent narrow linear features in drainage lines.
Spatial Data Organization Information	
Spatial data type	Raster
Spatial Reference Information	
Map projection name	Geographic, WGS84
Map Units	Decimal Degrees
Attribute Overview	
Attribute label and description	Land cover class: • water • wetlands • urban • grassland • closed savanna • open savanna • cultivation • plantations • bare soil • clouds and shadow • mangrove • sand forest • riverine forest • swamp forest • dune forest • dens coastal woodland • open coastal woodland
Distribution Information	
Distributor Organization	Agricultural Research Council (ARC) - Institute for Soil, Climate and Water
Distribution contact person	Althea Grundling
Address	Private Bag X79, Pretoria, 0001
Phone no.	(012) 310-2500/2561
Fax no.	(012) 323-1157
E-mail	althea@arc.agric.za
Liability	
Liability held by distributor	None

Title and Description			
Title of data set	Metadata for north-eastern Maputaland Land Cover 2008		
Description	Land-Cover map for north-eastern Maputaland, KZN province		
Supplemental Information	Coastal Plain, Dry year 2008		
Theme Keywords	Land-Cover		
Bounding Coordinates in Decimal degrees			
Upper left X	32.25 degrees		
Upper left Y	-26.86 degrees		
Lower right X	32.89 degrees		
Lower right Y	-27.24 degrees		
Place Keywords	Phongolo Floodplain, Tembe Elephant Park, eManguze, Mozambique border post (Farazel).		
Scale Denominator			
Scale	1:50 000	Pixel size	30m x 30m
History			
Originator	Agricultural Research Council (ARC) - Institute for Soil, Climate and Water		
Publication date (YYYYMMDD)	2012		
Publication Place	Pretoria		
Presentation Form	Digital raster data		
Online linkage	From Landsat TM 5 satellite images Scene ID 167079 and 167080; Date 7 September 2008.		
Purpose	Done for the Water Research Commission (Project K5/1923)		
Access Details			
Conditions of use	To all non-profit organizations		
Access rights	Water Research Commission		
Contact details			
Contact Organization	Agricultural Research Council (ARC) - Institute for Soil, Climate and Water		
Contact Person	Althea Grundling		
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Phone no.	(012) 310-2500/2561		
Fax no.	(012) 323-1157		
E-mail	althea@arc.agric.za		
Native data set environment			
Full path name where data is stored			
Data stored on	Hard drive		
Size of data set	3.4 Mb		
Data Format	Erdas Imagine raster (.img)		
Time Period			
Date of data collection, publication etc (YYYYMMDD)	Data collected from satellite images of 2008. Land-Cover Data produced in 2012.		
To what does date refer, collection, publication, etc.	WRC Project (K5/1923) Final Report 12 Dec 2012 (publication only in 2013).		
Progress			
Progress of data	Complete		
Data set maintenance and update frequency	Irregular		

Data Quality	
Attribute Accuracy	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%
Positional Accuracy	The 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.
Other data quality issues	High mapping confidence (75% to 100%) was obtained for land-cover classes: open water, wetlands (sedge/moist grasslands), cultivation, plantation and bare soil. Classes difficult to map include: grassland and the overlap with cultivation practices and temporary wetlands; woodland, savanna and other forest classes (e.g. dune forest, sand forest) due to the similar spectral signatures; urban areas represent scattered homesteads with mixture of bare soil and croplands, and the swamp forest class that represent narrow linear features in drainage lines.
Spatial Data Organization Information	
Spatial data type	Raster
Spatial Reference Information	
Map projection name	Geographic, WGS84
Map Units	Decimal Degrees
Attribute Overview	
Attribute label and description	Land cover class: • water • wetlands • urban • grassland • closed savanna • open savanna • cultivation • plantations • bare soil • clouds and shadow • mangrove • sand forest • riverine forest • swamp forest • dune forest • dens coastal woodland • open coastal woodland
Distribution Information	
Distributor Organization	Agricultural Research Council (ARC) - Institute for Soil, Climate and Water
Distribution contact person	Althea Grundling
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Phone no.	(012) 310-2500/2561
Fax no.	(012) 323-1157
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Liability	
Liability held by distributor	None

Title and Description			
Title of data set	Metadata for north-eastern Maputaland Wetness Map		
Description	Wetness map for north-eastern Maputaland, KZN province		
Supplemental Information	Coastal Plain, Dry year 2008		
Theme Keywords	Wetlands, Open water and Swamp Forest		
Bounding Coordinates in Decimal degrees			
Upper left X	32.25431 degrees		
Upper left Y	-26.86 degrees		
Lower right X	32.89 degrees		
Lower right Y	-27.24 degrees		
Place Keywords	Phongolo Floodplain, Tembe Elephant Park, eManguze, Mozambique border post (Farazel).		
Scale Denominator			
Scale	1:50 000	Pixel size	30m x 30m
History			
Originator	Agricultural Research Council (ARC) - Institute for Soil, Climate and Water		
Publication date (YYYYMMDD)	2012		
Publication Place	Pretoria		
Presentation Form	Digital raster data		
Online linkage	From land Cover data sets 1992, 2000 and 2008 specifically created for this project		
Purpose	Done for the Water Research Commission (Project K5/1923)		
Access Details			
Conditions of use	To all non-profit organizations		
Access rights	Water Research Commission		
Contact details			
Contact Organization	Agricultural Research Council (ARC) - Institute for Soil, Climate and Water		
Contact Person	Althea Grundling		
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E-mail	althea@arc.agric.za		

Native data set environment	
Full path name where data is stored	
Data stored on	Hard drive
Size of data set	3.4 Mb
Data Format	Erdas Imagine raster (.img)
Time Period	
Date of data collection, publication etc (YYYYMMDD)	Data collected from satellite images of 2008. Land-Cover Data produced in 2012.
To what does date refer, collection, publication, etc.	WRC Project (K5/1923) Final Report 12 Dec 2012 (publication only in 2013).
Progress	
Progress of data	Complete
Data set maintenance and update frequency	Irregular

Data Quality	
Attribute Accuracy	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%
Positional Accuracy	The 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.
Other data quality issues	High mapping confidence (75% to 100%) was obtained for land-cover classes: open water, wetlands (sedge/moist grasslands), cultivation, plantation and bare soil. Classes difficult to map include: grassland and the overlap with cultivation practices and temporary wetlands; woodland, savanna and other forest classes (e.g. dune forest, sand forest) due to the similar spectral signatures; urban areas represent scattered homesteads with mixture of bare soil and croplands, and the swamp forest class that represent narrow linear features in drainage lines.
Spatial Data Organization Information	
Spatial data type	Raster
Spatial Reference Information	
Map projection name	Geographic, WGS84
Map Units	Decimal Degrees
Attribute Overview	
Attribute label and description	Land cover class: Wetlands non-permanent Wetlands Permanent saturated Wetlands inundated Permanent open water Swamp forest
Distribution Information	
Distributor Organization	Agricultural Research Council (ARC) - Institute for Soil, Climate and Water
Distribution contact person	Althea Grundling
Address	Private Bag X79, Pretoria, 0001
Phone no.	(012) 310-2500/2561
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Liability	
Liability held by distributor	None

A2. APPENDIX 2: WATER-TABLE MONITORING SITES

NO	SITE NAME	ELEV	LAT	LONG	TYPE	WETLAND
1	Z3	43.26	-27d -3m -23.8s	32d 29m 44.7s	well	Yes
2	Z4	53.13	-27d -5m -4.8s	32d 29m 44.8s	Pan/depression	Yes
3	Z5	49.82	-27d -4m -37.6s	32d 29m 28.5s	well	No
4	Z6	52.09	-27d -4m -36.7s	32d 29m 47.9s	borehole	No
5	Z7	56.08	-27d -5m -5s	32d 30m 50.3s	borehole	Yes
6	Z8	54.54	-27d -3m -22.5s	32d 31m 23s	well	Yes
7	Z9	61.81	-27d -4m -58.6s	32d 31m 55.3s	well	Yes
8	Z10	65.98	-27d -3m -25.1s	32d 33m 6s	borehole	No
9	Z11	60.64	-27d -3m -14.3s	32d 32m 36.2s	well	Yes
10	Z12	72.59	-27d -4m -20.5s	32d 33m 16s	borehole	No
11	Z13	69.76	-27d -4m -32.9s	32d 33m 3.8s	well	No
12	Z16	72.73	-27d -7m -23.8s	32d 32m 16.7s	well	No
13	Z17B	73.92	-27d -6m -26.5s	32d 33m 17.2s	well	Yes
14	Z18B	74.53	-27d -4m -4s	32d 34m 30.1s	well	Yes
15	Z20	74.88	-27d -5m -33.9s	32d 34m 21.2s	well	Yes
16	Z22	73.08	-27d -3m -3.4s	32d 35m 58.4s	well	Yes
17	Z23	73.94	-27d -3m -46.7s	32d 35m 55.6s	well	Yes
18	Z24	75.00	-27d -4m -34.3s	32d 35m 58.9s	Pan/depression	Yes
19	Z25	73.79	-27d -3m -16.5s	32d 37m 46.3s	well	Yes
20	Z26	74.36	-27d -2m -58s	32d 38m 20.1s	well	Yes
21	Z27	70.41	-27d -1m -30.4s	32d 37m 40s	well	Yes
22	Z28	77.74	-27d -4m -49.1s	32d 38m 32.2s	borehole	No
23	Z30	78.92	-27d -2m -25.5s	32d 39m 42.8s	borehole	No
24	Z31A	75.54	-27d -2m -28.3s	32d 39m 29.7s	borehole	No
25	Z32	72.95	-27d -1m -33.4s	32d 40m 11.4s	borehole	Yes
26	Z33	73.79	-27d 0m -31.8s	32d 39m 59.9s	well	No
27	Z34A	71.64	-27d -3m -38.9s	32d 41m 23.2s	well	Yes
28	Z35	63.40	-27d -1m -2s	32d 42m 54.7s	well	Yes
29	Z36A	46.99	-27d -1m -9.5s	32d 44m 23.7s	well	Yes
30	Z36B	48.54	-27d -1m -9.5s	32d 44m 23.7s	well	Yes
31	Z37A	36.70	-26d -59m -54s	32d 44m 25.7s	well	Yes
32	Z38	33.12	-26d -59m -36.5s	32d 44m 26.9s	drain	Yes
33	Z39	37.63	-26d -59m -21.7s	32d 43m 33.5s	spring	Yes
34	Z40A	45.18	-26d -59m -21.4s	32d 43m 0.3s	river	Yes
35	Z41	65.16	-26d -59m -4.4s	32d 43m 52.6s	borehole	No
36	Z42	24.54	-27d -1m -31.1s	32d 46m 58.9s	lake	Yes
37	Z43	20.80	-26d -59m -34.8s	32d 46m 40.3s	drain	Yes
38	Z44	25.42	-26d -57m -3.3s	32d 46m 13.8s	wetland	Yes
39	Z45	13.48	-26d -57m -13.6s	32d 48m 7.7s	lake	Yes
40	Z46	39.23	-26d -55m -9.9s	32d 47m 5.1s	well	Yes
41	Z47	39.97	-26d -53m -13.5s	32d 47m 1s	well	Yes
42	Z48	28.19	-26d -52m -20.5s	32d 49m 12.8s	wetland	Yes
43	Z49	26.88	-26d -53m -15s	32d 49m 39.4s	well	Yes
44	Z50	24.20	-26d -55m -22.1s	32d 49m 44s	well	No
45	Z51	19.07	-26d -56m -7.7s	32d 49m 9.3s	well	Yes
46	Z52	1.87	-26d -57m -36.9s	32d 49m 37.1s	lake	Yes
47	Z53	2.23	-26d -53m -42.2s	32d 51m 49.3s	wetland	Yes
48	Z54	1.45	-26d -53m -43.7s	32d 51m 57s	Stream at estuary	Yes
49	Z56	61.70	-26d -53m -8.5s	32d 43m 14.7s	well	Yes

50	Z57	64.64	-26d -56m -22.4s	32d 39m 15s	well	Yes
51	Z58	52.79	-26d -54m -54.8s	32d 37m 28.1s	river	Yes
52	Z59	41.08	-26d -54m -5.2s	32d 36m 21s	well	No
53	Z61	43.70	-27d -1m -22.2s	32d 29m 38.2s	borehole	No
54	Z62	44.80	-27d -1m -23.2s	32d 29m 31.9s	Pan/depression	Yes
55	Z63	9.68	-27d -4m -52s	32d 47m 12.2s	river	Yes
56	Z64	14.72	-27d -5m -18.5s	32d 45m 54.3s	river	Yes
57	Z65	81.72	-27d -11m -55.4s	32d 35m 2.5s	lake	Yes
58	Z66	63.41	-27d -5m -56.1s	32d 42m 0s	borehole	No
59	Z67	50.06	-27d -7m -14.1s	32d 41m 47s	river	Yes

A3. APPENDIX 3: HYDROLOGY MODEL

Paper to be submitted as:
Kelbe, B.E., Grundling, A.T. and Price, J.S. Modelling water-table depth in a primary aquifer to identify potential wetland hydrogeomorphic settings on the, northern Maputaland Coastal Plain, KwaZulu-Natal, South Africa.

A3.1 OVERVIEW

It is believed that the primary aquifer on the Maputaland Coastal Plain in northern KwaZulu-Natal, South Africa is the principle source of water for rivers, lakes and most of the wetlands in dry periods and is recharged by these systems in wet periods. However, the temporal and special variability of these wetlands make their identity and characterisation difficult. Modelling hydrologic processes such as regional water-table depth can provide insight into the spatial and temporal patterns of wetland occurrence. This project aimed to populate the database of a single layer groundwater model (MODFLOW) to simulate water-table profile fluctuations for a transient 10-year simulation period (from January 2000 to December 2010) with wet and dry years. The extent and distribution of permanent and temporary wetlands in dry and wet years assessed with remote sensing were used as a source of information for the model. The model parameters were configured and calibrated against measured in situ data. The results confirm that topography plays an important role on a sub-regional and local level to support wetland formation. The wetlands' extent and distribution are directly linked to spatial and temporal variation of the water-table. Groundwater discharge zones in the lowland (1-50 m.a.s.l.) areas support more permanent wetlands with dominantly peat or high organic soil substrates, including swamp forest and most of the permanent open water. Most temporary wetlands associated with low % clay occurrence are through-flow interdune systems characterised by regional fluctuation of the water-table. Other temporary wetlands are perched or partially perched conditions, where local or deeper low permeability formations retain groundwater in a way that sustains wetland processes. To capture the extent and behaviour of perched wetlands, a more sophisticated saturated-unsaturated modelling approach is required.

A3.2 INTRODUCTION

Wetlands form where water is present at or near the land surface for a sufficiently long time to promote hydric soils and support vegetation communities adapted to wet conditions. These conditions can arise when the hydrogeomorphic setting and climate result in a high water-table connected to the regional groundwater regime, or where perched water-tables intersect the surface topography. The Maputaland Coastal Plain, also known as the Mozambique Coastal Plain, in the northeastern region of KwaZulu-Natal Province in South Africa, consists of a low relief, undulating sandy dune landscape that contain the highest percentage of wetland area per province area in South Africa (SANBI, 2010) and 60 % of South Africa's known peatlands (Grundling et al., 1998). According to Taylor (1991) rainwater infiltrates into the coastal dunes to recharge the shallow aquifer linked to adjacent ecosystems. Many interdune or topographic lows are wet (inundated or saturated), forming aquifer dependent ecosystems of the Maputaland Coastal Plain (Colvin et al., 2007; Taylor et al, 2006).

It is postulated that in this environment the shallow aquifer is the dominant hydrological feature that is closely linked to the aquatic and terrestrial ecology (Taylor et al., 2006; Colvin et al., 2007; Le Maitre and Colvin, 2008; Kelbe and Germishuyse, 2010). There is a need to clarify the source and persistence of water in these wetlands (Begg, 1989) since this affects wetland form and function (Barker and Maltby, 2009). While this information is not generally available for wetlands of the Maputaland Coastal Plain (Ewart-Smith et al., 2006), there is good evidence that many wetlands serve as groundwater discharge areas (Taylor et al., 2006). The wetlands may be linked through surface drainage systems forming low gradient streams that can directly influence the water-table profile and hence the wetlands themselves. However, wetlands can form from perched water-tables that are not directly connected to the regional water-table (Dempster et al. 2006). It is difficult to identify these linked and perched systems without detailed field studies.

Determination of the water-table profile is often derived from the interpolation and extrapolation of water level measurements at monitoring sites and exposed water surfaces that are assumed to be extensions of the groundwater system. Often these interpolation methods fail to include the impact of changing groundwater fluxes associated with known hydrogeomorphic features including drainage boundaries, topographic expression and lithological discontinuities or heterogeneity. Groundwater storage is represented by the water-table profile which changes in direct response to recharge and discharge fluxes. These fluxes can induce significant changes in the temporal and spatial patterns of groundwater storage that can produce rapid changes in the water-table profile, and hence the requisite conditions for wetland development. This is particularly relevant in the shallow aquifers along the coastal plain where the water-table hydrographs can resemble the stream hydrographs (Kelbe and Germishuyse, 2010). Groundwater models can be used to characterise the spatial and temporal patterns of groundwater storage (Gilvear and Bradley, 2009) that are linked to the distribution and function of wetlands and lakes (Kelbe and Germishuyse, 2000, Winter, 1999).

The application of numerical methods to support environmental studies is a pragmatic approach that provides increasingly reliable estimates of the form, function and dynamics of aquatic systems as conceptual modelling and data assimilation of the system progresses during model development and calibration. If the appropriate conceptual model(s) and ground truth information are available to support the simulation of all the relevant driving features of the system that create the water level responses, the numerical model will provide a strong analytical tool to evaluate the groundwater relations driving the environmental system.

Insight is needed into how groundwater discharge and the depth to water-table relate to wetland types of the Maputaland Coastal Plain. The derivation of a reliable estimate of the water-table profile and its variability are important factors in the study of these environmental systems, particularly the distribution of the permanent and temporary wetlands. An accurate profile of the water-table in these situations would greatly assist in determining the type of ecosystem dependency of a region, particularly on the identification of wetland types and their dependency on the regional aquifer. Various studies have been published on the use of groundwater models in the support of environmental studies for the study region (Kelbe and Germishuyse, 2000, 2001, 2010; Været et al (2009). For example forestry (plantations) is an emerging threat to the wetlands on the Maputaland Coastal Plain (Walters et al., 2011). Macfarlane et al. (2012) and Grundling et al. (2013a) reported on an increase in afforestation in the study area. Dennis (2014) stated that forestry does affect the inflows and water levels in the lakes and recommend that no forestry plantations be within 2 km of a sensitive wetland as this would significantly increase the water deficit and potentially impact these groundwater dependent ecosystems.

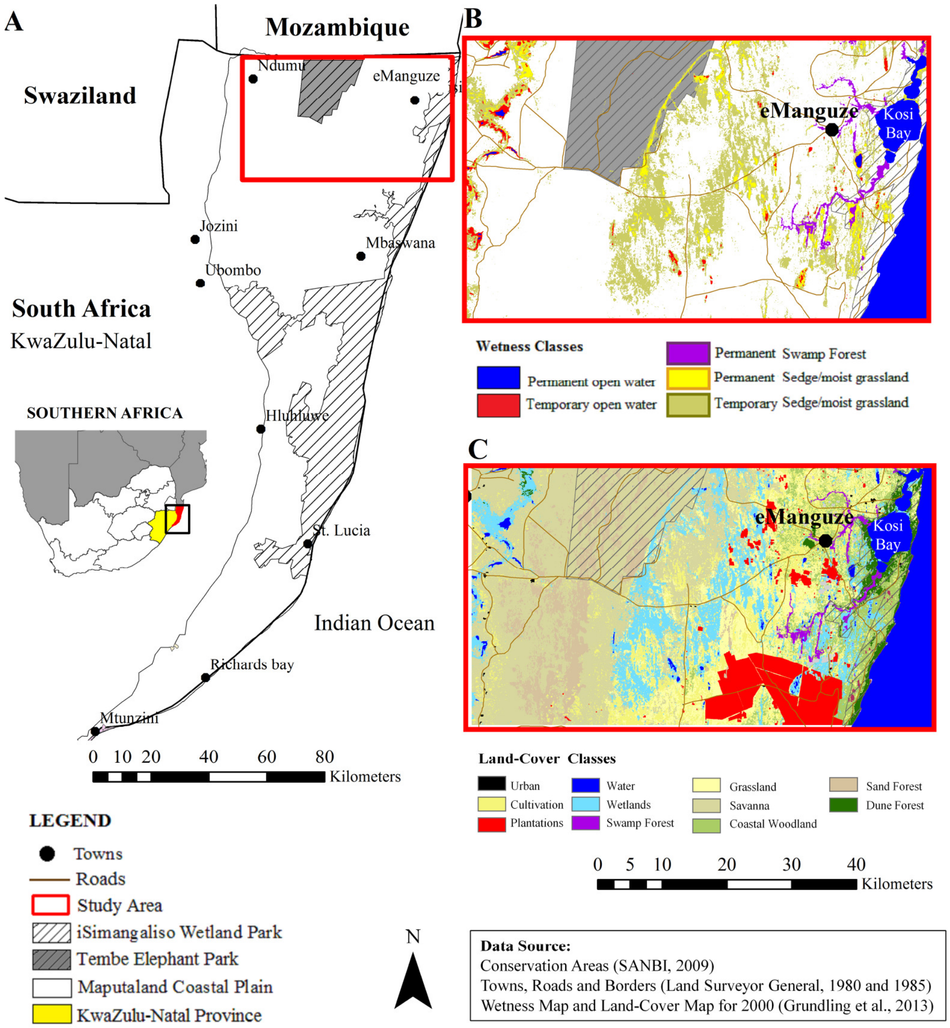
The unique importance of groundwater in this area for the estuarine ecosystems during severe droughts has been studied by Taylor et al. (2006). These studies and subsequent changes in land-use have led to management controls that enhance groundwater recharge to protect the ecological resources of the Maputaland Coastal Plain. The aim of this study is to use groundwater modelling to derive the best estimate of the regional water-table profile during a wet and dry period to aid in the delineation and characterisation of wetland types.

A3.3 STUDY AREA

The Maputaland Coastal Plain in north-eastern KwaZulu-Natal province, South Africa (Figure A3.1A and 1B) is renowned for its biodiversity, conservation areas, and World Heritage Site that include a variety of fresh and saline water wetlands such as swamp forest, saline reed swamp, salt marsh, submerged macrophyte beds, mangroves and riverine woodlands (Taylor, 1991). The study area is situated in the north-eastern part of the Maputaland Coastal Plain between the Tembe Elephant Park and the Kosi Bay Lake system (Figure A3.1A). Economic activity on the Maputaland Coastal Plain consists predominantly of subsistence agriculture (croplands and rangelands), forestry (plantations) and eco-tourism centred around the coastal wetlands (Figure A3.1C). The iSimangaliso Wetland Park is a World Heritage Site that protects the environment along the coastal strip around the Kosi Bay lake system up to the Mozambique border. The Tembe Elephant Park is a proclaimed community conservation area that is being linked to the Maputo Elephant Park as part of a Transfrontier park with Mozambique and Swaziland. The Maputaland Coastal Plain has poor soils (Lubke et al., 1996) that are generally unsuitable for commercial grain farming. However, the region is under severe threat from regulated large scale commercial forestry, as well as an increase in uncontrolled small scale forestry by subsistence farmers, both of which can have significant impacts on groundwater levels and wetlands (Været et al., 2009; Grundling et al., 2013a). The local communities in the region rely on subsistence agriculture in wetlands for crop production.

Grundling et al. (2013) used Landsat TM and ETM imagery acquired for 1992 and 2008 (dry) and Landsat ETM for 2000 (wet) along with ancillary data such as a digital elevation model, vegetation and soil maps to identify and map permanent and temporary (inland) wetlands and open water (Figure A3.1B), based on land-cover classification for the different years. All three datasets were used for land-cover change analysis to describe the spatial extent and distribution of wetlands and open water as well as land-use classes during the three different years to determine wetland loss from land-use changes due to cultivation, plantation and urbanisation.

The study area hosts a complex array of wetland types that range from “permanent wetlands” with dominantly peat or high organic soil substrates to temporary wetlands with mineral soils (Grundling et al., 2013a; Pretorius, 2011). The distribution of wetlands varies in response to periods of water surplus or drought, from large temporary wetlands systems to permanent linear interdune wetlands between the parabolic dunes (KwaMbonambi Formation).



Data Source:
Conservation Areas (SANBI, 2009)
Towns, Roads and Borders (Land Surveyor General, 1980 and 1985)
Wetness Map and Land-Cover Map for 2000 (Grundling et al., 2013)

Figure A3.0.1: A) The study area on the Maputaland Coastal Plain in north-eastern KwaZulu-Natal province, South Africa (Grundling et al., 2013a). B) The distribution of wetlands and C) land cover types (Grundling et al., 2013a) with leaf area index (LAI) for application in the mode. (NLC2000 Management Committee, 2005).

“Permanent wetlands” have a relatively fixed boundary e.g. peat swamp forests (Grobler, 2009), while sedge/moist grassland wetlands that occur on the deep sandy soil in areas where the water-table fluctuations are greater (conditions not ideal for peat development) are referred to as “temporary wetlands” (Pretorius, 2011). The boundaries of temporary wetlands appear to grow or shrink in wet or dry periods (Begg, 1989), potentially causing their area to be underestimated in periods of water shortage (Grundling et al., 2013a). . During very wet years, some areas including wetlands can be temporarily inundated with pools of open water for a short period. These can be described as “temporary open water” (Grundling et al., 2013a). In contrast, there are “permanent open water” areas including the Kosi Bay lake system and smaller lakes such as Lake Shengeza (Grundling et al., 2013a).

In general the regional geology that slope towards the east and the precipitation (rainfall) gradient that decreases from east (>820 mm) to west (~680 mm) (Grundling et al., 2013a) dictates the distribution of wetlands. Most of the permanent wetlands occur along the coast to the east. The upland (≥50 m.a.s.l.) has a greater proportion of temporary sedge/moist grassland wetlands, while the lowland areas (<50 m.a.s.l.), mostly in the east 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 A3.1B and Figure A3.2A). 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 total study area, and all of the swamp forest are congruent with the high water-table in the coastal region.

The wetland distribution and temporal character are related to the nature of the aquifer, topography and rainfall distribution i.e. hydrogeomorphic setting (Grundling et al., 2013a). Hydrogeomorphic wetland units identified by Grundling et al. (2014) include: a floodplain, channelled valley-bottom, unchannelled valley-bottom, depression and seep areas. However, wetland occurrence is not dependent on rainfall or elevation but rather depth to water-table, which is dependent on the hydraulic characteristics of the regional aquifer and localised topographical features and associated hydrological processes. Some temporary wetlands are perched pans (e.g. Kwamsomi Pan, parallel to the Muzi wetland system) while other are flow-through interdune systems characterised by fluctuation of the regional water-table (Grundling, 2014).

A3.4 HYDROLOGICAL MODEL

This project aimed to populate the database of a single layer groundwater model (MODFLOW) (Harbaugh et al., 2000) to determine the water-table profile fluctuations over a period with wet and dry years. The simulations are used to provide insight of how hydrogeomorphic setting and climate conspire to produce persistent or transient high water-tables conducive to the evolution of wetland types in specific geomorphic settings. This study presents the MODFLOW (Harbaugh, 2005) results for a transient 10-year simulation period from January 2000 to December 2010. This period includes a wet year 2000 and dry years when the average annual rainfall received was below average. e.g., 2002, 2003, 2004 and 2008 (Grundling et al., 2013a).

The model parameters were configured and calibrated against measured data in boreholes, wells, wetlands, streams and lake levels (Grundling, et al., 2014) and the results analysed using the Groundwater Vistas Interface. In this study groundwater recharge and evaporation were simulated for various land-cover classes (Grundling et al., 2013a) using the Unsaturated-Zone Flow Package (Niswonger et al., 2006) that incorporated the stream flow package (Prudic et al, 2004) coupled to the lake package (Merritt and Konikow, 2000). These models are highly parametrised and need representative values and/or calibration.

MODFLOW requires detailed description of the hydrogeological features that control the movement of water within the aquifer. These features were intially configured as Hydrostratigraphic Units (HSU) with homogeneous hydraulic properties (hydraulic conductivity and storativity) but spatial heterogeneity was introduced using inverse calibration modelling techniques (Doherty, 2010. These HSU zones represent the different aquifers formed by the various geological formations that are described in the next section. The recharge to groundwater storage is derived from infiltration after evaporation/transpiration losses from the unsaturated zone have been satisfied (Niswonger et al., 2006), assuming no surface runoff occurs. Infiltration across the model domain is derived from the incident rainfall after accounting for interception losses Interception losses are assumed to be directly proportional to the canopy storage as measured by the LAI. The incident rainfall was reduced by applying a simple proportion (1/100) of the Leaf Area Index (LAI) for the winter and summer periods. This model configuration requires the temporal and spatial distribution of rainfall and potential evaporation.

A3.4.1 Hydrogeological Setting

The Maputaland Coastal Plain was formed by sedimentary processes during periods of marine regressions and transgressions (Botha et al. 2013) that created a sedimentary sequence of unconsolidated formations. Subsequent aeolian depositions formed paleo-dune ridges orientated parallel to the coast and more recent high frontal dunes along the shoreline (Figure A3.2C). The coastal plain is characterised by a sequence of sediments overlying consolidated rocks of Jurasic basalts and rhyolitic rocks that generally slope to the east at an angle of about 3 degrees to the horizontal (Botha et al., 2013). During the Cretaceous Period much of the area was below sea level, creating a hydrogeological unit of claystones and siltstones with very low hydraulic conductivity, porosity and storativity, which behaves as an aquiclude with residual brackish water (Zululand Group), and forms the base of the regional aquifer.

Overlying the Zululand Group are unconsolidated to partially consolidated sedimentary deposits formed by a succession of marine, alluvial and aeolian processes (Worthington, 1978; Meyer and Godfrey, 1995, Kelbe et al, 2013 and Botha et al., 2013) with varying combinations of sand, silt and clay. The strata have sufficiently different hydraulic properties to form several hydrogeological units that create both unconfined and partially confined (leaky type) aquifers (Figure A3.2C).

The lowest part of this primary porosity aquifer (*Mio-Pliocene* sediments) consists of karst-weathered calcarenites with intercalated mudstone beds (Maud and Botha, 2000) often referred to as the Uloa Formation (Figure A3.2C). This hydrostratigraphic unit (HSU) (i.e. stratigraphic zones with uniform hydraulic properties) is generally overlain by sedimentary units with finer grained, less permeable sediments creating a leaky type aquifer (Todd, 1980). Along the coastal margin this overlying unit comprises an extensive layer of *Middle to Late Pleistocene* marine, estuarine clay, silt and sand of the Port Durnford Formation. These sediments generally have lower hydraulic conductivities and storativities than the underlying Uloa Formation, creating a partially confined leaky aquifer that is hydraulically connected to the Indian Ocean in places (Kelbe and Germishuyse, 2010).

Overlying the extensive *Middle to Late Pleistocene* Port Durnford sediments are younger porous and more permeable sandy formations of *Late Pleistocene* to *Holocene* age. These layers form the Kosi Bay Formation that cover an extensive area from the coast to the western interior (Figure A3.2B and A3.2C). Separating the Kosi and older formations are interspaced bands of lignite and red sands. The uppermost, youngest *Holocene* sediments

(Sibaya Formation) and the reworked sands of the KwaMbonambi Formation covering a large section of the study area have relatively high hydraulic conductivity and drain rapidly (DLP, 1992). However, they generally occur above the phreatic zone (DLP, 1992) and play little role in groundwater movement.

Since the focus of this study is the characterisation of the fluctuating water-table profile it is assumed that the deeper formations will not influence the water-table profile to a significant extent and the main controlling factors are the upper saturated stratigraphic layers and drainage boundaries. Consequently, the development and calibration of the water-table profile was based on a single layer model.

The spatial distribution of the upper geological units were mapped by Botha and Porat (2007) and plotted in Figure A3.2C, along with the available water level monitoring sites (WL Targets). It is assumed that not all these lithological units play a significant role in the hydrodynamics of the groundwater and would likely be insensitive to model calibration, particularly where few water level measurements exist within these units to support the calibration process. Most of these monitoring sites are wells installed below the water-table and may not represent the lithological units in the upper layers above the phreatic zone. This may induce errors in the representation of the units being calibrated.

Based on the distribution of the lithological units and monitoring points it is not possible to calibrate those units that have no monitoring data or that are outside the model domain. The two predominant units that require hydraulic properties based on the mapped units in Figure A3.2C are the Arenite (KwaMbonambi Fm) and Aeolanite (Kosi Bay Fm) Quaternary Sands. However, it is highly likely that these lithological units are heterogeneous and they are expected to exhibit a large variability in their hydraulic properties. Consequently, calibration techniques are required to account for the spatial variability in these properties.

A3.4.2 Modelling Approach

Groundwater is water stored in the aquifer, where the volume is subject to change, reflected by water-table fluctuations that result from the imbalance between the recharge to groundwater (influx of the rainfall component making up the recharge) and the efflux of the discharge through the various surface features, mainly evaporation and surface discharge). The recharge and discharge occurs at different rates through various processes involving the different surface features. It is essential to identify the important hydrological features that will directly influence the change in groundwater storage as reflected in the groundwater elevation measurements (water-table). While these hydrological features reflect the geomorphic history of the region they are only important in developing the model in the way they allow the flow of water into and out of the aquifers. According to Franke et al. (1987), setting boundary conditions is the step in model design that is most subject to serious error. In many situations the recharge and evaporation fluxes dominate the groundwater seepage rates. Consequently, small errors in the derivation of the recharge and evaporation rates may be significantly larger than the groundwater seepage rates. In this study area, the average annual precipitation is approximately 908mm for the last 100 years (Consortium for Spatial Information, 2013) while below average annual rainfall of 753 mm was measured over the previous 23 years for the period January 1989 to December 2011 (Grundling et al., 2013a). The mean annual potential evaporation rate is 1904 mm (Mucina and Rutherford, 2006).

The difference between the rainfall and actual evaporation is often referred to as the effective recharge and is a small percentage of the rainfall. Consequently, small errors in the spatial or temporal measurement of rainfall can create large relative errors in the determination of effective rainfall (or recharge). Hence, the selection of the appropriate conceptual model for inclusion in the groundwater model is a crucial step in the model development if the hydrodynamics of the groundwater system is the main purpose of the model development.

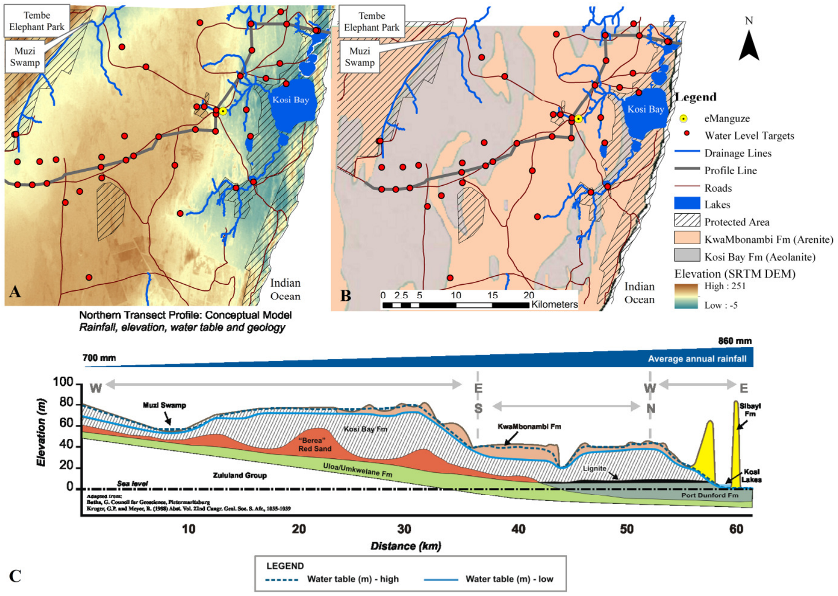


Figure A3.0.2*:* A) The regional elevation profile (DEM) derived from SRTM data (Jarvis et al, 2008). B) The main geological units that are considered important in regulating the groundwater dynamics in a shallow primary aquifer (Botha and Porat, 2007).Inset is the inferred schematic geological transect (AB) from Tembe Elephant Reserve to Kosi Bay (Grundling and Grundling, 2010).

A3.4.2.1 Rainfall and Leaf Area Index

It has been common practise in geohydrology studies in the region to assume the recharge in shallow unconfined aquifers is a simple proportion of the rainfall rate (Meyer and Godfrey, 1995; Dennis and Dennis, 2009). However, the soils in the study area are highly permeable and there is little evidence of overland flow with the exception of some wetland areas where the water-table is very close to the surface. Therefore, it is assumed that all the rainfall that is not intercepted by vegetation will infiltrate into the sub-surface layers. Interception losses are a function of the rainfall rate and the land-cover as defined by the Leaf Area Index (LAI). LAI defines an important structural property of a plant canopy which is the one-sided leaf area per unit ground area.

The infiltration (rainfall-interception) and percolation model adopted in this study is based on the UZF1 package described by Niswonger et al. (2006) for use with MODFLOW-2005. In this model the infiltration (rainfall-interception) rate is limited by the unsaturated vertical hydraulic conductivity and all excess flow is routed to surface runoff. The infiltration in the unsaturated rooting zone is further depleted by evapotranspiration. The evapotranspiration losses are removed from the unsaturated zone before the evaporative demand is met by groundwater evapotranspiration when the water-table is within the rooting zone. The UZF1 routine uses a kinematic wave approximation to Richards' equation to simulate vertical unsaturated flow of the wetting front (Niswonger et al., 2006).

Leaf Area Index (LAI) values were derived from MODIS (ESDT: MOD15A2) 8-day Composite NASA MODIS Land Algorithm (Reed, 2002). The MOD15 LAI and Fraction of Photosynthetically Active Radiation absorbed by vegetation products are available on a daily and 8-day basis provided at 1 km^2 pixel resolution. The following steps were used:

1) Monthly MODIS LAI images from March, 2000 to March, 2010 were used. The winter monthly LAI values for April to September were summed for every pixel overlaying a groundwater monitoring point and an average value was calculated for the winter months. The same were done for the summer monthly LAI values for October to March. Both images (winter and summer) were then used in the creation of zonal statistics from the National Land-Cover 2000 data set (NLC2000 Management Committee, 2005). For each National Land-Cover 2000 polygon the summer and winter average values were calculated for years 2000 to 2010.

2) LAI monthly averages were calculated using images captured from March 2000 to March 2010. Average LAI values were extracted for the groundwater monitoring points for the 12 months.

The rainfall distribution for the study area has a declining trend from east to west (Figure 2C). However, the temporal variability greatly exceeds the spatial variability across the study area (Figure A3.3). The region is dominated by convective storms and synoptic fronts that migrate up the coast (Kelbe, 1988). These convective storms and frontal systems generally produce rainfall events with high rates of precipitation which are less affected by interception (canopy storage) losses. Everson et al. (2014) indicate that under various commercial forestry species the interception losses in the region are between 10-35% of gross precipitation depending on the LAI. The interception storage is incorporated in this study by reducing the gross rainfall by a factor of 1% of LAI which induced an interception loss of between10 to 30% depending on the LAI. Since the purpose of the model simulation is to define the seasonal variation in the water-table defining the wetland system, it was decided to use monthly rainfall for this study.

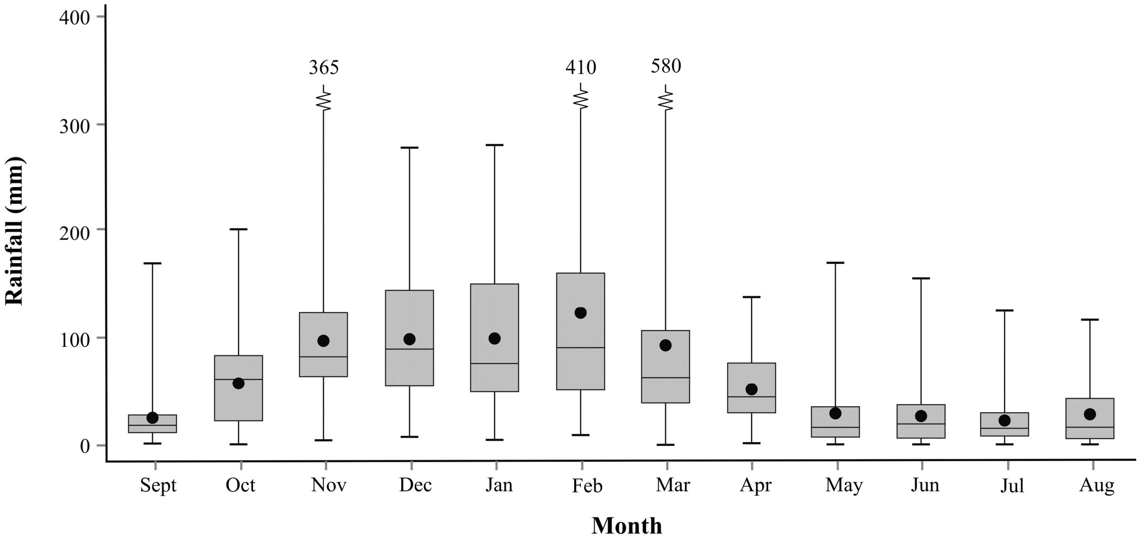


Figure A3.0.3*:* Average, minimum and maximum (box-and-whisker plots) rainfall over 23 years (Jan 1989 - March 2012) arranged according to the hydro-calendar (Sept-Aug) for the study area. The box is the range from first to third quartiles in which the rainfall values with the median (line in box) and average (dot in box); the whiskers are the minimum value and maximum values recorded. (Grundling et al., 2014).

A3.4.2.2 Evaporation

Evaporation is a major loss of water from the hydrological system that has a big impact on the water balance. It occurs from surface, unsaturated and saturated storage zones that are difficult to measure at catchment scales. Consequently, conceptual and numerical models of the evaporation process are a pragmatic approach to estimating the impact of evaporation processes on the water balance, hence groundwater storage. The model adopted for the evaporation process in this study is based on the UZF1 package described by Niswonger et al. (2006). The UZF1 routine extracts the evaporation component from the unsaturated zone above the extinction depth (rooting depth) of the vegetation. If the evaporative losses are less than the atmospheric demand then evaporation continues from the saturated zone whenever groundwater is within the rooting zone (extinction depth). This model requires the spatial distribution of land-cover type to define the rooting depth and evaporative demand. The land-cover types for the study area are shown in Figure A3.1C.

Evaporation measurement by Clulow et al. (2012) on the Maputaland Coastal Plain have established some baseline rates for different vegetation types that are typical of the study area. Clulow et al. (2012) recorded daily total evaporation rates for five common natural vegetation groups (Table A3.1) south of the study area at St. Lucia. Their studies indicated that only the Swamp Forest average ET values came close to meeting the atmospheric demand. In others studies, Clulow et al. (2011) measured evaporation from commercial forests in the riparian zone (i.e. shallow water-table conditions) and determined that the annual evaporation rate of 2.5 mm/day was 75% of the FAO 56 reference evaporation (Allen et al., 1998) and 94.5% of the annual rainfall. These values have guided the initial parametrisation of the evaporation model.

Table A3.1: Daily average total evaporation (mm) for St Lucia (adapted from Clulow et al., 2011), including the crop reference evaporation using the FAO 56 method (Allen et al. 1998).

Period	**Swamp Forest**	**Fen**	**Sedge**	**Dry Grass**	**Dune Forest**
August 2009	2.7	1.1	0.9	0.3	
November 2009	3.8	2.2	1.8	1.9	1.2
March 2010	4.5	2.0	2.8	2.0	1.3
Reference ET	4.5	4.5	4.5	4.5	4.5
% reference ET	81.5	39.3	40.7	31.1	27.8

A3.4.2.3 Drainage lines (discharge boundaries)

There are two main types of drainage boundaries that need to be considered. The vertical processes driven by rainfall and evaporation that occur over the entire surface domain of the region and those lateral fluxes that involve the flow of water down a hydraulic gradient to the lowest energy source which is generally taken as mean sea level (MSL) because of its consistent water level.

The lateral boundaries are formed by groundwater seepage through valley bottoms into streams and rivers. These are characterised by a range of flow rates and residence time that are generally one or more orders of magnitude greater, than the groundwater flow rates. In the model domain there are many different types of drainage boundaries that need to be identified and their physical features realistically determined. An error in specifying the elevation of a drainage boundary will be directly transferred to the derivation of the water-table profile. Since the water-table profile is determined by the surrounding drainage boundary features (such as stream bed elevation), it is essential to define the external (outer) drainage boundaries that will completely determine the groundwater profile for the area of concern. Internal drainage boundaries will then influence the local variation in the regional groundwater profile. The main focus area of this study was the region between the Kosi Lakes and Tembe Elephant Reserve. The groundwater profile in this area is strongly influenced by the fluctuation of water levels in the Kosi Lakes and the Muzi river/swamp drainage network. While one can assume with some confidence the water level in the Kosi Lakes, it is not possible to do the same for the swamps. Consequently, both of these boundaries were simulated as internal boundaries by extending the model domain to include distant boundaries that could be more accurately defined. This includes the Indian Ocean on the east and the Pongola/Maputo Rivers in the west as the external boundaries. The model domain to the west of the Pongola River has no influence on the model simulations. The northern and southern domain boundaries are assumed to be zero flux (*Neumann* type) boundaries, since the primary hydraulic gradients along these external boundaries are perpendicular to the coast.

Advanced studies of certain boundaries such as lakes will require much more complex conceptual and numerical models that have to account for the mass balance involving all sources and sinks. The lakes have been incorporated into the model using the LAK3 package of Merritt and Konikow (2000). This model requires, amongst other fluxes, the stream flow into and out of the lakes which was simulated using the SFR1 package of Prudic et al. (2004).

A3.4.2.4 Numerical modelling

The numerical model configuration was based on the conceptual model described above and comprises mathematical functions with numerous parameters to regulate the various processes depicting the hydrodynamics of the groundwater. The initial specification of all these parameters was derived mostly from other studies of the coastal environment in the region (Kelbe, 2009, Kelbe and Germishuyse, 2010, Været,et al. 2009, Kelbe et al, 2013). However the final estimates of important parameters were derived from calibration techniques of the identified sensitive parameters.

The calibration process systematically changed the model parameters to achieve the best agreement between the measured and predicted values of model variables. For the groundwater storage, the calibration was based on measurements for the water levels in the monitoring wells shown in Figure A3.2A and A3.2B. The hydraulic properties were derived using the Model-Independent Parameter Estimation (PEST) techniques developed by Doherty et al. (2010). However, before applying PEST an attempt to calibrate the recharge rate to the aquifer was conducted by systematically adjusting the recharge rates (interception and infiltration) to achieve an acceptable balance with the discharge rates and change in storage of the groundwater (as measured by the water-table elevation). The discharge from the aquifer is through the land surface (evaporation) and seepage along the drainage lines forming the streams and lake shorelines. These discharge rates are calculated by the model and should be validated against measured flow rates where possible. However, no runoff measurements have been recorded for any of the streams in the study area so it was not possible to calibrate the recharge using direct runoff measurements. Nevertheless, the lake model requires the stream flow into and out of the lake to balance all the other fluxes and change in storage. There is no known abstraction from these lakes so it is assumed that the change in storage is due to the natural fluxes comprising rainfall, evaporation, runoff and groundwater seepage. The rainfall and evaporation rates are taken from local station records. Lake water level measurements (change in volume) have been recorded by the national Department of Water Affairs at sub-hourly rates for the simulation period. It is assumed that good agreement between the simulated and measured lake water storage (±0.25m) signifies reasonable rates of inflow and outflow from the stream and groundwater. These discharge rates from the system must be in balance with the recharge rate to the regional aquifer if the change in water-table (groundwater storage) is close to the measured water-table.

The high correlation between the simulated and measured lake water levels and the groundwater profile (Figure A3.4) are considered to provide the best estimates of the water balance of the system and adequately represent the hydrodynamics of the aquifer for the evaluation of the spatial and temporal changes in the depth to the water-table for this study. Consequently, these calibrated model predictions have been used to evaluate the effectiveness of the model in defining the wetland type and distribution for the study area. The accuracy of the evaluation rests on the reliability of the topographical surface (DEM).

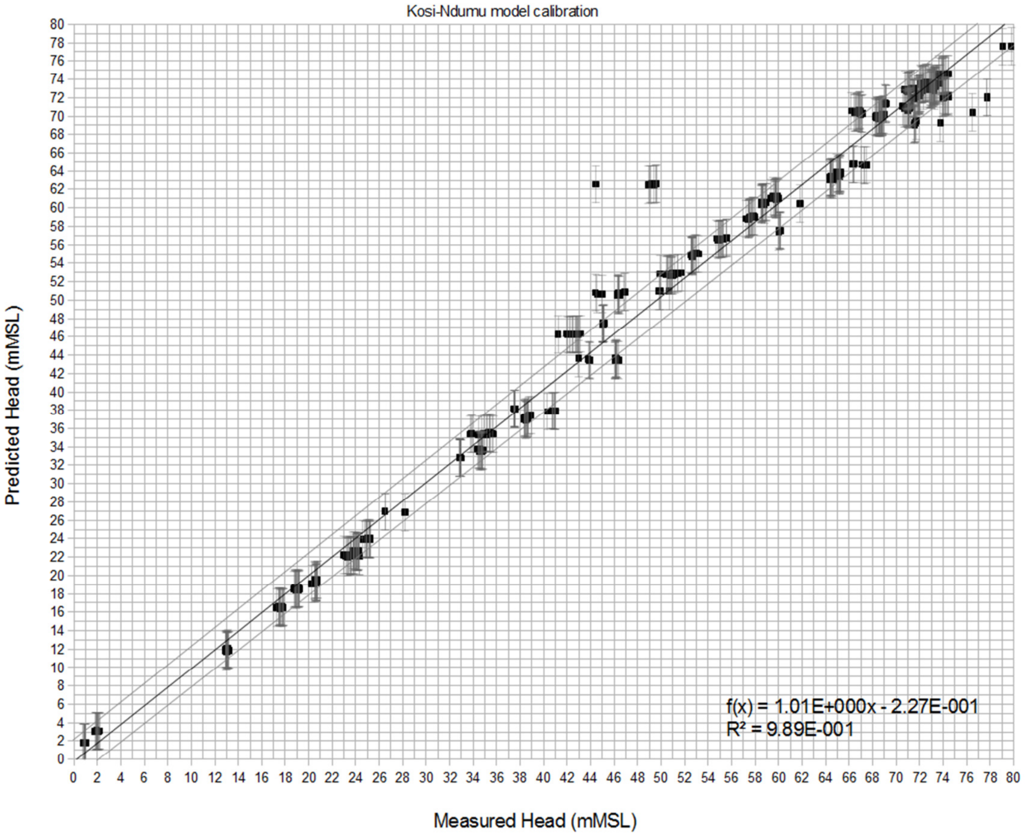


Figure A3.0.4*:* Model generated head predictions (2000-2012) plotted against measured heads. The error bars represent 2m range for the measured values. Least squares fit gives an r2=0.99 and a gradient of 1.01.

A3.4.2.5 Topographic Elevation Profile (Digital Elevation Model)

Wetlands will form when the water-table elevation is within the rooting zone of the wetland vegetation. Consequently it is necessary to establish those locations or sites where the depth to the water-table is suitable for the development of the wetlands. To establish the depth to the fluctuating water-table it is necessary to derive the topographical surface elevation profiles. The model predictions of the water-table profile have been described above and are considered to be accurate to within ±2 m of the actual water-table. Topographical elevation based on freely available SRTM data (Farr et al, 2007; Hirt et al, 2010) for an area near St Lucia (50 km to the south of Kosi Bay) was found to have vertical errors at pixel resolutions (90 by 90 m) that can exceed 10 m for those areas with tall dense forests but generally within 2 m for areas with short vegetation or bare soil (Kelbe and Taylor, 2011). Consequently an alternate source was located. Five meter elevation contours acquired for the study area excluding the section in Mozambique (NGI, 2013) were used to gnerate the Digital Elevation Model (DEM). It is assumed that these contours will provide a DEM with a vertical accuracy of ±1 m for the whole study area.

A3.5 RESULTS AND ANALYSIS

This study has adopted the concept that the depth to the water-table is the main criteria for the development and sustainability of wetlands of various forms. Consequently, the model evaluation is based on an assessment of the correspondence between the spatial distribution of the classified wetland types derived by (Grundling et al., 2013a) and the spatial distribution of the proposed minimum water-table depth that will support the main wetland types in the coastal aquifer.

The mean depth to the water-table for the simulation period from January 2000 to December 2010 is shown in Figure A3.5 for locations where the water-table was no deeper than 2 m below ground surface, where permanent or semi-permanent wetlands were expected (Grundling et al., 2013a). The model shows specific regions of the study area along drainage boundaries with shallow water-table that is likely to be supportive of wetland vegetation. The distribution of these simulated wet areas compares favourably in many areas to the wetlands classified by Grundling et al. (2013) in an assessment of the model's predictive capabilities. Generally the 2 m contours of the depth to the water-table show the expected close correspondence with the wetlands in the low lying river courses in the Muzi system along the Tembe Elephant Park boundary and to the south of Lake KuHlange (Figure A3.5). As expected, the water-table fluctuation are very small (standard deviation <0.1 m) near the streams and lakes due to the static nature of these discharge boundaries (Figure A3.6). However, there are large fluctuations of >1 m standard deviation in the aquifer between these drainage boundaries that imply changing water levels of >2 m during the simulation period. If the type and form of the wetlands is controlled by the fluctuation in the water-table then these areas are likely to have different types of wetlands (i.e. more transient). The zones of high variability are associated with the areas for which low hydraulic conductivity values were derived in the model calibration. While many of these zones are close to monitoring points the localised zone of high fluctuation directly west of Lake KuHlange may be an artifact of the calibration process where there are no monitoring points.

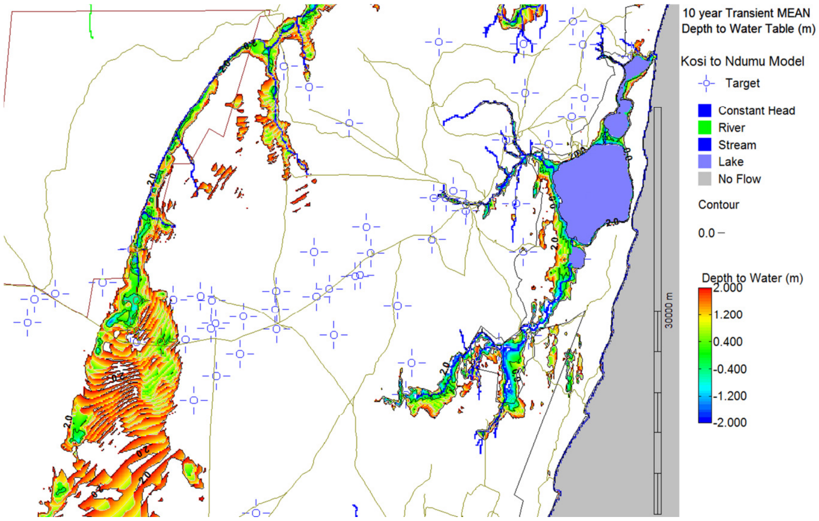


Figure A3.0.5: The 11-year mean simulated depth to the regional water-table for areas when it was <2 m. Contours units are meters below surface.

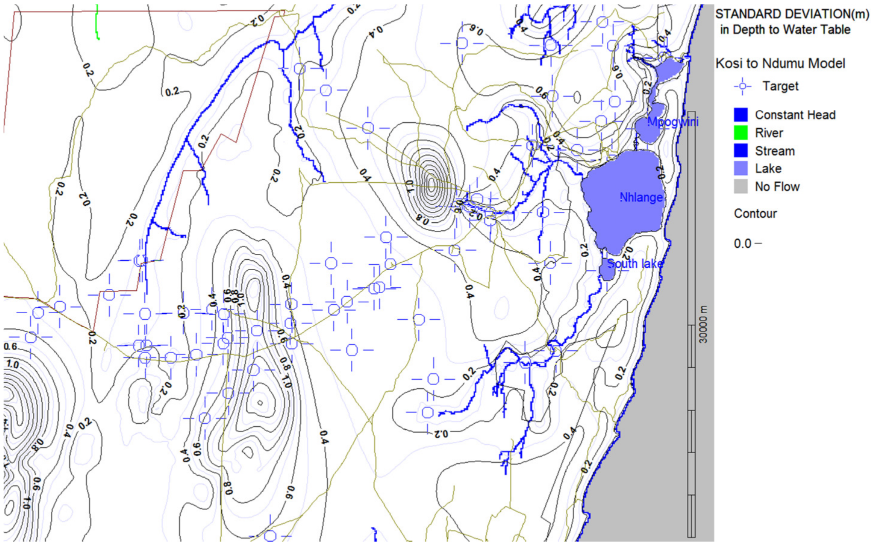


Figure A3.0.6: The Standard Deviation of the simulated depth to the Water-table (mBGL). The standard deviation is closely aligned to the derived hydraulic properties of the regional aquifer.

The minimum and maximum water-table profile for the simulation period (2000-2010) was extracted from the simulation series and used to compare the wetland distribution under dry and wet conditions (Figure A3.7 and A3.8). Figure A3.7 shows the predicted areas where the water-table is shallower than 2 m below ground surface for this dry period. This minimum water-table profile is assumed to represent the spatial distribution of suitable hydrological conditions for the continued existence of wetlands of various types under prolonged dry hydrological conditions. During these periods temporary wetlands become dry and some permanent wetlands become reduced in size (Grundling et al., 2013a). The model indicates greatly reduced areas favourable for wetlands along the Muzi valley and in the vicinity of the Kosi Bay Lakes. In the upland plateau between the Muzi and Kosi Bay Lakes drainage systems the model shows very few areas where the regional water-table is higher than 2 m below the surface, implying the area is generally unfavourable for permanent wetlands linked directly to the regional groundwater.

The simulated depth to the water-table for the wet period (Figure A3.8) shows the area with shallow groundwater (<2 m depth) has greatly expanded and covers large areas of the upland between the Muzi and Kosi Bay lake systems. These represent areas more favourable for wetlands, thus are likely locations for the development of temporary wetlands.

To evaluate these model predictions of the areas favourable for wetlands, as defined by the 2 m contour of the depth to the water-table, comparisons were made with the classified wetland areas for the two periods identified as wet and dry by Grundling et al. (2013). The simulated 2 m contour of the depth to the water-table was overlaid on the classified wetland types (Grundling et al., 2013a) for 2008 (Figure A3.7) and 2000 (Figure A3.8). The model identified most of the wetlands within the river valleys but the 2 m contour did not extend to the extensive area between Tembe Elephant Park and the Kosi Bay catchments where a predominance of temporary wetland had been classified. The selection of a 3 m depth may have included these regions. The simulated and mapped wetlands for a dry season are shown in Figure A3.7. The model does capture the general outline of the wetlands in the vicinity of the Muzi and Kosi Bay systems but shows no indication of suitable hydrological conditions for the formation of wetlands in the upland between these two drainage systems.

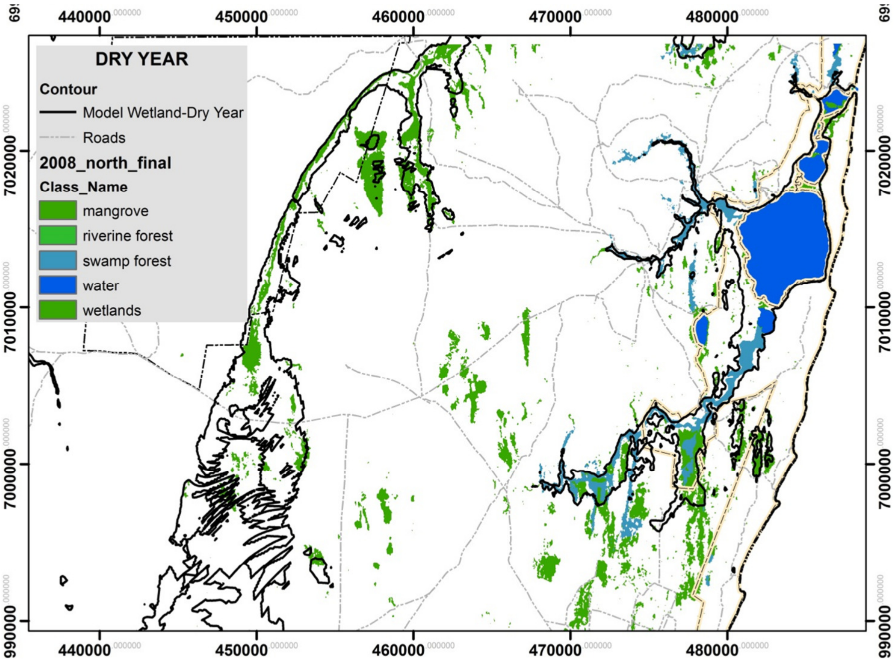


Figure A3.0.7*:* The classified wetland distribution during a dry period for 2008. Superimposed on these images is the predicted 2 m depth to the water-table contour for corresponding dry conditions (i.e. the maximum depth to the regional water-table during the 11-year simulation period from 2000 to 2010).

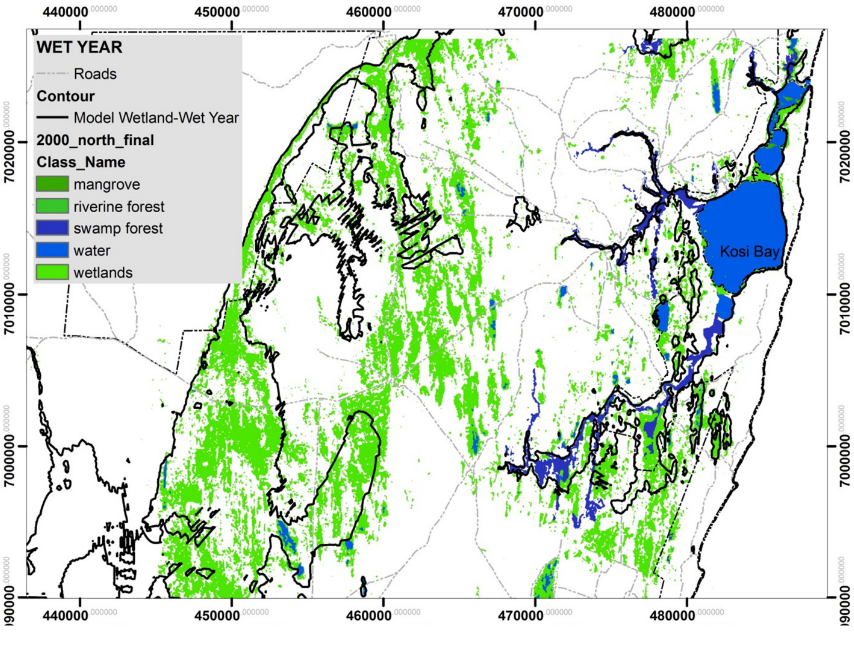


Figure A3.0.8*:* The classified wetland distribution during a wet period (2000). Superimposed on these images are the predicted 2 m depth to the water-table contour for corresponding wet conditions (i.e. the minimum depth to the regional water-table during the 11-year simulation period from 2000 to 2010).

Further examination of the wetlands located in the study area show clear relation to the topographic features and clay content (Figure A3.9). The clay occurrence map (Van den Berg et al., 2009) is shown in Figure A3.9.A and indicates the weathered clay-enriched soil found in soil profiles, which corresponds well with the wetlands mapped in Figure A3.1B (Figure A3.9B). Grundling et al., (2014) compared the clay occurrence with wetland distribution and indicates that ~49 % of permanent wetlands in the study area are associated with areas >16% clay content. In contrast, ~63% of wetlands occur on soil with <5% clay, and correspond with the distribution of temporary wetlands (Grundling et al., 2014).

It is concluded that most temporary wetlands (those that fall within the 2 m water-table depth during the wet period; Figure A3.8) are linked to the regional water-table, generally being associated with low % clay occurrence. At some temporary wetlands, notably those that occur in the central upland plateau outside the 2 m water-table depth contour), it is likely that lower hydraulic conductivity caused by higher clay content, buried ferricrete or paleo-peat layers contribute to a prolonged hydroperiod (Grundling et al., 2014). In wet years with prolonged wet periods these wetlands could also be connected to the regional water-table. As the regional water-table subsides, perched water apparently persists on lenses of fine-grained sediments in the soil profile. More hydrological detail is needed to substantiate this.

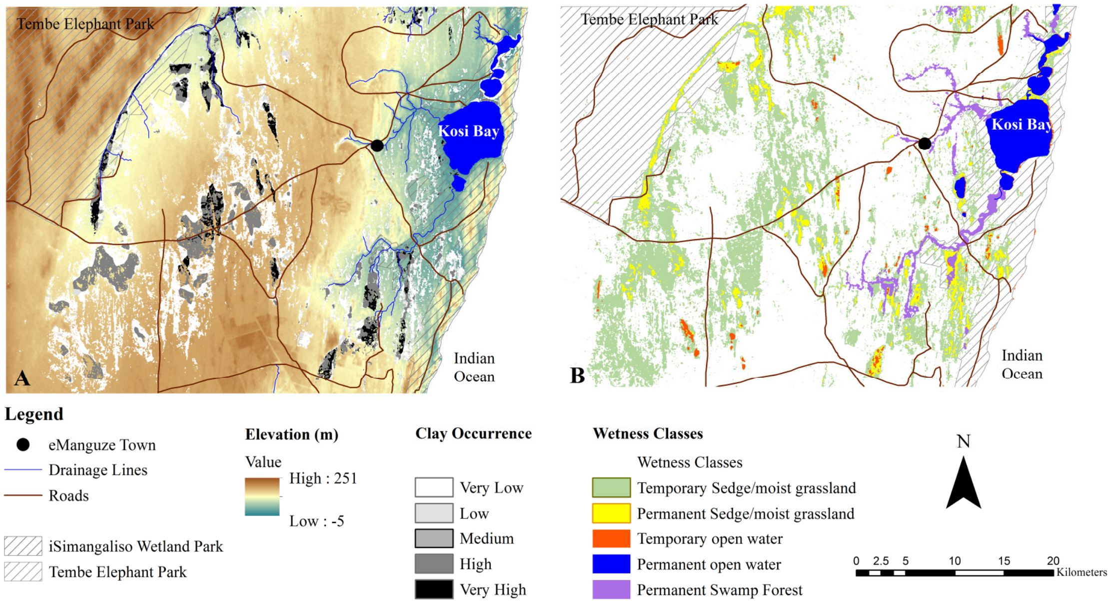


Figure A3.0.9*:* Clay occurrence (A) and the wetland distribution (B) for the area between the Muzi and Kosi Bay drainage systems (Grundling, 2014).

A3.6 DISCUSSION AND CONCLUSIONS

This study examines the use of a numerical groundwater model to predict the water-table conditions in the north-eastern Maputaland Coastal Plain, under wet and dry conditions, to improve our understanding of the relation between water-table and the spatial distribution of wetlands and their temporal behaviour. The simulated water-table profile is considered alongside previously identified temporary and permanent wetland and open water areas to provide a more comprehensive understanding of the groundwater-dependent ecosystem.

Water-table conditions under dry climatic conditions (2008) showed a strong correspondence between areas with water-table shallower than 2 m below ground surface and permanent wetlands (Figure A3.7) previously identified (Grundling et al., 2013a). These areas were strongly associated with Muzi River and Kosi Bay Lakes fluvial systems, where a high and steady regional water-table dominates (Grundling et al., 2014). These wetlands typically contain peat, which indicates they remain in a state of sustained saturation (Grundling et al., 2013b; Grundling et al., 2014). The model was also used to predict water-table depth less than or equal to 2 m below the surface during a wet period (2000). The area encompassed by the 2 m water-table depth contour was considerably larger than that simulated for the dry period, extending into the upland zone that primarily supports temporary wetlands (Grundling, et al. 2013a). However, the zone of temporary wetlands extended well beyond the 2 m water-table depth contour, in an area where the surficial deposits are from the lower permeability sediments of the Kosi Formation, and previously shown to be an area of gently undulating landforms with extensive flat-bottomed features on the upland areas, many of which have soils with a high clay content (Grundling et al., 2014). The deeper regional water-table associated with these areas suggest that wetland processes rely on transient perched conditions that occur during wet seasons and especially during wet years (Grundling, et al. 2013). To capture the zone of temporary, perched wetlands, a more sophisticated saturated-unsaturated modelling approach would be required, along with representation of the layered heterogeneity of soils associated with the different formations and soil types that occur. Nevertheless, the groundwater simulations done here highlight the temporary wetlands that are most likely disconnected to the regional water-table, and thus more susceptible to climatic, and perhaps anthropogenic stressors.

Hydrological model contain inherent uncertainties and weaknesses. Schultz (2013) considers that the projections of hydrological models, as numerical abstractions of the complex systems they seek to represent, suffer from epistemic uncertainty due to approximation errors in the model, incomplete knowledge of the system, and in more extreme cases, flawed underlying theories. Faulty data (e.g. biases water-table data or the inaccuracies of the DEM) used for calibration or validation can also be problematic. However, where the model is used as a simple tool for defining the water-table profile of an area where sufficient hydrological and geological information is incorporated, the level of uncertainty can be acceptably low. While the model in this study has been used solely to predict the water-table profile it is well recognised that the model parameter set is not unique, and there is a high likelihood that other sets of parameters will provide equally good representation of the water-table profile. Therefore, no attempt has been made to validate the model hydrodynamics, which would require a priori knowledge of transient processes. Consequently, the main concern with the model is the accuracy of the water-table prediction compared to measured values (Figure A3.4) and the suitability of extrapolation to areas with little or no monitoring. Here, kriging functions were used to extrapolate hydraulic properties so that model predictions of water-table could be made in areas where no measurement are available. The relative vertical accuracy of the elevation data is up to 1 m, which adds uncertainty in the evaluation of shallow water-table depths below the surface. However, the elevation at each of the *in situ* water-table monitoring sites was measured with a Differential Geographical Positioning System with accuracy 3-6 mm (Grundling et al., 2014), and water-table measurements within +/- 1 cm. We believe the numerical methods used to estimate the water-table profile in this shallow unconfined aquifer had acceptable accuracy for the purpose of delineating zones where the permanence of wetlands can be explained.

A3.7 ACKNOWLEDGEMENT

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A4. APPENDIX 4: HYDROGEOMORPHIC UNIT ACCURACY ASSESSMENT

Hydrogeomorphic comparison results between verified sites with the semi-automated hydrogeomorphic classification in this study and the automated NFEPA Wetland Ecosystem type classes also based on hydrogeomorphic approach.

No	Name	LANDSCAPE SETTING	VERIFIED HGM SITES	HGM UNIT MAP (Figure 4.5)	NFEPA Wetland Ecosystem Types	ELEVATION	HGM MAP	NFEPA MAP
1	Z003	Valley Floor	Unchannelled VB	Unchannelled Valley-bottom	Channelled Valley-bottom	43	1	0
2	Z004	Valley Floor	Depression	Unchannelled Valley-bottom	Unchannelled Valley-bottom	53	0	0
3	Z007	Valley Floor	Unchannelled VB	Unchannelled Valley-bottom	Not Mapped	56	1	0
4	Z008	Valley Floor	Unchannelled VB	Unchannelled Valley-bottom	Valleyhead Seep	55	1	0
5	Z009	Slope	Seep	Seep	Not Mapped	62	1	0
6	Z011	Plain Upland	Depression	Not Mapped	Unchannelled Valley-bottom	61	0	0
7	Z017B	Plain Upland	Depression	Depression	Seep	74	1	0
8	Z018B	Plain Upland	Depression	Depressions	Flat	75	1	1
9	Z020	Plain Upland	Depression	Depression	Seep	75	1	0
10	Z022	Plain Upland	Depression	Depression	Seep	73	1	0
11	Z023	Plain Upland	Depression	Depression	Seep	74	1	0
12	Z024	Plain Upland	Depression	Depression	Flat	75	1	1
13	Z025	Plain Upland	Depression	Depression	Seep	74	1	0
14	Z026	Plain Upland	Depression	Depression	Not Mapped	74	1	0
15	Z027	Plain Upland	Depression	Depression	Seep	70	1	0
16	Z032	Plain Upland	Depression	Depression	Depression	73	1	1
17	Z034A	Plain Upland	Depression	Depression	Seep	72	1	0
18	Z035	Slope	Depression	Depression	Depression	63	1	1
19	Z036B	Slope	Depression	Depression	Seep	49	1	1
20	Z037	Valley Floor	Unchannelled Valley-bottom	Unchannelled Valley-bottom	Unchannelled Valley-bottom	37	1	1
21	Z038	Valley Floor	Channelled Valley-bottom	Channelled Valley-bottom	Channelled Valley-bottom	33	1	1
22	Z039	Valley Floor	Channelled Valley-bottom	Channelled Valley-Bottom	Channelled Valley-bottom	38	1	1
23	Z040	Valley Floor	Channelled Valley-bottom	Unchannelled Valley-bottom	Not Mapped	45	0	0

24	Z042	Plain Lowland	Depression	Depression	Flat	25	1	1
25	Z043	Valley Floor	Channelled Valley-bottom	Channelled Valley-bottom	Channelled Valley-bottom	21	1	1
26	Z044	Valley Floor	Channelled Valley-bottom	Channelled Valley-bottom	Channelled Valley-bottom	25	1	1
27	Z045	Valley Floor	Unchannelled Valley-bottom	Unchannelled Valley-bottom	Unchannelled Valley-bottom	13	1	1
28	Z046	Plain Lowland	Depression	Depression	Unchannelled Valley-bottom	39	1	0
29	Z047	Valley Floor	Unchannelled Valley-bottom	Unchannelled Valley-bottom	Channelled Valley-bottom	40	1	0
30	Z048	Plain Lowland	Depression	Unchannelled Valley-bottom	Unchannelled Valley-bottom	28	0	0
31	Z049	Plain Lowland	Depression	Depression	Flat	27	1	1
32	Z051	Slope	Seep	Not Mapped	Not Mapped	19	0	0
33	Z053	Slope	Seep	Channelled Valley-bottom	Not Mapped	2	0	0
34	Z054	Valley Floor	Channelled Valley-bottom	Channelled Valley-bottom	Not Mapped	1	1	0
35	Z056	Plain Upland	Depression	Not Mapped	Not Mapped	62	0	0
36	Z057	Plain Upland	Depression	Depression	Flat	65	1	1
37	Z058	Valley Floor	Unchannelled Valley-bottom	Unchannelled Valley-bottom	Flat	53	1	0
38	Z062	Plain Lowland	Depression	Unchannelled Valley-bottom	Not Mapped	45	0	0
39	Z063	Valley Floor	Floodplain	Floodplain	Floodplain	10	1	1
40	Z064	Valley Floor	Channelled Valley-bottom	Channelled Valley-bottom	Channelled Valley-bottom	15	1	1
41	Z065	Plain Upland	Depression	Depression	Seep	82	1	0
42	Z067	Valley Floor	Channelled Valley-bottom	Channelled Valley-bottom	Channelled Valley-bottom	50	1	1
				3 Not Mapped	9 Not Mapped		**34**	**17**
							81%	**40%**

A5. APPENDIX 5: SOIL ORGANIC CARBON AND HYDROPERIOD

Paper to be submitted as
Grundling, A.T., Pretorius, M.L. and Grundling P. Association between Soil Organic Carbon and Hydroperiod in wetlands, Lake St. Lucia's Eastern Shores, KwaZulu-Natal, South Africa.

A5.1 INTRODUCTION

The delineation of wetlands on sandy coastal aquifers is problematic due 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 in mineral soil: >4% SOC and in permanent and/or seasonal zone of wetness typically peaty character >10% in topsoils (at least 200 mm thick).

Anaerobic conditions (not having molecular oxygen (O_2) present) are typically found in wetlands with an extended hydroperiod (Kotze, 2000) favouring the decomposition and accumulation of organic matter in the soil profile. The decomposition rate is strongly influenced by water-table depth (Hilbert et al., 2000) and water-table fluctuation (Belyea and Clymo, 2001), and therefore SOC will increase with an increase in soil water (Brady and Weil, 2007). Carbon pools are consequently expected to be greater in the permanent wetland zones than in the seasonal/temporary zones (Bernal and Mitsch, 2008). 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; Adhikari et al., 2009). During dry periods a considerable portion of the carbon that would have been retained in the saturated soil is oxidised. Carbon fluxes and pools also vary in different wetlands types (Adhikari et al., 2009). For, example, the Eastern Shores in the iSimangaliso Wetland Park, South Africa, hosts a variety of wetlands including estuaries, tidal flats, lakes , fens, marshes and swamp forest, but with only the groundwater dependant wetlands (fens and peat swamp forests) hosting significant carbon pools (Grundling, 2011). Clearly not all wetland types accumulate peat.

Hydroperiod (the degree, duration and level/extent of inundation and/or saturation) results in specific structural and functional attributes for different wetland types. Generally, it is not valid to equate the measurement of groundwater levels (i.e. depth to water-table) with the hydroperiod. Such a relation 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 outflow by evapotranspiration with (Clulow et al., 2012; 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. SOC associated with hydroperiod can help with the delineation of a wetland if the wetland has a clear boundary on predominantly deep sandy soils that have species not exclusive to the type of wetland. However, except for two other WRC projects including the Mfabeni mire and seasonal inundated grassland no monitoring has been done in terms of water-table levels in different wetlands types on the Eastern Shores and the effect of the prolong dry period (2002-2013) are unknown.

The main aim of the WRC project K5/1923 funded 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 (Grundling et al., 2014). The primary focus of the study was based on the three main themes of mapping, classifying and characterising the different wetland types (Grundling et al., 2014). The relation between SOC and hydroperiod complement the main objectives to map the distribution of wetlands in wet and dry years classify wetlands using the hydrogeomorphic classification; to characterise the relation between rainfall, topography and water-table depth. This research project formed the basis of this PhD thesis and included an MSc study (Pretorius, 2011), also contributing to an in-depth PhD investigation of SOC and hydroperiod interaction on the on the Maputaland Coastal Plain (Pretorius, *in progress*). The aim of this paper was to define the relation between SOC and hydroperiod in different wetness zones of wetlands on the Eastern Shores of Lake St. Lucia.

A5.2 STUDY AREA

The study area is located on the Eastern Shores of Lake St. Lucia within the iSimangaliso Wetland Park. The 2.15 km transect stretch across the south-western point of the Mfabeni mire system (Figure A5.1) (WRC project K5/1857), supplementing hydrological studies of the Mfabeni Mire system. The transect includes wetlands that occur on an undulating plain with a central drainage line and a swamp forest. Six wetlands were selected 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: elevation, groundwater-table level, soil form, % SOC and vegetation description.

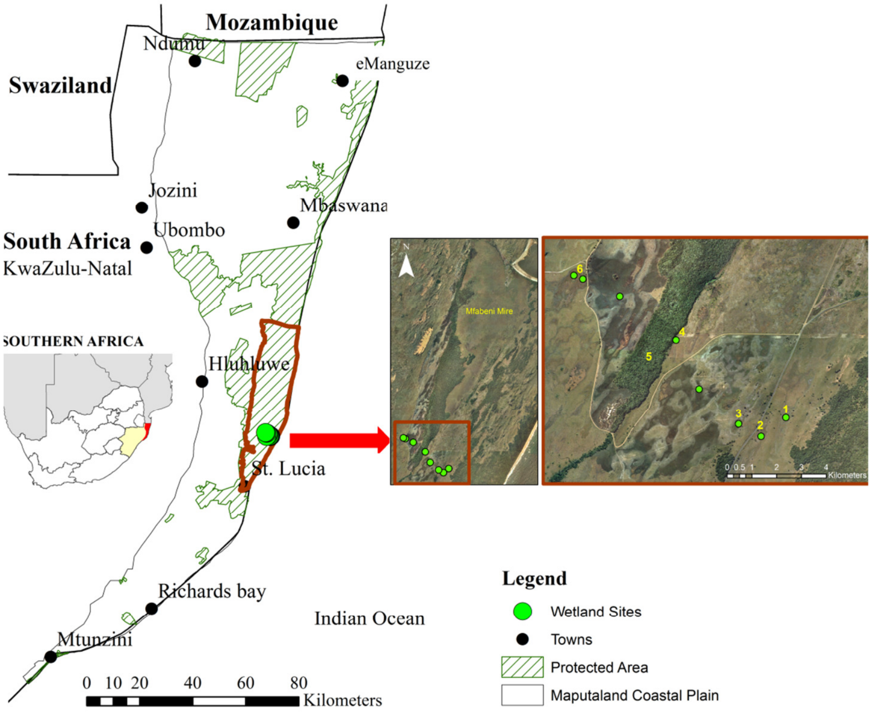

Figure A5.0.1: Groundwater monitoring sites in six wetlands on the Eastern Shores (green points).

A5.3 METHODOLOGY

A5.3.1 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 A5.1). 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).

A5.3.2 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. Each well was protected with a steel pipe against veld fires, and marked with a numbered plate. Bi-weekly readings were taken between the period June 2010 to February 2011 and January to March 2012. The Solinst water-level meter was used to take the groundwater measurements.

A5.3.3 Soil Investigations and Percentage Soil Organic Carbon

Soil samples were collected in at each site where soil profile pits 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 was determined using the dry combustion (Total C) method (The Non-Affiliated Soil Analysis Work Committee, 1990). The Total C and Walkley-Black methods have been shown to have a 1:1 relation (Grundling et al., 2010). Statistical analyses for the SOC data were done using MS Excel 2007.

A5.3.4 Vegetation Descriptions

Vegetation surveys were conducted by Dr. Erwin Sieben on 1-5 November 2010 using the South African Wetland Vegetation Survey - Field Data form (Sieben, 2010). The vegetation and environmental data from the survey datasheets was imported into Turboveg (Hennekens and Schaminée (2001) to classify the plant communities where after further classification analysis was done using PC-ord (McCune and Mefford, 2011) and Juice (Tichy, 2002). These data sets were also imported into the National Wetland Vegetation Database for South Africa (Sieben, 2014).

A5.4 RESULTS

Table A5.1 list the result summary % SOC, Average water-table depth, hydroperiod (months of the year the wetland were saturated) and soil form (Detailed list in Table 2 at the end). For example 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 A5.2). During dry months the water-table drops at least 1 m. 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). The high SOC is probably due to the high and stable water-table for most of the year (Table A5.1 and Figure A5.3), which also explains the dominant wetland vegetation in zone 1 (15/I) (Table A5.2). However, animal trampling, oxidazes the peat, resulting in a decline of SOC as noted in September 2013 at the same wetland 3 site.


Photo A: 21 May 2008

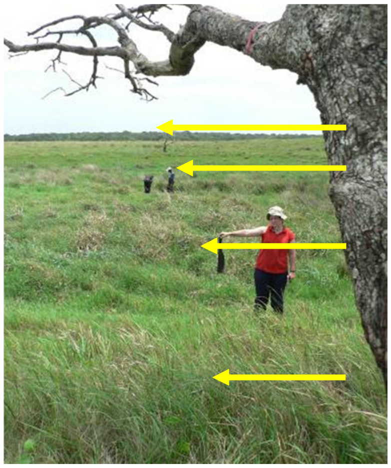

Photo B: 8 December 2009


Photo C: 2 November 2010


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

Figure A5.0.2: Wetland 3 vegetation and surface water during different months and years

Table A5.1: Soil Organic Carbon (SOC), average water-table depth, hydroperiod (months the wetlands were saturated) and soil form.

No	SOC (%)	Average Water-table Depth	Soil Form	Hydroperiod months
2/BB	0.06	3.78	Clovelly	0
3/A	0.89	2.54	Fernwood	0
4/CC	1.07	1.82	Fernwood	0
5/B	1.29	1.19	Fernwood	0.5
6/C	2.75	0.47	Kroonstad	8
8/D	1.67	2.02	Clovelly	0
9/E	1.3	1.47	Constantia	0.5
10/F	5.75	0.92	Katspruit	4
12/FF	0.32	2.25	Clovelly	0
13/G	1.52	1.53	Fernwood	0
14/H	3.07	0.88	Fernwood	3
15/I	**16.05**	**0.15**	**Champagne**	**13**
19/J	1.34	0.83	Kroonstad	0
20/K	2.58	0.53	Kroonstad	0
21/L	4.97	0.22	Champagne	3
22/M	5.45	0.15	Champagne	13
23/N	28.79	0.00	Champagne/Peat	20
25/O	4.56	0.28	Kroonstad	7
26/P	7.97	0.37	Champagne	13
27/Q	2.25	1.04	Fernwood	0
28/R	1.1	1.72	Fernwood	0

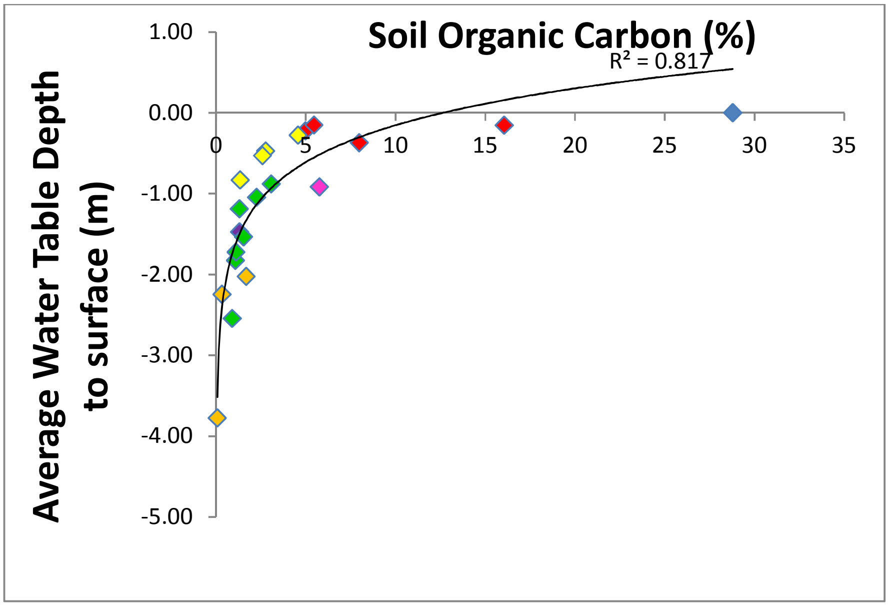

Figure A5.0.3: Relation between Soil Organic Carbon and Hydroperiod.

A5.5 DISCUSSION

The primary accumulation of SOC was correlated with the hydrological regime: higher organic production took place in lower-lying landscape positions (Figure A5.4). The % SOC content is directly linked to the period of inundation (hydroperiod) (Table A5.1 and Figure A5.3). In South Africa soil with 10% or more organic carbon is referred to as Champagne soil (Soil Classification Working Group, 1991) , while peat comprises at least 30% (dry mass) of dead organic matter (Joosten and Clark, 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 (Table A5.1). However, soils classified infield as Champagne soil 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 (Tables A5.1 and A5.2). The SOC profiles indicated no significant difference between the seasonally and temporarily saturated zones (Table A5.3), especially on the wetlands occurring on the higher elevations because of the large groundwater fluctuation (0-2 m) (Figure A5.4). In all the wetlands, average % SOC (0-200 mm soil depth) in the terrestrial zone is low (0.32-1.67%) in the topsoil (Tables A5.1 and A5.2).

A5.6 CONCLUSIONS

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.

A5.7 ACKNOWLEDGEMENT

The authors would like to thank the Water Research Commission for financial support. The iSimangaliso Wetland Park, Ezemvelo KZN Wildlife and the Tembe Tribal Authority are also thanked for additional project support and logistics in the study area. We also appreciate help with the vegetation survey by Dr. Erwin Sieben and Mr. Bikila Dullo and vegetation analysis by Me Miranda Deutschlander.

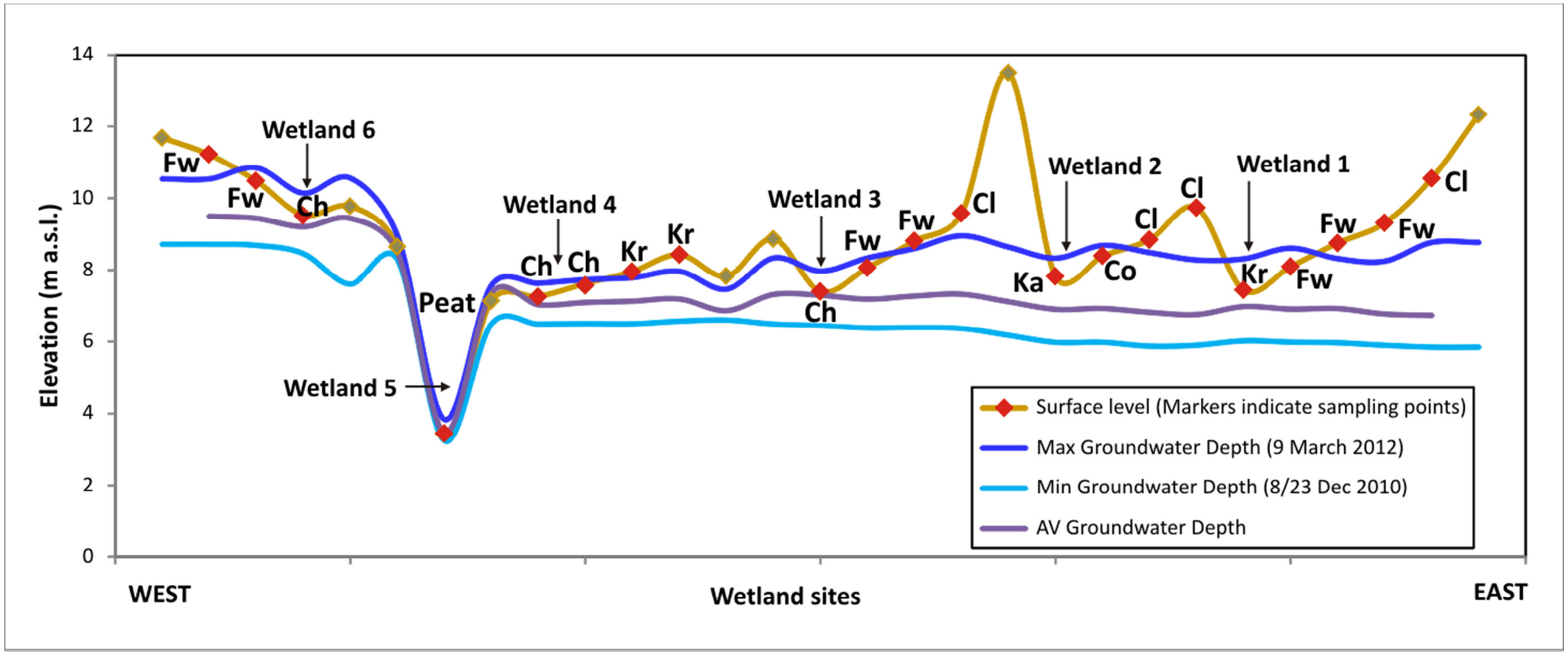

Figure A5.0.4: Groundwater profile and soil forms along the southern transect. Fw = Fernwood; Ch = Champagne; Kr = Kroonstad; Cl = Clovelly; Co = Constantia; Ka = Katspruit.

Table A5.2: 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*

Table A5.3: The phytosociological classification using the Turboveg, PC-ord and Juice methods.

Relevés number: 13	2/bb-3/a	4cc	5b	6c	7dd	8d	9e	10f	12ff	13g	14h	15l(1)	15l(2)
	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	1	1	1	1	0	0	0	0	0	0
Species	8	3	4	2	1	3	0	2	7	6	5	9	1
Stenotaphrum secundatum	.	.	4	.	.	.	.	.	.	.	.	.	.
Scleria poiformis	.	.	+	.	.	.	.	.	.	.	.	.	.
Pentodon pentandrus	.	.	+	.	.	.	.	.	.	.	.	.	.
Pycreus polystachyos	.	.	r	.	.	.	.	.	.	.	.	.	.
Fimbristylis bivalvis	.	.	+	.	.	.	.	.	.	.	.	.	.
Senecio species	.	.	+	.	.	.	.	.	.	.	.	.	.
Paspalum species	.	4	.	.	.	.	.	.	.	.	.	.	.
Alectra species	.	r	.	.	.	.	.	.	.	.	.	.	.
Setaria sphacelata	.	+	.	.	.	.	.	.	.	.	.	.	.
Lobelia anceps	r	.	.	.	.	.	.	.	.	.	.	.	.
Eragrostis sclerantha	.	.	.	.	+	.	.	.	.	.	.	.	.
Pycreus nitidus	.	.	.	.	+	.	.	.	.	.	.	.	.
Leersia hexandra	.	.	.	1	.	+	.	.	.	.	.	.	.
Cyperus fastigiatus	.	.	.	2	.	4	.	.	.	.	.	.	.
Eleocharis limosa	.	.	.	3	.	+	.	.	.	.	.	.	.
Cynodon hirsutus	.	.	.	2	.	.	.	.	.	.	.	.	.
Cyperus sensilis	.	.	.	2	.	.	.	.	.	.	.	.	.
Cyperus sphaerospermus	.	.	2	+	r	r	.	.	.	.	.	.	.
Paspalum vaginatum	2	.	.	.	3	.	.	.	.	.	.	.	.
Rhus species	.	.	.	.	.	.	+	.	.	.	.	.	.
Senecio erubescens	.	.	.	.	.	.	r	.	.	.	.	.	.
Senecio inornatus	.	.	.	.	.	.	+	.	.	.	.	.	.
Linum thunbergii	.	.	.	.	.	.	r	.	.	.	.	.	.
Commelina benghalensis	.	.	.	.	.	.	+	r	.	.	.	.	.
Aristida junciformis	.	.	.	.	.	.	.	1	.	.	.	.	.
Aspalathus chortophila	.	.	.	.	.	.	.	+	.	.	.	.	.
Abrus laevigatus	.	.	.	.	.	.	.	+	.	.	.	.	.
Syzygium cordatum	.	.	.	.	.	.	.	1	.	.	.	.	.
Eriosema species	.	.	.	.	+	.	+	.	.	.	.	.	.
Hydrocotyle bonariensis	.	.	.	.	2	+	1	.	.	.	.	.	.
Panicum glandulopaniculatu	+	.	+	3	1	.	2	.	.	.	.	.	.
Eriosema cordatum	.	.	.	.	.	.	.	.	.	1	.	.	.
Litogyne gariepina	.	.	.	.	.	.	.	.	.	r	.	.	.
Wahlenbergia species	.	.	.	.	.	.	.	.	.	+	.	.	.
Restio zuluensis	.	.	.	.	.	.	.	.	3	.	.	.	.
Xyris natalensis	.	.	.	.	.	.	.	.	1	.	.	.	.
Trachypogon spicatus	.	.	.	.	.	.	.	2	.	1	.	.	.
Sporobolus subtilis	.	.	.	.	.	.	.	3	3	4	.	.	.
Hemarthria altissima	2	+	2	.	.	.	2	.	1	.	.	.	.
Centella asiatica	4	4	2	.	2	.	2	+	r	.	.	.	.
Themeda triandra	.	.	.	.	.	.	.	.	.	.	.	.	2
Parinari capensis	.	.	.	.	.	.	.	.	.	.	.	1	2
Justicia protracta	.	.	.	.	.	.	.	.	.	.	.	r	+
Stylosanthes fruticosa	.	.	.	.	.	.	.	.	.	.	2	1	.
Rhynchospora barrosiana	.	.	.	.	.	.	.	.	.	.	+	.	+

Helichrysum kraussii	.	.	.	.	.	.	.	.	.	.	2	2	2
Aeschynomene species	.	.	.	.	.	.	.	.	.	.	1	+	1
Garcinia livingstonei	.	.	.	.	.	.	.	.	.	.	.	.	+
Rhynchospora species	.	.	.	.	.	.	.	.	.	.	.	.	1
Justicia anagalloides	.	.	.	.	.	.	.	.	.	.	.	.	+
Tinospora species	.	.	.	.	.	.	.	.	.	.	.	.	+
Ehrharta erecta	.	.	.	.	.	.	.	.	.	.	.	.	1
Tephrosia longipes	.	.	.	.	.	.	.	.	.	.	.	.	1
Achyranthes aspera	.	.	.	.	.	.	.	.	.	.	.	.	+
Acalypha villicaulis	.	.	.	.	.	.	.	.	.	.	.	.	1
Asparagus spinescens	.	.	.	.	.	.	.	.	.	.	.	.	+
Diospyros austro-africana	.	.	.	.	.	.	.	.	.	.	.	.	+
Cymbopogon plurinodis	.	.	.	.	.	.	.	.	.	.	.	.	1
Vernonia oligocephala	.	.	.	.	.	.	.	.	.	.	.	.	+
Mystroxylon aethiopicum	.	.	.	.	.	.	.	.	.	.	1	.	.
Urelytrum agropyroides	.	.	.	.	.	.	.	.	.	.	+	.	.
Achyranthes species	.	.	.	.	.	.	.	.	.	.	r	.	.
Aspidoglossum species	.	.	.	.	.	.	.	.	.	.	r	.	.
Acalypha caperonioides	.	.	.	.	.	.	.	.	.	.	r	.	.
Aristida species	.	.	.	.	.	.	.	.	.	.	2	.	.
Gazania krebsiana	.	.	.	.	.	.	.	.	.	.	1	.	.
Diospyros lycioides	.	.	.	.	.	.	.	.	.	.	1	.	.
Senecio coronatus	.	.	.	.	.	.	.	.	.	.	1	.	.
Pavonia burchellii	.	.	.	.	.	.	.	.	.	.	+	.	.
Ledebouria species	.	.	.	.	.	.	.	.	.	.	.	r	.
Protasparagus species	.	.	.	.	.	.	.	.	.	.	.	1	.
Justicia species	.	.	.	.	.	.	.	.	.	.	.	+	.
Agathisanthemum bojeri	.	.	.	.	.	.	.	.	.	.	.	r	.
Tristachya leucothrix	.	.	.	.	.	.	.	.	.	.	.	1	.
Thesium species	.	.	.	.	.	.	.	.	.	2	1	.	.
Phyllanthus maderaspatensi	.	.	.	.	.	.	.	.	.	r	+	.	.
Tephrosia capensis	.	.	.	.	.	.	.	.	.	+	+	.	.
Cyperus obtusiflorus	.	.	.	.	.	.	.	.	.	1	+	1	.
Pentanisia angustifolia	.	.	.	.	.	.	.	.	.	+	1	+	.
Helichrysum setosum	.	.	.	.	.	.	.	.	.	+	.	+	.
Schizachyrium sanguineum	.	.	.	.	.	.	.	.	+	2	.	.	2
Fimbristylis species	.	.	.	.	.	.	.	2	+	r	2	+	+
Ischaemum fasciculatum	.	.	.	.	.	.	1	2	2	1	2	.	1
Eugenia natalitia	.	.	.	.	.	.	r	.	.	.	.	1	.
Kyllinga erecta	.	.	.	.	.	.	+	.	.	.	+	1	.
Imperata cylindrica	.	.	.	.	r	.	2	1	.	2	1	1	.
Cyperus natalensis	.	.	.	.	+	.	2	+	.	1	.	r	+

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