Factors influencing wetland distribution and structure, including ecosystem function of ephemeral wetlands, in Nelson Mandela Bay Municipality (NMBM), South Africa

BY:

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PLAGIARISM DECLARATION

1. In accordance with Rule G4.6.3 at Nelson Mandela Metropolitan University, I, Brigitte Melly, hereby declare that this thesis, submitted in fulfilment of the requirements for the degree of ***Philosophiae Doctor***, is my own work, except where otherwise mentioned.

2. This work has not previously been submitted for assessment to another University or for another qualification.

3. This thesis does not contain other persons' data, pictures, graphs or other information unless specifically acknowledged as being sourced from other persons.

4. The field data obtained for this research was carried out under the auspices of a three-year project funded by the Water Research Commission (Report number: 2181/1/15) on "Ephemeral Wetlands of the Nelson Mandela Bay Metropolitan Area: Classification, Biodiversity and Management Implications" by Schael, Gama and Melly (2015). Certain text and maps may be similar to that found in the report; however, that which is found in this thesis is my own work.

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SUMMARY

The Nelson Mandela Bay Municipality (NMBM) is a semi-arid area along the southern coastline of South Africa (SA). Until recently, there was no systematic approach to research on wetland systems in the NMBM. The systematic identification of wetlands was made more difficult by the relatively large number of small, ephemeral systems that can be difficult to delineate. This has meant that fundamental knowledge on wetland distribution, structure and function has been limited and, consequently, management and conservation strategies have been based on knowledge on systems from other regions of the country.

Environmental processes occur at different spatial and temporal scales. These processes have an effect on the abiotic factors and biotic structure of wetlands, resulting in inherently complex systems. The location of the NMBM provides a good study area to research some of these environmental and biological attributes at different spatial scales, due to the variability in the underlying geology, geomorphology, vegetation types and the spatial and temporal variability in rainfall, within a relatively small area of 1951 km^2. Thus, the aim of this study was to determine the factors influencing wetland distribution, structure and ecosystem functioning within the NMBM.

The first Research Objective of work presented here was to identify wetlands using visual interpretation of aerial photographs. A total of 1712 wetlands were identified within the NMBM using aerial photographs, covering an area of 17.88 km^2 (Chapter 5). The majority of these wetlands were depressions, seeps and wetland flats. Valley bottom wetlands (channelled and unchannelled) and floodplain wetlands were also identified. A range of wetland sizes was recorded, with 86% of the wetlands being less than 1 ha in size and the largest natural wetland being a floodplain wetland of 57 ha, located south of the Swartkops River.

The identified wetlands were used to create a wetland occurrence model using logistic regression (LR) techniques (Chapter 5), in accordance with Objective 2 of the study. An accuracy of 66% was obtained, which was considered acceptable for a semi-arid climate with a relatively high degree of spatial and temporal rainfall variability. The model also highlighted several key environmental variables that are associated with wetland occurrence and distribution at various spatial scales. Some of the important variables included precipitation, evapotranspiration, temperature, flow accumulation and groundwater occurrence.

Wetland distribution patterns were described in Chapter 6. Spatial statistics were used to identify whether wetlands are clustered and, therefore, form mosaics within the surrounding landscape (Objective 3). Systems were found to be highly clustered, with 43% of wetlands

located within 200 m of another system. Clustering and wetland presence was especially prominent in the southern portion of the Municipality, which is also associated with a higher mean annual precipitation. Smaller wetlands were also significantly more clustered than larger systems (Average Nearest Neighbour statistic, p-value < 0.0001). Average distances also significantly varied according to HGM type, with depressions being the most geographically isolated wetland type compared to the other HGM types. Overall, distances between wetlands indicated good proximal connectivity.

Potentially vulnerable areas associated with wetland systems were identified successfully using landscape variables, in accordance with Objective 4. These variables were: land cover, slope gradient, flow accumulation, APAN evaporation, mean annual precipitation (MAP) and annual heat units. The existing Critical Biodiversity Network was also used in connection with these variables to further identify potentially vulnerable areas.

The abiotic and biotic characteristics were decribed for three hydrogeomorphic (HGM) types at a total of 46 wetland sites (Chapter 7), as per Objective 5. Depressions, seeps and wetland flats were sampled across the different geological, vegetation and rainfall zones within the NMBM. The wetland sites were delineated up to Level 6 of the Classification System used in SA, and the various abiotic and biotic characteristics of these systems were defined. A total of 307 plant, 144 aquatic macroinvertebrate and 10 tadpole species were identified. Of these species, over 90 species were Eastern Cape and SA endemic species, as well as three threatened species on the IUCN Red List. Multivariate analyses (including Bray-Curtis similarity resemblance analyses, distance-based redundancy analyses, SIMPER analyses and BIOENV analysis in Primer), together with environmental data, were used to define community structure at an HGM level, in accordance with Objective 5.

The importance of the spatial scale of the environmental data used to define plant and macroinvertebrate community structure was described in Chapter 7, to address Objective 6. The results showed that both broad-scale and site-level characteristics were important in distinguishing community structure within the HGM types that superseded general location, the sample timing or the stage of inundation. These results also indicated that a combination of both landscape and site-level data are important in defining the community structure in the various HGM types. Some of the important environmental variables that explained some of species assemblages were similar to those in the wetland occurrence model (Chapter 5), with some additional hydrological and soil physico-chemical parameters (e.g. soil electrical conductivity, soil pH, and surface and subsurface water nutrients). These significant variables indicate the complex, multi-scalar role of environmental attributes on wetland distribution, structure and function.

The final Objective (7) addressed management and conservation strategies for the NMBM. The NMBM wetland database that was produced during this research is currently being used by the Municipality and will be added to the latest National Wetland Map. From the database, and tools developed in this research, approximately 90 wetlands have been identified as being highly vulnerable due to anthropogenic and environmental factors (Chapter 6) and should be earmarked as key conservation priority areas. Based on field experience and data collected, this study has also made conservation and rehabilitation recommendations for eight locations. Recommendations are also provided for six more wetland systems (or regions) that should be prioritised for further research, as these systems lack fundamental information on where the threat of anthropogenic activities affecting them is greatest.

This study has made a significant contribution to understanding the underlying geomorphological processes in depressions, seeps and wetland flats. The desktop mapping component of this study illustrated the dominance of wetlands in the wetter parts of the Municipality. Perched wetland systems were identified in the field, on shallow bedrock, calcrete or clay. The prevalence of these perches in depressions, seeps and wetland flats also highlighted the importance of rainfall in driving wetland formation, by allowing water to pool on these perches, in the NMBM. These perches are likely to be a key factor in the high number of small, ephemeral wetlands that were observed in the study area, compared to other semi-arid regions. Therefore, this research highlights the value of multi-faceted and multi-scalar wetland research and how similar approaches should be used in future research methods has been highlighted. The approach used, along with the tools/methods developed in this study have facilitated the establishment of priority areas for conservation and management within the NMBM. Furthermore, the research approach has revealed emergent wetland properties that are only apparent when looking at different spatial scales. This research has highlighted the complex biological and geomorphological interactions between wetlands that operate over various spatial and temporal scales. As such, wetland management should occur across a wetland complex, rather than individual sites, to account for these multi-scalar influences.

Key words: connectivity, distribution, ephemeral wetland, ecosystem function, hydrogeomorphic (HGM) unit, landscape ecology, multi-scalar spatial patterns, structure.

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ABBREVIATIONS

AGIS	Agricultural Geo-referenced Information System
AIC	Akaike's Information Criterion
ANN	Average Nearest Neighbour
ANOVA	Analysis of Variance
ARC	Agricultural Research Council
ARC SCW	Agricultural Research Council for Soil, Climate and Water
AUC	Area Under the ROC Curve
CAP	Canonical Analysis of Principal Coordinates
CBA	Critical Biodiversity Area
CESA	Critical Ecological Support Area
Chl *a*	Chlorophyll *a*
CI	Confidence Interval
CN	Condition Number (collinearity)
CS	Classification System for Wetlands and other Aquatic Ecosystems in South Africa. Previously known as the NWCS.
CSIR	Council for Scientific and Industrial Research
DAFF	Department of Agriculture, Forestry and Fisheries
dbRDA	Distance Based Redundancy Analysis
DEDEAT	Department of Economic Development, Environmental Affairs and Tourism
DEM	Digital Elevation Model
DistLM	Distance Based Linear Model
DO	Dissolved Oxygen measured in mg/L or %
DWA	Department of Water Affairs. Formerly DWAF
DWAF	Department of Water Affairs and Forestry
EC	Electrical Conductivity measured in µS/cm or mS/m
ESA	Ecosystem Support Area (as defined by DEDEAT 2015)
ET	Evapotranspiration
GCS	Geographic Coordinate System
GIS	Geographic Information Systems
GLM	Generalised Linear Model
GPS	Global Positioning System
HBH	Hartebeesthoek (South African coordinate system)
HGM	Hydrogeomorphic
HU	Heat Units
IBA	Important Bird and Biodiversity Area
IPCC	International Panel on Climate Change
IUCN	International Union for the Conservation of Nature and Natural Resources
KZN	KwaZulu-Natal

LD	Laser Diffraction
LR	Logistic Regression (model)
Max.	Maximum
MDS	Multi-Dimensional Scaling
Min.	Minimum
MOSS	Metropolitan Open Space System
MPB	Microphytobenthos
NFEPA	National Freshwater Ecosystem Priority Areas
NMBM	Nelson Mandela Bay Municipality
NMMU	Nelson Mandela Metropolitan University
NRCS	Natural Resources Conservation Service
NWA	National Water Act of South Africa (Act 38 of 1998)
NWCS	National Wetlands Classification System. See “CS”
OM	Organic matter
PA	Protected area (as defined by DEDEAT 2015)
PC	Physico-chemical (properties)
PCA	Principal Components Analysis
PE	Port Elizabeth
PSD	Particle Size Distribution
RH	Relative Humidity
ROC	Receiver Operator Characteristic
SA	South Africa
SANBI	South African National Biodiversity Institute
SANWA	South African National Water Act
SAWS	South African Weather Service
SD	Standard Deviation
SE	Standard Error
SIMPER	Similarity of Percentages
Spp.	Species
SSW	Sub-surface Water
SW	Surface Water
TDS	Total Dissolved Solids measured in mg/L
TIN	Total Inorganic Nitrogen
TM	Transverse Mercator
TMG	Table Mountain Group
TSS	Total Suspended Solids measured in mg/L
U.S. EPA	United States Environmental Protection Agency
UNEP	United Nations Environmental Programme
USA	United States of America
VDP	Variance Decomposition Proportion

VWC	Volumetric Water Content
WC	Western Cape
WGS	World Geodetic System
WMA	Water Management Areas
WRC	Water Research Commission
XrD	X-ray Diffraction

UNITS OF MEASUREMENT

cm	centimetre
km	kilometre
m	metre
mm	millimetre
ha	hectare
km^2	square kilometre
m^2	square metre
s	second
min	minute
L	litre
ml	millilitre
g	gram
mg	milligram
ppt	parts per thousand
%	percentage
rpm	revolutions per minute
µ	micro-
$\bar{x}$	mean
^{o}	degree
^{o}C	degree Celsius

1. INTRODUCTION

1.1. RATIONALE

South Africa is a semi-arid country, with limited water resources (Faramarzi *et al.* 2013, McClain 2013). These water resources are important for human livelihood and ecosystem functioning (including the fauna and flora within). It is therefore imperative that water is conserved and used sustainably (Department of Water Affairs and Forestry 2005, McClain 2013). Wetlands form a critical component of a region's water resources, found at the interface between aquatic and terrestrial environments, as well as between surface and groundwater systems (Ellery *et al.* 2009, Keddy 2010). Consequently, these systems are reported to be highly productive, diverse and provide critical habitats for many species (Semlitsch 2000, Keddy 2010, Martin *et al.* 2012). These habitats include many terrestrial animals (including birds, amphibians, mammals and reptiles) which utilise wetlands at some stage during their life-cycle (Meyer *et al.* 2003, Machtinger 2007).

Wetland systems are strongly affected by anthropogenic activities (Machtinger 2007, Shine and Mesev 2007), despite their protection under the South African National Water Act (Act 38 of 1998). Many wetlands, especially ephemeral (any non-permanent) wetlands, have been converted to other land uses, and are no longer recognised as wetlands (Brinson and Malvárez 2002, Kotze *et al.* 2009a). Some of these areas are considered permanent losses (e.g. land drained and converted to urban and industrial regions), and some may be reversible (e.g. farmland and pastures) (Brinson and Malvárez 2002, Martin *et al.* 2012) or have retained some level of ecological functioning.

Globally a large number of wetlands have been lost. For instance, 50% of peatlands in 11 European countries are gone and 53% of the total area of wetlands in the USA are recorded as having disappeared between the 1780s and 1980s (Dugan and Bellamy 1993, Schuyt 2005). Recent research has indicated that up to 64% to 71% of inland wetlands have been lost during the 20th century (Davidson 2014, Gardner *et al.* 2015). In some catchments in South Africa, it is thought that over 50% of the wetlands have been destroyed (DWAF 2005). Such loss of habitat has contributed to a decline of biodiversity and abundance of wildlife species as well as having a negative impact on the water cycle and contributing to the increase of atmospheric carbon dioxide (Brinson and Malvárez 2002, Mitsch *et al.* 2009, Kobayashi *et al.* 2013).

In terms of wetland ecology, management and conservation, most research in South Africa has focused on perennial rivers and estuaries (Malan 2010), as they are perceived as being

more valuable resources for human use (dams, irrigation, aesthetics and recreation) than wetlands. Despite ephemeral fresh and brackish wetland ecosystems playing a key role (e.g. biodiversity, dispersal of faunal and floral populations) in the surrounding landscape, these wetlands have been studied less (Rossouw *et al.* 2005, Day *et al.* 2010, Malan 2010). Although progress has been made to develop a national, broad-scale dataset (e.g. Nel *et al.* 2011, van Deventer *et al.* 2016), there is still a need to establish fine-scale wetland distribution, especially when ephemeral systems dominate.

The recent surge in wetland research in South Africa is crucial as a number of key tools have been developed to help standardise the approach to research, management and conservation of these systems. This includes two report series available from the Water Research Commission (WRC): Wetland Management Series and the Wetland Health and Importance Research Programme. However, a large portion of this research has taken place in Mpumalanga, the winter rainfall region of the Western Cape (WC), and the summer rainfall region of KwaZulu-Natal (KZN). Baseline knowledge on wetlands in the Eastern Cape, however, has lacked.

The current system used to classify wetlands in South Africa is known as "*Classification System for Wetlands and other Aquatic Ecosystems in South Africa, User Manual: Inland Systems*" by Ollis *et al.* (2013). Hereafter referred to as "the Classification System" (CS). This report was updated from the previous National Wetland Classification System (NWCS) by South African National Biodiversity Institute (2009), with the rationale behind the updated CS described in a paper by Ollis *et al.* (2015). Notably, this classification system takes a hydrogeomorphic (HGM) approach to facilitate wetland inventories across South Africa (discussed further in Section 2.3).

At a Ramsar conference held in 2010, it was noted that there is still a significant lack of information on fundamental and baseline knowledge on wetlands in South Africa (Malan 2010). The need for this knowledge was further highlighted by the diversity of the wetland systems that exist in different regions of the country, and particularly the lack of knowledge on the ecological processes underpinning these systems (Malan 2010). Consequently, this limits the ability to predict the various environmental and anthropogenic impacts on wetland systems including their responses to such impacts (Day *et al.* 2010, Malan 2010).

Section 1.2 below is a brief description of the study area to provide the context in which this study took place, which is followed by the introduction of the research approach and aims of the study in Section 1.3.

1.2. OUTLINE OF THE STUDY AREA: NELSON MANDELA BAY MUNICIPALITY (NMBM)

The Nelson Mandela Bay Municipality (NMBM) is surrounded by the Sarah Baartman District Municipality, along the Eastern Cape coastline of South Africa (Figure 1-1). This Municipality is situated within a semi-arid region (see Section 3.2 on page 37 for the definition) in South Africa, with a mean annual precipitation (MAP) of 613 mm that ranges from approximately 423 mm in the north to 690 mm in the south. Port Elizabeth (PE) is the major city, and it is located on the south-eastern corner of the study area. The Municipality is approximately 1951 km^2 and is bordered by the Indian Ocean on the south and east, with a coastline of approximately 185 km. The Van Stadens River borders the western part of the Municipality and the Sundays River forms part of the northern border (Figure 1-1). There is a wide range of rainfall, geological, geographic and vegetation types which characterise this relatively small area, which are described further in Chapter 3.

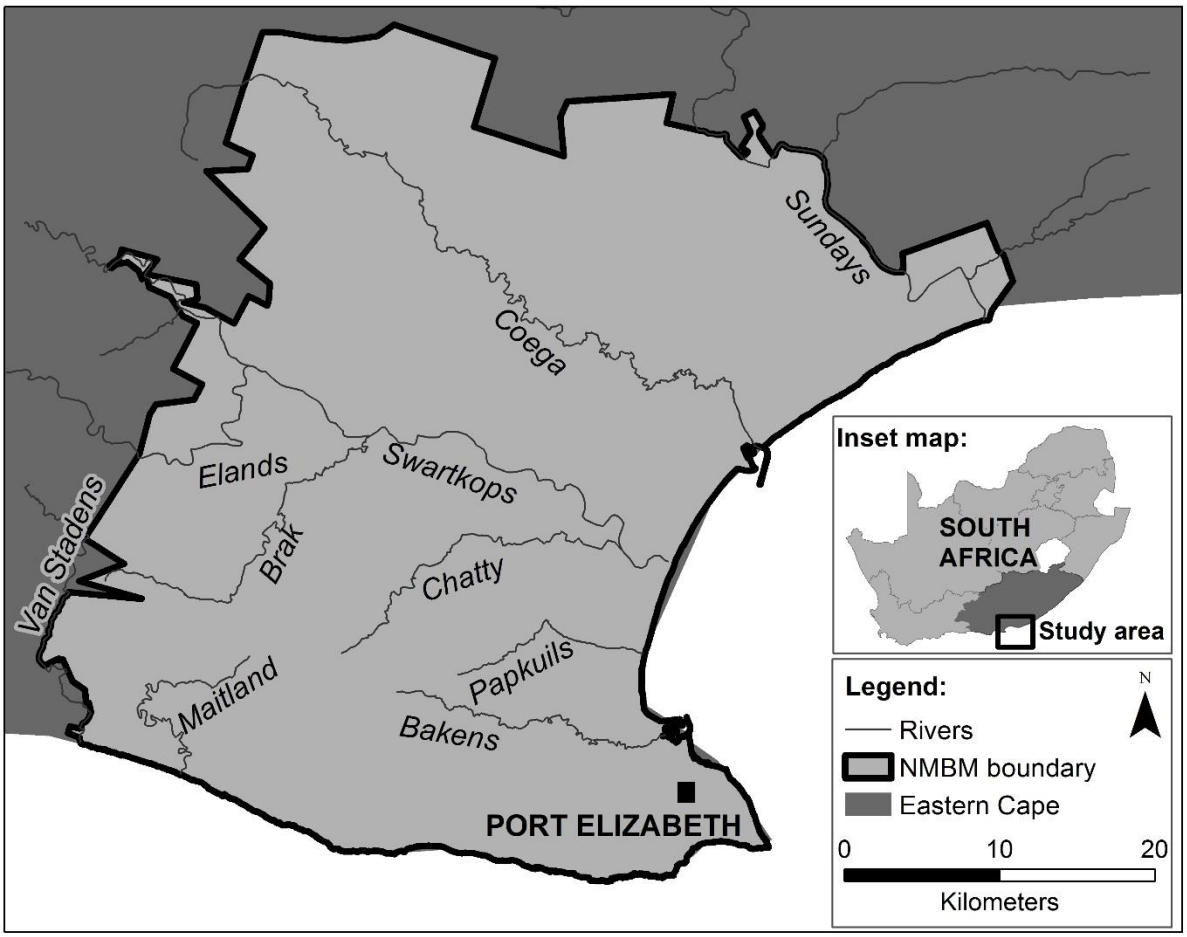

Figure 1-1 Broad study area map of the Nelson Mandela Bay Municipality (NMBM) with an inset map indicating the relative location of the study area within the Eastern Cape, South Africa.

1.3. RESEARCH PROBLEM AND AIM OF THE STUDY

As mentioned in Section 1.1, there has been a lack of fundamental knowledge on wetland ecosystems in the Eastern Cape, especially ephemeral systems and how they function, until recently. This information is critical for proper wetland management and conservation. First and foremost, the location and structure of wetlands needs to be known, and then classified, before wetland function can be established.

The diversity of vegetation types within the NMBM is renowned and is considered to be an ecological 'hot spot' with the intersection of five floristic biomes: Fynbos, Subtropical thicket, Nama karoo, Forest and Grassland (based on the most high resolution dataset available by Stewart (2010)). The occurrence of these biomes suggests that there also could be a fair diversity of aquatic fauna and flora (Mucina and Rutherford 2006). However, limited research has been conducted on wetland vegetation and macroinvertebrates in wetland habitats with the exception of a few selected provinces (Bird 2010, Sieben 2011). The ecosystem diversity in the primarily semi-arid landscape of the NMBM, along with the lack of research, further highlights the importance of defining wetland distribution, structure and function to ascertain whether wetlands illustrate similar variability in the NMBM.

The functioning of an ecosystem provides a framework for understanding various links between abiotic factors and the community structure. Understanding these links is important because wetland systems are fundamentally linked to various landscape processes, such as the movement of water, nutrients, sediment and energy (Granger *et al.* 2005, Cook and Hauer 2007). Furthermore, only a few studies have compared aspects of wetland function across different wetland types (e.g. Leibowitz and Nadeau 2003, McCartney *et al.* 2011).

Environmental processes also occur at different spatial and temporal scales, making these systems inherently complex in nature. A special issue in *Frontiers in Ecology* has reiterated the need to address ecological questions at broader geographical scales that integrate various spatial datasets (Soranno *et al.* 2014, Soranno and Schimel 2014). An article by Euliss *et al.* (2004) further emphasised the complex dynamics of wetlands as systems that function on a continuum of hydrological and biological patterns. These papers highlight the need to undertake a multi-scalar research approach, across various wetland types, to ascertain which aspects of the surrounding ecosystems are influencing wetland structure and function.

Ephemeral wetland research has predominantly concentrated on areas that are driven by seasonal precipitation which results in more "seasonal" type systems (see Table 2-4 for definition). Some of these systems include snow-melt and seasonal rains in playa lakes,

vernal pools and prairie potholes in the USA, and turloughs, karst systems in Ireland and Slovenia. An exception is inland Australia, where Roshier *et al.* (2001) have studied the distribution of ephemeral wetlands that are driven by precipitation events that are highly variable over space, time and intensity. This unpredictable and variable rainfall makes these types of ephemeral systems particularly susceptible to land use and climate changes (Roshier *et al.* 2001, Junk *et al.* 2013). This emphasises the value of research in the NMBM which has similar unpredictability and variability in rainfall patterns.

In summary, the motivation and importance of this study lies in the presence of small, geographically isolated ephemeral wetlands in an understudied region of South Africa. The NMBM is unique in its diverse physical geographical setting and has a number of ecologically sensitive habitats (Stewart 2010). This makes the study area a good platform to conduct multi-scalar and multi-faceted research, the outcomes of which can potentially be applied to other semi-arid and sub-humid areas with aseasonal rainfall. In addition, the expansion of urban and rural activities within the Municipality pose a current threat to the wetlands in the NMBM (discussed further in Chapter 3), highlighting the importance of conducting timely research.

1.3.1. Research aim and objectives

The aim of this study is:

> *To determine the factors influencing wetland distribution and structure, including ecosystem functioning of a subset of ephemeral wetlands, in the Nelson Mandela Bay Municipality (NMBM).*

The research objectives are:

1) *To identify wetlands using visual interpretation of aerial photographs, and to use this output to create a wetland occurrence model (Objective 2);*

2) *To determine whether a logistic regression (LR) modelling technique can be used to accurately predict the likelihood of wetland occurrence and whether there are key environmental variables that are associated with wetland distribution in a predominantly semi-arid climate such as the NMBM;*

3) *To describe patterns of wetland distribution using spatial statistics and identify whether wetlands are clustered and form mosaics within the surrounding landscape in relation to wetland size and HGM type;*

4) *To determine whether potentially vulnerable (in terms of anthropogenic activities and changes in climate) wetlands can be quantifiably chosen using landscape variables;*

5) *To assess ecosystem functioning of a subset of ephemeral wetlands using abiotic and biotic characteristics to establish whether these features are distinguishable at a HGM level;*

6) *To describe the relationship between landscape or site level data (or a combination thereof) and the plant and macroinvertebrate community structure in depressions, seeps and wetland flats; and*

7) *To provide general management and conservation strategies for wetlands in the NMBM based on the data collected, as well as identify priority areas for conservation, rehabilitation and research.*

1.4. RESEARCH DESIGN AND METHODS

An overview of the research design and methods, used to achieve the aim and objectives of this study, is highlighted in this section.

Information from many fields within ecology was accessed for this research. This study used site-specific data collected in the field combined with secondary spatial data available from various sources that have been collected at different scales to answer the objectives, principles were taken from landscape ecology, geomorphology, biogeography and ecohydrology. This systems approach was used to handle the complexity of wetland systems and the multi-scalar interactions within a landscape. Consequently, the main data chapters assess the wetlands in the NMBM at both fine and broad scales.

A wide variety of analytical methods were used to address the objectives in this research and handle the multi-scalar nature of the wetland systems. Desktop GIS and existing environmental spatial data were used to identify wetlands across the Municipality. Data were also collected at 46 wetlands. A variety of non-spatial and spatial statistics were also used, many of which were non-parametric and multivariate in nature.

1.5. THESIS OUTLINE

This chapter **(Chapter 1)** provides a general introduction to the study by establishing the context and rationale of this research. Aims, objectives and research questions are discussed herein.

Chapter 2 provides a review of literature pertaining to the theoretical framework of this thesis. An outline of the Classification System is provided as it forms a crucial backbone to the research methods. Ephemeral wetlands are characterised, as well as the abiotic and biotic components of these systems. The review also addresses landscape ecological processes that influence wetland distribution and function at different spatial scales. Anthropogenic and climate change effects are also discussed.

Chapter 3 gives the background context of this research in the Nelson Mandela Bay Municipality (NMBM). The study area illustrates the unique landscape on which the wetlands are located and perform various ecosystem functions. The novelty of this study area is due to various geographical, hydrological and biological features, which are described. Various anthropogenic activities that influence wetland structure and function are also discussed.

The general methods used to achieve the aims and objectives of this study are described in **Chapter 4**. The use of both secondary and primary sources of spatial and non-spatial data are defined, as well as how these data sources have been used at multiple scales. Methods that pertain to specific sections of work are described in their respective data chapters.

Chapters 5, 6 and 7 address the outcomes of the research conducted in this study. Figure 1-2 outlines the spatial scale for each of these chapters.

Chapter 5 addresses Objectives 1 and 2 of the research and covers wetland delineation and classification in the NMBM using high resolution aerial photography. This is expounded on through the creation of a wetland occurrence model using logistic regression techniques. One of the outcomes of this chapter is the identification of several landscape variables that are associated with the presence of a wetland.

Chapter 6 reports on wetland distribution at a finer scale within the landscape and pertains to Objectives 3 and 4. At this scale, various spatial statistical analyses are conducted to explain the proximity (structural connectivity) of wetlands to other systems and the implications of such. This chapter also highlights the impact of various anthropogenic activities on the distribution of wetlands within a catchment.

The abiotic and biotic characteristics of 46 wetlands that were visited during 2012 and 2013, are described in **Chapter 7**. These systems were comprised of depressions, seeps and

wetland flats. Data were collected on soils, water chemistry, vegetation, macroinvertebrates and amphibians (tadpoles). The outcomes of the analyses were used to infer general patterns within the different HGM types and specific sites were used as examples to illustrate these patterns. Accordingly, this chapter addresses Objectives 5 and 6.

A general overview of the findings of the research are described in **Chapter 8** (Figure 1-2). The effect of spatial scale on the data collected, results obtained and the associated management implications, is described herein. The key findings, limitations of study, and future considerations for management, conservation and research are also discussed.

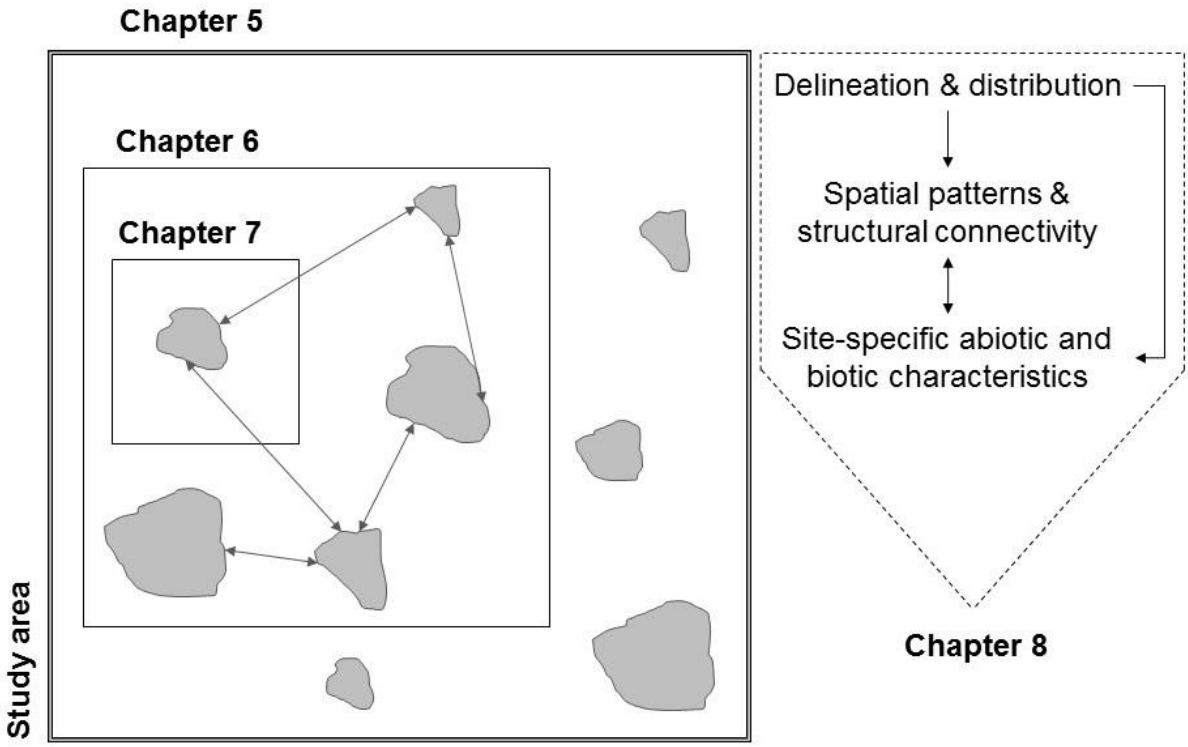

Figure 1-2 Conceptual outline of the thesis by chapter. This framework illustrates the changes in spatial scale associated with each chapter and the relationships between each of the chapters.

2. LITERATURE REVIEW

A multi-faceted, cross-disciplinary approach was used in this research, an approach often used in landscape ecology studies. Cross-disciplinary knowledge is needed to establish spatial and temporal patterns across different scales. Therefore, the aim of this review is to introduce key literature on wetland systems, as well as examine the current knowledge on classification, characteristics, structure and functioning of wetlands, on a national and global scale. Wetland indicators are also discussed as a foundation for the different abiotic and biotic variables that were considered during this research. The relevance of understanding wetland structural connectivity and the associated landscape ecological processes that influence wetland distribution are outlined. This review will also place ephemeral wetland systems within a broader context of wetland function and health, as well as what is currently affecting these systems in South Africa (SA) in terms of climate and anthropogenic activities.

2.1. CONCEPTS FROM LANDSCAPE ECOLOGY

Tobler's first law of geography states that "everything is related to everything else, but near things are more related than distant things" (Tobler 1970: pg. 36). The importance of statistically calculating the spatial relationships in a landscape comes from the field of landscape ecology. This field emphasises the structure of the landscape in terms of scale (both spatial and temporal), patterns within a landscape, and the processes (occurring at different scales) within the landscape (Turner *et al.* 2003, Fu *et al.* 2011). Accordingly, the structure of the landscape affects the associated abiotic and biotic functions (Turner *et al.* 2003, Schröder and Seppelt 2006).

Landscape ecology breaks down the landscape into two components, the patch (in this case, wetland) and the surrounding matrix (catchment or upland area) (Turner *et al.* 2000, Wagner and Fortin 2005). Various abiotic and biotic interactions (processes) occur within and between wetland patches (Turner *et al.* 2000, Wagner and Fortin 2005). The spatial arrangement of wetlands within a landscape can be calculated using spatial statistics (for example: spatial autocorrelation, kernel density analyses and nearest-neighbour indices), and is often described as the spatial heterogeneity of a landscape (Turner *et al.* 2000, Wagner and Fortin 2005). The connectivity between wetlands is also influenced by anthropogenic and environmental factors (Turner *et al.* 2000, Wagner and Fortin 2005). These factors determine the distance and magnitude (gradient of flow) of connectivity. The role of connectivity in wetland research is discussed in Section 2.9 of this review.

There are many other concepts related to the field of landscape ecology such as edge effects, regional groundwater flows, dispersal and movement of organisms and population dynamics (Wagner and Fortin 2005, Fu *et al.* 2011). As data were not collected to specifically address these components they are not discussed further.

2.2. WETLAND TERMINOLOGY

Wetlands are shaped by interactions between climatic, geological, biological, chemical and anthropogenic factors (Machtinger 2007). Wetlands have been both defined and classified differently in the various regions across the globe, including SA (Mitsch and Gosselink 2000). The current definition for wetlands in SA is from the National Water Act (NWA) (Act 36 in 1998; pg. 9), which 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.” An ephemeral wetland is a system that is not permanently inundated and, therefore, refers to either seasonally or intermittently inundated systems. This is defined within the classification structure for wetlands in SA (see Section 2.3 and Table 2-4).

Wetlands also have a wide variety of names, depending on their location, hydrology and vegetation cover. These names illustrate the diversity of underlying factors driving wetland structure and function in different environments and are discussed in various texts (e.g. Noble *et al.* 2002, Tiner 2003b, Mitsch and Gosselink 2007). Developments in wetland classification in SA have resulted in more specific terms being used to attempt to describe the variety of wetland types. These types are known as hydrogeomorphic units. These wetland types are further described in Section 2.3, to the level of the HGM unit of the current wetland classification system used in SA.

Wetland structure pertains to the physical shape or form of a wetland system (Mitsch and Gosselink 2007, Ellery *et al.* 2010). Water inputs, outputs and throughputs that are used to define the wetland HGM type, also comprise the structure of the system (Ollis *et al.* 2013). Wetland structure differs from defining a wetland boundary using classical wetland delineation methods, which involves the systematic delineation of a wetland boundary using soil, terrain, vegetation and hydrological indicators (Department of Water Affairs and Forestry 2005). Wetland function is based on the term “ecosystem function” and pertains to the interaction, or link, between wetland structure and the related geochemical, physical and biological processes and components (Smith *et al.* 1995, Kobayashi *et al.* 2015).

2.3. SOUTH AFRICAN NATIONAL WETLAND CLASSIFICATION SYSTEM

There is a need to systematically classify wetlands, especially smaller, more ephemeral systems, in SA, as highlighted in Sections 1.1 and 1.3. The current wetland method is known as “the Classification System” (the CS). The development and a summary of the CS, as well as its strengths and weaknesses are discussed in a later publication by Ollis *et al.* (2015). Reference to the CS hereafter pertains to the Ollis *et al.* (2013) report.

The CS consists of six levels that are applied in a hierarchical manner to differentiate between the various wetland types, based on primary and secondary discriminators (features that can be used to identify a wetland) (Table 2-1). The discriminators describe wetlands both functionally and structurally from Level 4 of the CS. Levels 5A and 5B of the classification system deal with inundation and soil saturation (i.e. the hydrological regime) (Ollis *et al.* 2013). This research does not focus on permanently inundated wetlands, but addresses the inland systems that are unchannelled and predominantly ephemeral in nature. Rivers were also excluded. A breakdown of the different classification levels is described below, with particular reference to wetland types studied during this research.

At **Level 1**, the CS distinguishes between marine, estuarine and inland systems, the last of which is the focus of this study. Between 90% and 95% of the wetlands in the world are inland or non-tidal (Mitsch *et al.* 2009). As per the CS, these inland systems have no existing connection to the ocean and no exchange with marine systems and their associated tidal regimes (Ewart-Smith *et al.* 2006, Ollis *et al.* 2013).

Level 2 defines the regional setting for wetlands and is described using several spatial frameworks (Table 2-1). This setting is used as a reference for biophysical differences among ecosystems occurring in different regions, providing the ecological context within which the wetland occurs (Ollis *et al.* 2013). Ecoregions are defined using a combination of climate, physiography, geology, soils and vegetation patterns that occur in SA, all of which are of relevance to this study. At Level 2, the NMBM falls within the South Eastern Coastal Belt (Ecoregion 20) which consists of low lying plains, closed hills and mountains and a low to medium drainage density (Kleynhans *et al.* 2005).

Level 3 of the CS distinguishes between four landscape units: slope, valley floor, plain and bench (Table 2-2 and Figure 2-1), all of which were included in this study. These landscape units are used to indicate which geomorphological processes are occurring in association with the topographic position of the wetland (Ollis *et al.* 2013). These landscape units can be used to describe wetlands that have been identified at a desktop level in this study.

Table 2-1 Structure of the CS from Levels 1 to 6. Levels 4 and 5 are the functional units of a wetland with the wetland characteristics being described in Level 6 (modified from Ollis *et al*. 2013). Aspects of the CS not addressed in this research are in grey text.

Level 1: Connectivity to the ocean	Level 2: Regional setting	Level 3: Landscape unit	Level 4: HGM units	Level 5: Hydrological regime	Level 6: Descriptors
Inland	Ecoregions	Valley floor	Depression	Inundation period & depth	Natural vs. artificial
	OR	Slope	Seep	Saturation period	Salinity
Estuarine	NFEPA WetVeg Groups	Plain	Wetland flat		pH
	OR	Bench (Hilltop/Saddle/ Shelf)	Channelled valley bottom		Substratum type
Marine	Spatial framework		Unchannelled valley bottom		Vegetation cover type
			Floodplain wetland		Geology
			River		

Table 2-2 Landscape units (Level 4 of the CS) as defined by Ollis *et al.* (2013).

Landscape unit	Description
Slope	An area with a gradient that is generally located on the side of a hill/mountain or valley, generally with a slope that is greater than 1:100. Can consist of foot, mid or scarp slopes.
Valley floor	On the lowest surface of a valley between two side-slopes with gentle gradients. Fluvial and alluvial processes generally dominate.
Plain	An extensive low relief area that is gently undulating, level, or uniformly sloping. Includes coastal and interior plans and plateaus. There are no side-slopes like valley floor areas and gradients are generally less than 1:100.
Bench (hilltop/saddle/shelf)	Mostly level high ground, including areas on top of a mountain/hill (hilltops), between two down-slopes or two up-slopes (saddles) or between an up and a down-slope (shelf). Benches occupy a relatively smaller area than plains (typically less than 50 ha).

Level 4 of the CS defines the HGM units. The HGM approach uses water source (precipitation, groundwater etc.), hydrodynamics and the geomorphic setting to define functional groups (Brinson 1993, Noble *et al.* 2002). Many authors including Brinson (1993), Smith *et al.* (1995), Hauer *et al.* (2002), Noble *et al.* (2002), and Brooks *et al.* (2011), have used adaptions of the HGM approach to undertake a functional assessment of a wetland site. Different research questions pertaining to wetland function and health arise when considering structural composition of a wetland.

There are six HGM types of inland systems (Figure 2-1). Table 2-3 summarises the hydrological processes associated with each of the HGM types. The identified HGM type should be used with field data to deduce what wetland functions are occurring, and the associated ecological significance of those functions (Brinson 1993). This study aims to address the link between this level of the classification and the ecosystem functioning of wetlands in the NMBM.

Levels 5A and 5B describe the hydroperiod in terms of inundation and saturation (Table 2-4 and Table 2-5). The hydrological regime (water flowing into, out of, and through a wetland) affects chemical, physical and biological characteristics and, consequently, the overall functioning of a wetland system (Ollis *et al.* 2013, Ollis *et al.* 2015). This research focuses on systems that are predominantly ephemeral in nature, i.e. systems that are seasonally or intermittently inundated, with varying levels of saturation. The inundation and saturation period has a large influence on the physical and chemical properties of the soil, as well as which vegetation communities will establish in a particular inundation/saturation zone. Data from Levels 5 and 6 are collected in the field.

Other parameters (descriptors) are recorded at **Level 6** of the CS. This level describes the structural, chemical and biological characteristics of wetlands and includes: natural versus artificial wetlands, underlying geology, vegetation cover type, substratum type, salinity, and acidity/alkalinity (pH), with their respective sub-categories.

As with any classification system, there are limits and exceptions. Although this system was used, classifying the wetland was not restricted to the CS, and deviations were recorded. This is particularly important when applying a classification system in areas or regions where the classification system has not been well tested, as is the case in the NMBM.

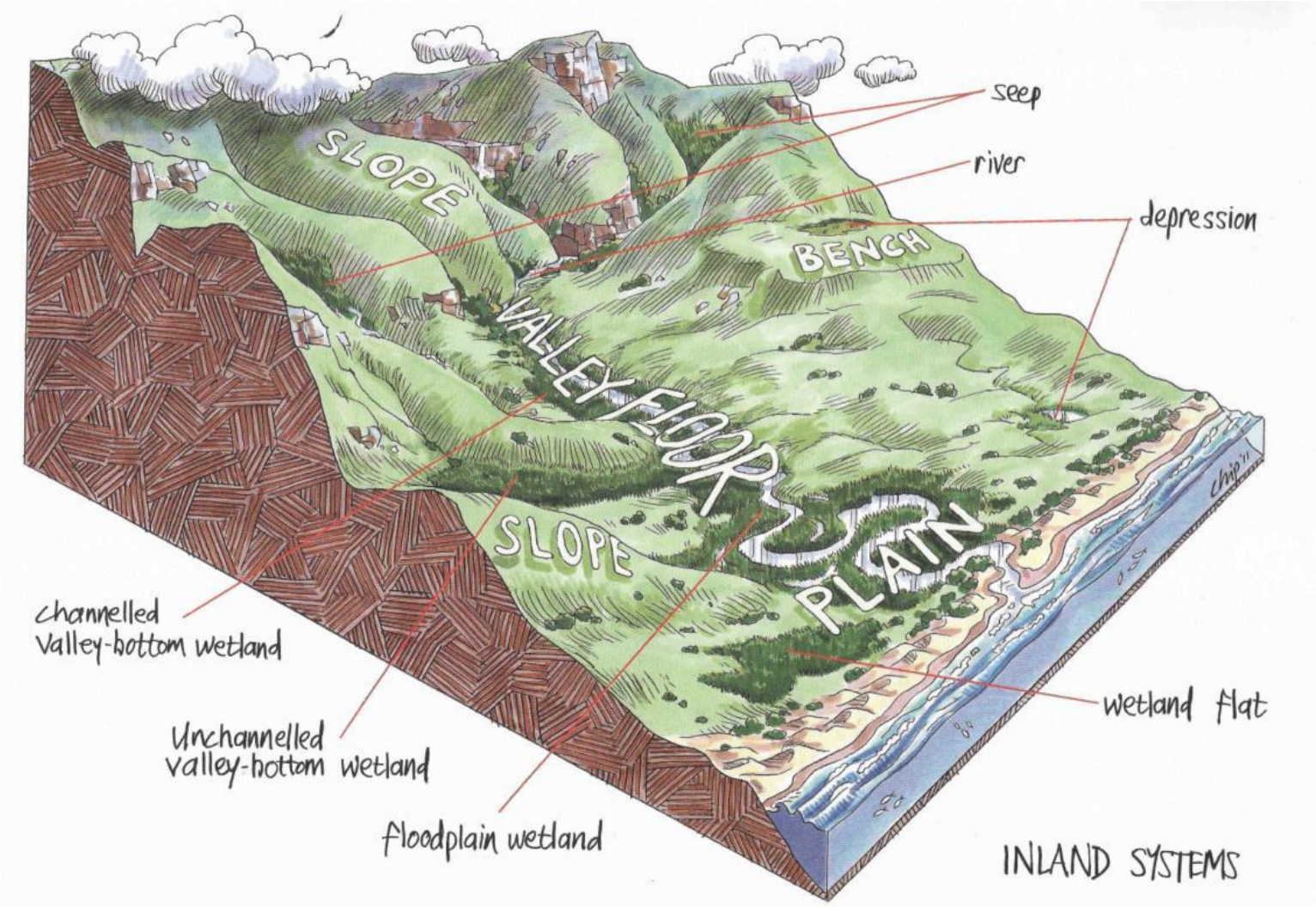

Figure 2-1 Landscape setting and the associated HGM units. Taken from pg. 17 of Ollis *et al.* (2013). Artist: Chip Snaddon.

Table 2-3 Characteristics of the different HGM types in the CS. Asterisks (*) indicate wetland types identified at a desktop level only. VB = valley bottom. Modified from Ollis *et al*. (2013).

HGM unit	Description	Inflow	Through-flow	Outflow/water loss	Hydrodynamics
Depression	Closed elevation contours that increase in depth towards centre of wetland. Pans have flat bottoms whereas basins have rounded bottoms	Precipitation, groundwater inflow, interflow & overland flow. Sometimes channelled inflow	Water is contained & temporarily stored. Slow through-flow. Vertical water level fluctuations	In exorheic (outward draining) wetlands: concentrated surface flow or in endorheic wetlands: evaporation & infiltration	Vertical (bidirectional) fluctuations. Horizontal, unidirectional water movement
Seep	Located on gently to steeply sloping land. Colluvial processes dominate	Overland inflow & interflow. Mostly groundwater inflow	Diffuse unidirectional flow	Infiltration & evapotranspiration. Sometimes channelled outflow	Horizontal, unidirectional water movement
Wetland flat	Near-flat wetland with little or no relief. Found on plains & benches	Precipitation & sometimes groundwater (mostly in coastal areas)	Diffuse multidirectional flow	Infiltration & evapotranspiration	Bidirectional vertical fluctuations. Horizontal, multidirectional water movement
Channelled VB wetland*	Mostly flat wetland area connected with a river channel	Overland inflow, interflow, lateral seepage & flooding. Sometimes groundwater	Flooding	Infiltration, evapotranspiration & lateral seepage	Not addressed in this study
Unchannelled VB wetland*	Mostly flat wetland area with no distinct channel running through the wetland	Overland flow & interflow. Sometimes channelled inflow &/or groundwater inflow	Diffuse unidirectional flow. Temporary containment in wetland	Infiltration & evapotranspiration	Not addressed in this study
Floodplain wetland*	Mostly flat area next to and formed by an alluvial river channel	Periodic inundation from adjacent river channel & lateral seepage. Sometimes groundwater		Infiltration, evapotranspiration & lateral seepage	Not addressed in this study
Rivers	Not addressed in this study				

Table 2-4 Definitions of wetland inundation periodicity (modified from Ollis *et al*. 2013). In this study, ephemeral wetlands pertain to those that are both seasonally and intermittently inundated.

Inundation periodicity	Description
Permanently inundated	Surface water is present throughout the year.
Seasonally inundated	Surface water is present for extended periods (usually 3 to 9 months) during the wet season, but dries up annually during the dry season, either to complete dryness or to saturation.
Intermittently inundated	Surface water is held irregularly for changeable periods of less than one season's duration (but generally less than 3 months), at intervals varying from less than a year to several years.
Never inundated	Surface water is present for less than a few days at a time (maximum one week).
Unknown	For situations where the inundation periodicity is unknown.

Table 2-5. Definitions of wetland saturation periodicity (upper 0.5 m of the soil surface) (modified from Ollis *et al*. 2013).

Saturation periodicity	Description
Permanently saturated	All the spaces between the soil particles are permanently filled with water. This corresponds to the 'permanent (inner) zone' of a wetland, according the terminology used by DWAF (2005).
Seasonally saturated	All the spaces between the soil particles are filled with water for extended periods (3 to 9 months of the year), usually during the wet season, but dry for the rest of the year (during the dry season). This equates to the 'seasonal zone' of a wetland mentioned by DWAF (2005).
Intermittently saturated	All the spaces between the soil particles are filled with water for changeable time periods of less than 3 months (i.e. less than 1 season's duration). This equates to the 'temporary (outer) zone' of a wetland used by DWAF (2005).
Unknown	For situations where the saturation periodicity is not known.

2.4. EPHEMERAL WETLAND SYSTEMS

In a global context, wetlands are considered 'temporary' or 'ephemeral' when the substrate is inundated from a few days to years, with subsequent dry periods (which can range from months to several years) (Ellery *et al.* 2009, Day *et al.* 2010). This study uses the term "ephemeral" when referring to any non-permanent systems.

Wetlands that occur in areas where annual rainfall is less than annual evaporation rates are driven by ecological factors that can overcome this negative water balance (Tooth and McCarthy 2007, Day *et al.* 2010). This negative water balance is a key driving factor affecting ecosystems in the dryland regions of the world (Figure 2-2) and, wetlands in these regions are often known as dryland wetlands (Tooth and McCarthy 2007). A large portion of SA is considered to be dryland, including the study area (Figure 2-2).

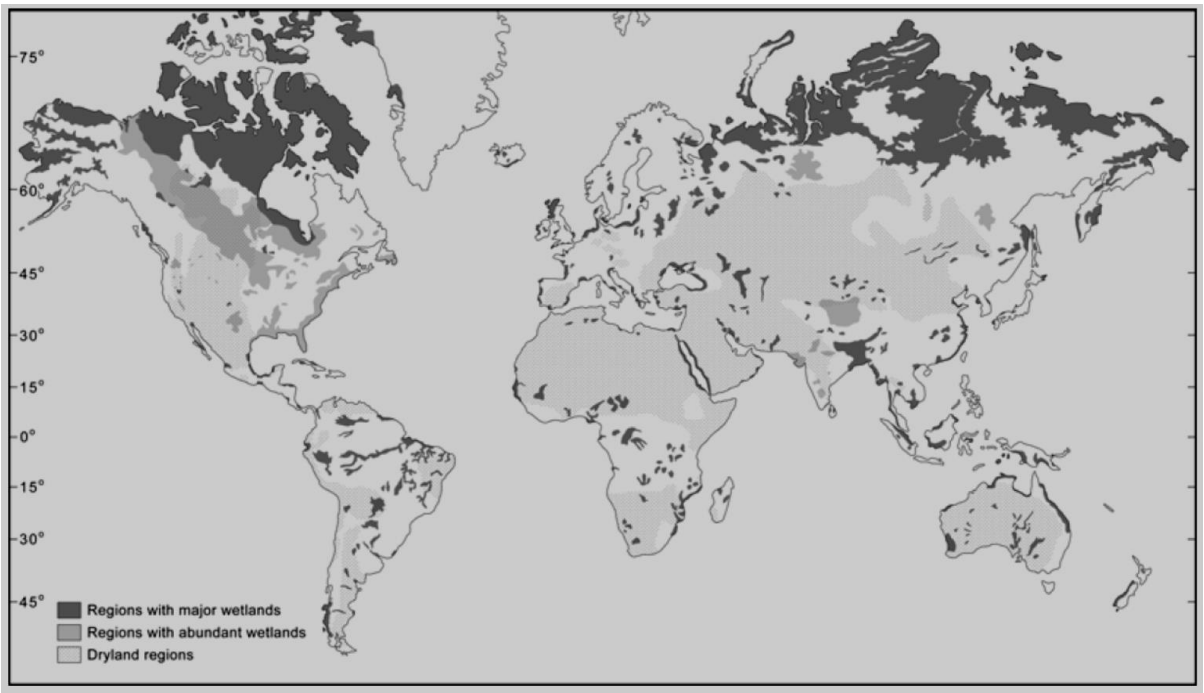

Figure 2-2 Global distribution of the main dryland and wetland regions. Extracted from Tooth and McCarthy (2007), with permission for use from Sage Journals.

Cryptic wetlands are defined by Day *et al.* (2010; pg. 2) as wetlands that "*cannot be reliably identified as wetlands during the dry season on the basis of standard wetland identification and delineation tools"*. This is because wetland-associated fauna and flora are not easily visible and/or die off when the wetland is dry (Job 2009, Day *et al.* 2010). Therefore, several abiotic and biotic characteristic features need to be used to identify such systems (Job 2009, Day *et al.* 2010). Fieldwork based primary classification of a wetland usually takes into account both abiotic and biotic factors (Ewart-Smith *et al.* 2006). These cryptic systems are therefore of particular interest to this study as it is thought that these systems are vastly under-represented in wetland inventories of the region (as can be seen by the lack of small systems in the NFEPA wetland inventory at a national level).

The ephemeral nature of a wetland is defined by its hydroperiod, i.e. the pattern of water level fluctuations in a wetland (Ellery *et al.* 2009). Wetlands from diverse geomorphic settings have different dominant sources of water (such as precipitation, overland/surface flow or groundwater) which result in different hydroperiods (Brinson and Malvárez 2002, Machtinger 2007) (more illustrations in Appendix A). As a result, wetlands also have diverse floral and faunal communities that inhabit them (Brinson and Malvárez 2002, Mitsch *et al.* 2009).

Ephemeral wetlands illustrate varied characteristics. In general, they are usually shallow (less than 2 m in depth), oval in shape and range in diameter between one metre and tens of kilometres (Leibowitz and Nadeau 2003). The abiotic characteristics give rise to specialised community structures that are adapted to both wet and dry periods (Leibowitz 2003, Meyer *et al.* 2003). These adaptions result in a number of endemic species, and/or a potentially high biodiversity than other aquatic ecosystems (Leibowitz 2003, Keddy 2010).

DWAF (2005) describes four main indicators, besides the presence of water, which can be used to identify a wetland: the terrain, soil form, soil wetness and vegetation (Table 2-6). The vegetation indicator is generally applied when greater than 50% of the vegetation cover is comprised of facultative and/or obligate wetland plants (woody or herbaceous). However, even when wetland vegetation cover is less than 50% there is still a possibility that hydric conditions exist (Tiner 1991, Day *et al.* 2010), as is the case in cryptic systems. Thus, it is important that other wetland indicators are also used to assess wetland conditions. This is where abiotic factors can provide further information on the presence and type of cryptic/ephemeral wetland, including: water levels, soil characteristics (e.g. soil wetness and colour), topography, the presence of a shallow clay layer, surface organic matter (detritus), water marks on rocks or trees, and/or the presence of shells or the remains of aquatic invertebrates (Machtinger 2007, Van den Broeck *et al.* 2015). A combination of these (as well as some other) indicators are needed to assess, with some confidence, that wetland conditions are present, and to understand the structure and functioning of the system (Tiner 1993a, Van den Broeck *et al.* 2015).

Wetland indicators can also be used to determine the wetland/terrestrial boundary. The indicators distinguish different zones of wetness from the permanent zone (permanently wet) to the seasonal zone (wet for at least three months per year) to the temporary zone (wet for less than three months of the year) (DWAF 2005). The outer edge of the temporary zone is defined as the wetland boundary (DWAF 2005). Thus, wetland indicators that can be used to characterise these systems are: hydrology, soils, vegetation and wetland fauna. These indicators are described in the following sections. This study used these indicators and the CS to determine the underlying wetland structure of ephemeral wetlands in the NMBM.

Table 2-6 Wetland indicators as defined by DWAF (2005).

Indicator	Description
Terrain Unit	The parts of the landscape where wetlands are more likely to occur.
Soil Form	The soil forms, as defined by the Soil Classification Working Group (1991), which are associated with prolonged and frequent saturation.
Soil Wetness	The morphological 'signatures' developed in the soil profile as a result of prolonged and frequent saturation.
Vegetation	The hydrophilic vegetation associated with frequently saturated soils.

2.5. WETLAND HYDROLOGY

The hydrology of the wetland refers to the frequency and period of flooding in a wetland (Environmental Laboratory 1987, Lewis 1995). Water enters, is stored, and leaves a wetland through various pathways occurring both at and below the soil surface, affecting the size and boundary of a wetland (Brinson 1993, Winter and Rosenberry 1995). The 'wetted edge' (i.e. the surface water boundary) of a wetland refers to this boundary where sub-surface water becomes surface water. This boundary is affected by the loss of surface water and depends on factors such as climate, vegetation and the surrounding geomorphology (Brinson 1993, Winter and LaBaugh 2003).

Ephemeral wetlands occur where the total hydrological input is greater than the total outputs for a period of time (Ellery *et al.* 2009). The water balance (between input and output) can produce unique systems, many of which have resulted in depressions. For example: in the USA, prairie pothole wetlands are mostly comprised of depression (pothole) wetlands that were formed by previously glaciated valleys or alpine glaciers (LaBaugh *et al.* 1998, Cook and Hauer 2007). These potholes are shaped by shallow groundwater connections and periodic surface water connections (van der Kamp and Hayashi 1998, Cook and Hauer 2007). These connections predominantly occur in spring and are associated with snow melt and sometimes, rainfall (Cook and Hauer 2007). These connections, alongside geomorphic setting and landscape position, are thought to be key factors in determining current depression wetland structure and function in the region (Cook and Hauer 2007).

Turloughs are depressions formed in the karst limestone region in Ireland (Sheehy-Skeffington *et al.* 2006, Proctor 2010). Their formation and structure, like the prairie potholes, are primarily driven by seasonal hydrological flows (Sheehy-Skeffington *et al.* 2006, Proctor 2010). Autumn/winter rainfall raises the local water table, linking underground passages and producing springs (Sheehy-Skeffington *et al.* 2006, Proctor 2010). Consequently, in spring, water then recedes back through these underground passages (Sheehy-Skeffington *et al.*

2006, Proctor 2010). Sporadic rainfall events at other times of the year can also result in inundation of these systems (Sheehy-Skeffington *et al.* 2006, Proctor 2010). These examples illustrate how the hydrological component drives wetland formation and structure (wetland type), and combined with the biota, contributes to wetland function (Cook and Hauer 2007, Ralph and Hesse 2010). Accordingly, these abiotic and biotic characteristics are a reflection of the hydrological regime driving wetland structure, and can provide an indication of wetland function (Lewis 1995, Kaplan and Muñoz-Carpena 2011). This research uses this approach.

Many anthropogenic activities and environmental changes, occurring at both a local and broad catchment scale, affect catchment hydrology. As a large component of wetland structure and function is driven by hydrology, wetlands serve as an indicator of hydrological changes occurring at a catchment scale. Grenfell *et al.* (2005) have illustrated this concept in a seep located in the KwaZulu-Natal Midlands (SA). Land use in the catchment changed from natural grassland to commercial forestry, which decreased water runoff further downstream and, consequently, in the wetland. As a result, the decrease in water input affected the plant communities within the wetland. This, in turn, affected the water regime further downstream in the catchment, illustrating the multi-scale environmental processes affecting wetlands.

2.6. SOILS

Various factors contribute to the development of soils, including the weathering and eroding of parent rock material, biota (fauna and flora), topography (angle of slope and catena effect), climate (temperature, wind and moisture) and time (Foth 1990, Brady and Weil 1999, Du Preez *et al.* 2011). These factors establish the physical properties of the soil, such as texture, structure, porosity, density, consistence, colour and temperature (Foth 1990, Ashman and Puri 2002). In wetlands, the period of inundation and soil saturation further affects these underlying soil properties (Tsheboeng *et al.* 2014) thereby creating spatial and temporal variations in the system. These spatial and temporal variations in soil properties influence the overall soil/sediment chemical composition and, consequently, influence the composition of plant communities within a wetland (Koerselman *et al.* 1993). Thus, it is important to understand what the basic sediment composition of a wetland is in order to understand the interaction between plant communities and the hydrology of the wetland system. The properties that are of importance to wetland soils in this study are explained below.

2.6.1. Physico-chemical properties of soils

Soil texture refers to the size of soil particles and, specifically, the relative proportions of sand, silt and clay (Foth 1990, Brady and Weil 1999). The broad particle size classes are defined

in Table 2-7. Soil comprised of a high percentage of coarse material (gravel and coarse sands) has little plasticity and stickiness and, consequently, facilitates drainage. Whereas clay soils, expand and shrink with wetting and drying and, can potentially hold a large amount of water (Foth 1990, Brady and Weil 1999).

Table 2-7 Broad sediment particle size classes based on the Wentworth scale (1922).

Particle size	Diameter (mm)
Boulders, cobbles, pebbles, gravels	> 2
Sand	2 – 0.063
Silt	0.063 – 0.002
Clay	0.002 – 0.001

Soil colour gives an indicator of other soil characteristics such as soil aeration, water drainage and amount of organic matter (Foth 1990, Brady and Weil 1999). Soils with high percentages of organic matter, usually over 20%, tend to be dark brown (peat) to black colour (humus), and are termed “organic soils” (Foth 1990). The presence of iron in subsoil horizons also affects soil colour, with oxidised iron producing a reddish colour (iron oxide), and hydrated and oxidised irons producing a yellow to yellowish-brown colour (Ashman and Puri 2002, DWAF 2005). Well-drained soils tend to be brighter in colour (brownish and reddish colours), while soils in depressions (i.e. sink areas) tend to have a gleyed matrix with grey coloured B horizons (Brady and Weil 1999, Ashman and Puri 2002). Soil colour is read using the Munsell Soil Colour Chart (1994) which characterises soil colour by hue, value and chroma.

Soil moisture is affected by factors, including, vegetation cover, topography, water table depth, sediment particle size and rainfall (Gómez-Plaza *et al.* 2001). Water in soils is vital for the growth and survival of plants and organisms living in the soil (Brady and Weil 1999). Soil water is related to the pore size, where large pores result in rapid drainage and smaller pores hold water more tightly, resulting in a higher moisture content (Ashman and Puri 2002). This plays an important role in the vegetation cover in a wetland.

Soil fertility is largely affected by the organic matter component of the soil, as well as other soil structural properties (e.g. clay content). The organic matter is formed as a result of the decomposition of the debris of fauna and flora communities by a variety of soil organisms (White 1979, Barko and Smart 1986). This decomposition results in the release of mineral nutrients and complex organic compounds which are important for plant growth (White 1979, Du Preez *et al.* 2011). The presence of organic matter in a soil also increases the water

holding capacity of the soil which affects vegetation cover (White 1979). Furthermore, the anoxic conditions in wetlands slow down the mineralisation rate of the organic matter in the soil, which facilitates the accumulation of the organic matter (Ashman and Puri 2002). Consequently, soils in wet environments typically have higher percentages of organic matter than soils in the surrounding environment.

Soils are able to store chemicals which in turn affects the acidity (Ashman and Puri 2002). Soil acidity is influenced by microbial activity and nutrient availability, as well as climate and vegetation, all of which consequently affect soil fertility (White 1979, Ashman and Puri 2002). Soil electrical conductivity (EC) is a measure of soil salinity, i.e. the amount of soluble salts in a soil. The EC is influenced by rainfall and evaporation, elevation, groundwater seepage and surface water (The Non-Affiliated Soil Analysis Work Committee 1990).

Soil mineralogy

The chemical properties of soils are largely influenced by weathering of the underlying parent geology (Schaetzl and Anderson 2005). This chemical weathering is affected by climatic conditions (such as temperature and moisture). Weathering is an important part of pedogenesis, affecting the availability of nutrients and the physico-chemical properties of the soil (Schaetzl and Anderson 2005). Several processes describe the breaking down of old minerals and the subsequent synthesis of new minerals/compounds (Schaetzl and Anderson 2005). Soil mineralogy describes the resultant compounds and provides an indication of what chemical processes have occurred in an area (Schaetzl and Anderson 2005). These chemical processes include: hydration, dissolution, hydrolysis and oxidation-reduction reactions (Drever 2005, Schaetzl and Anderson 2005).The soil mineralogy can consequently provide an indication of the hydrological characteristics of a wetland.

2.6.2. Wetland (hydric) soils

Wetland soils are soils that remain saturated or flooded for significant periods, resulting in anoxic conditions (Tiner 1993a, Mitsch *et al.* 2009). These waterlogged soils are termed *hydric soils,* and have different morphological features to non-hydric soils. Due to the anoxic environment, some plants species have adapted to these conditions and are known as hydrophytic plants (DWAF 2005, Mitsch *et al.* 2009). When hydric soils support hydrophytic plants, then the soil may be called a wetland soil (Environmental Laboratory 1987). The various soil properties, outlined below, serve as important wetland indicators in a variety of climatic conditions. Note: not all ephemeral wetlands have hydric soils which can be a result of the limited inundation/saturation period or the soil characteristics.

Hydric soils can be mineral or organic (peat) in nature (Environmental Laboratory 1987, Ashman and Puri 2002). General guidelines state that mineral soils have between 12% and 18% organic matter, and organic soils have more than 20% to 30% organic matter (Environmental Laboratory 1987, Brady and Weil 1999, Drever 2005). Organic soils that are saturated for extensive periods can become peatlands, which are comprised of up to 30% to 50% organic matter (Environmental Laboratory 1987, Ollis *et al.* 2013).

Mineral soils are saturated for a sufficient period of time to result in an anaerobic environment, with the corresponding soil colours, textures and other soil properties (Environmental Laboratory 1987, Tiner 1993a). In a temporarily saturated environment, mineral soils tend to have a grey matrix with mottles in the sub-surface horizons (Foth 1990, Job 2009). Gleyed soils occur when various compounds have leached out of the profile, leaving the soil matrix a greenish, bluish or greyish colour that is more indicative of a seasonally wet environment (Environmental Laboratory 1987, Mitsch *et al.* 2009). This is contrasted to non-wetland soils which are uniform in colour and tend to be lighter red or brown. Organic soils form in the submerged hydric soils as the decomposition rates of organic matter is reduced in the anaerobic environment, resulting in the accumulation of organic matter (Stein *et al.* 2004).

In SA, 58% of topsoil contains less than 0.5% organic matter, while only 4% of topsoils have more than 2% organic matter (Du Preez *et al.* 2011). The low organic content is largely attributed to low average rainfall across SA which affects vegetation cover and, consequently, the amount of material available for decomposition (Du Preez *et al.* 2011). Therefore, the boundary between organic and mineral soils in SA is defined differently as 10% organic matter throughout a vertical distance of 200 mm (Soil Classification Working Group 1991, Job 2009). Peat soil distribution (greater than 30% organic matter) is more limited in SA, to areas that have a higher average rainfall per annum such as the Maputaland region, the Drakensberg escarpment and valley bottoms on the Highveld (Smuts 1992, Grundling *et al.* 2002, Grundling *et al.* 2013).

Mottles are a result of accumulation and the reduction/oxidation of irons, manganese, and sulfur compounds (Brady and Weil 1999, Department of Water Affairs and Forestry 2005). This accumulation and reduction that occurs in patches (the mottles) are a result of a fluctuating water table and, consequently, an alternation between anaerobic (wet season) and aerobic (dry season) conditions (Tiner 1993a, Department of Water Affairs and Forestry 2005). As a result, mottles and concretions (larger than 2 mm) are often features of seasonal or ephemeral wetlands (but do not have to be present for the wetland to exist. Other indicators of a hydric soil include: high organic matter in the surface horizon, sulphuric (rotten egg)

odour, streaking of sub-surface horizon, oxidised root channels and soils with a low chroma matrix (Environmental Laboratory 1987, Job 2009).

2.7. HYDROPHYTIC VEGETATION

Hydrology, topography, geomorphology and the physical properties of sediments influence of the types of vegetation in a wetland (Mitsch *et al.* 2009, Rossi *et al.* 2014). Thus, wetland plants have adapted to certain pH and EC ranges within the sediments and water (White 1979, Sánchez *et al.* 1998), as well as to anoxic or reducing conditions (van Ginkel *et al.* 2011, Corry 2012). These adaptations indicate that the plant assemblages present in a wetland system could be used to identify prominent sources of water in a system. The vegetation would also consequently be affected by changes in ion and nutrient availability (White 1979).

Vegetation patterns change over time as a response to inundation/desiccation of the system (Sieben 2011). Such changes in plant communities are known as vegetation succession. The Gleasonian model describes this as allogenic succession, which is when a new species becomes established, when an existing/established species dies off, or when both of these occur at the same time within a wetland ecosystem (van der Valk 1981). This succession could also occur when anthropogenic activities impact the hydrology/water quality of a system.

Wetland plants are different from terrestrial vegetation as they have certain physiological, morphological and/or reproductive adaptations to grow, compete and reproduce in saturated soil conditions (Tiner 1993b, Corry 2012). In SA, DWAF (2005) has distinguished between four classes of hydrophytic plants that have adapted fully or partially to wetlands (Table 2-8). Obligate wetland plants are known as “hydrophytes” (Day *et al.* 2010, van Ginkel *et al.* 2011). Facultative wetland plants are collectively known as *helophytes* which are terrestrial plants that can tolerate long periods of submergence (van Ginkel *et al.* 2011, Corry 2012). Both obligate wetland (OW) and facultative wetland (FW) plant species are considered hydrophytic indicators, as they are more commonly associated with wetlands rather than non-wetlands (van Ginkel *et al.* 2011, Corry 2012). These wetland plants are also associated with a soil moisture gradient within a wetland. Other plants occupy a wetland as opportunists, or can tolerate saturated soil conditions at times. These are known as wetland-associated or opportunistic wetland plants (Table 2-8). Several plant families are found in wetlands in the Eastern Cape and these are outlined in Table 2-9.

Wetland plants can exist in zones of dominant plant species, or in complex mosaics that provide an indication of the hydrological dynamics in different parts of a wetland system (Tiner 1991, Bledsoe and Shear 2000). Overall dominance can provide an indication of the extent of the spatial and temporal dynamics of the hydric conditions in the wetland (Tiner 1993b).

Table 2-8 Classification of plants according to occurrence in wetlands. Compiled from: DWAF (2005), van Ginkel *et al.* (2011) and Corry (2012).

Species class	Other terms used	Occurrence
Obligate wetland (OW)		Almost always grow in wetlands (> 99% of occurrences)
Facultative wetland (FW)	Facultative positive	Usually grow in wetlands (67-99% of occurrences) but occasionally are found in non-wetland areas
Wetland-Associated (WA)	Facultative negative	Are equally likely to grow in wetlands and non-wetland areas (34-66% of occurrences)
Opportunist wetland (O)	Facultative dry-land (FD)	Usually grow in non-wetland areas but sometimes grow in wetlands (1-34% of occurrences)
Terrestrial species (T)	Dryland species (D)	Almost always associated with the terrestrial zone (> 99% of occurrences)

Table 2-9 Overview of some of the well-known wetland plant families found in the Eastern Cape. CFR = Cape Floristic Region, OW = Obligate wetland. Compiled from: Manning and Paterson-Jones (2007) and van Ginkel *et al.* (2011).

Family name	Distribution	Description & habitat
Aponogetonaceae	Throughout southern Africa, as well as other sub-tropical areas	Submerged or floating aquatic perennials found mainly in seasonal freshwater ponds.
Cyperaceae	Throughout South Africa (SA)	Generally annual or perennial herbs. Leaves have closed sheaths surrounding a 3-angled culm. Found in a wide variety of habitats. Mostly OW plants.
Eriocaulaceae	Throughout SA except in the Western Cape (WC)	Flowerhead of small flowers that are generally white, grey, brown or black. Generally, OW plants found alongside rivers & wetlands.
Juncaceae	Throughout southern Africa	Grass-like plants, either annuals or perennials. Found sub-tropical to temperate areas in shallow water (OW).
Poaceae	Found worldwide. Some species have limited distributions	Most widespread plant family on earth. Found in all soil moisture conditions.

Table 2-9 continued

Family name	Distribution	Description & habitat
Prioniaceae	Western Cape (WC), Eastern Cape and Kwa-Zulu Natal (KZN)	Only one species within SA (used to fall under *Juncaceae*). Found along the edge permanent water bodies.
Restionaceae	Mostly in the Cape Floristic Region (CFR), also further north in SA	Grass-like plants found in permanent and ephemeral systems. 300 of 320 species endemic to CFR.
Typhaceae	Worldwide; two species found throughout SA	Perennial herbs with small flowers arranged in dense cylindrical spikes. Found in a wide range of habitats (aquatic to terrestrial).
Xyridaceae	Worldwide, throughout SA	Approximately 10 species in SA. Annual or perennial plants that look like tufted, rush-like herbs. Flowers can be yellow, white, blue and purple. Grow seasonally, found in wet, marshy areas

2.8. WETLAND FAUNA

Faunal species play an important role in determining wetland function. Faunal groups found in wetland ecosystems include: invertebrates, frogs (amphibians), birds (especially water birds) (Semlitsch and Bodie 1998, Cowan 1999, Bird 2010). Fish can also be found in large and more permanent systems or those with fluvial connections (Semlitsch and Bodie 1998, Cowan 1999). These animals consist of both terrestrial and aquatic species which utilise wetlands as feeding, breeding and nursery grounds, inhabiting these systems on a temporal or permanent basis (Semlitsch and Bodie 1998, Cowan 1999).

Wetland fauna in both permanent and ephemeral systems can be diverse; however, in the latter, they tend to be dominated by large branchiopod crustaceans and insects when inundated (Day *et al.* 2010). Several aquatic invertebrate groups have adapted to survive during dry periods as desiccated propagules, or ‘resting eggs’ (Day *et al.* 2010, Ferreira *et al.* 2012). These eggs are deposited in the sediments by invertebrates and lie dormant until re-inundation occurs. As a result, wetlands may be identified, after extensive periods of drought, through collecting soil samples and using the sample to conduct hatching experiments (where eggs are hatched out of the soil in the laboratory under environmental conditions that suit ephemeral wetland faunal species) (Williams 1998, Ferreira *et al.* 2012). Some of these invertebrate groups are found almost exclusively in ephemeral wetland systems, such as some Branchiopoda: Anostraca, Notostraca and the Conchostraca. Therefore, these species can be used to distinguish between an ephemeral and a permanent system, even when fully

inundated (Williams 1998, Ferreira *et al.* 2012). Cladocera, Ostracoda and Copepoda are found in a wide variety of aquatic habitats, but also have a resting egg stage (Day *et al.* 2010, Ferreira *et al.* 2012). Other wetland faunal species will migrate to the wetland during the wet season, such as Hemiptera, Diptera and Coleoptera (Day *et al.* 2010, Rouissi *et al.* 2014).

The different life stages and forms of macroinvertebrates can be used as an indicator of the "age" of a wetland (in terms of its lifespan from inundation to desiccation) (Snodgrass *et al.* 2000, Ferreira *et al.* 2012). Certain species have rapid life cycles and mature quickly, while other species/groups will only be present or develop during longer inundation periods (Bird 2010, Ferreira *et al.* 2012). Thus, the invertebrate community identified through sampling can provide insight into the functioning of a wetland system.

2.9. WETLAND ECOSYSTEM SERVICES AND HEALTH

The aspects of wetlands that are perceived to be of value are those that provide ecosystem goods and services to society. These services are often associated with the ecosystem functioning of the system (see Section 2.10). These have been discussed and reviewed by many authors and as such are not described in detail (e.g. Semlitsch and Bodie 1998, Keddy 2000, Leibowitz 2003, Meyer *et al.* 2003, Machtinger 2007, Kotze *et al.* 2009b, Mitsch *et al.* 2009). Some of the common ecosystem services provided by ephemeral wetlands are outlined in Table 2-10.

A healthy (wetland) ecosystem is characterised by its various stable or dynamic states, with some form of natural resilience to environmental stressors (Millennium Ecosystem Assessment 2005, Ellery *et al.* 2009). In impacted systems, the stressors exceed that of what is considered normal for the system and, consequently, may result in a decline in resilience, which can potentially result in a permanent loss of ecosystems structure or function (Rapport *et al.* 1998, Ellery *et al.* 2009). For example, Ellery *et al.* (2009) suggests that a wetland that has an increased water discharge without the associated increase in sediment supply from upstream (due to damming or hardening of surfaces within a catchment), can become sediment deficient. Consequently, this system would have the potential to become unstable and prone to erosion.

Wetland health is linked to wetland functioning. A wetland in good 'health' will deliver its ecosystem functions/services well, whereas a wetland in poor health/severely modified loses its ability to perform certain functions, thereby devaluing the associated ecosystem services (Hollis 1990, Macfarlane *et al.* 2009). Thus, and modified system *may* function well, albeit, it might differ from how it functioned when it was in pristine condition (Day and Malan 2010).

Table 2-10 Ecosystem services supplied by ephemeral wetlands around the world. Benefits refer to that which effects human well-being directly or indirectly (generally consists of ecosystem supporting services).

Direct benefits	Reference examples	Indirect benefits	Reference examples
Biodiversity maintenance (habitat provision)	B, C, E, G, H, I, J	Flood attenuation (reduce runoff, often more effectively then permanent systems due to high evaporation rates)	C, E, G, H, I
Harvestable resources (e.g. plants), cultivated foods	C, D, E, G, I, J	Sediment and nutrient trapping (e.g. phosphorus, nitrogen, heavy metals)	A, B, C, E, G, H, I
Recreation (e.g. birdlife, fishing). Often associated with the intrinsic value of wetlands	C, D, E, F, G, I, J	Carbon sink (trapping carbon as soil organic matter)	C, D, E, H, I, J
Education & research	D, E, G, I, J		

A. Brinson (1993) B. Smith *et al.* (1995) C. Barbier *et al.* (1997) D. Keddy (2000) E. Millennium Ecosystem Assessment (2005) F. van der Duim and Henkens (2007) G. Kotze *et al.* (2009b) H. Mitsch *et al.* (2009) I. Maltby and Acreman (2011) J. Junk *et al.* (2013).

The assessment process detailed for SA wetland systems involves evaluating ecosystem health in terms of hydrology, geomorphology and vegetation is outlined by Macfarlane *et al.* (2009) in the WET-Health document. This research will not attempt to quantify these states as it falls beyond the scope of the study. However, when taking a more general approach towards understanding the health of a specific ecosystem, it is important to still collect adequate data on all three of the abovementioned ecological components as they provide much of the foundational knowledge needed to understand wetland structure and function, which is relevant to this study.

2.10. WETLAND PROCESSES: THE LINK BETWEEN WETLAND STRUCTURE AND ECOSYSTEM FUNCTIONING

Once wetland structure has been defined (see Section 2.2), it is important to establish how this structure impacts on the functioning of an individual wetland or wetland complex, and how this function plays a role in the broader landscape.

Wetlands provide resources for the environment (ecosystem services), including water, land, soil, fauna and flora (see Table 2-10) (Mitsch and Gosselink 2000, Maltby and Acreman 2011). Within geographically isolated wetlands, few comparative studies have quantitatively contrasted function across different HGM units, particularly in SA (Leibowitz and Nadeau

2003, McCartney *et al.* 2011). For example, in semi-arid climates, such as in large portions of SA, wetlands are an important source/sink of water in the landscape (Turner *et al.* 2000, Schuyt 2005). However, wetland functions may differ in the type, the degree to which a function may occur or the scale of effect (Brinson 1996). A shallow, precipitation-driven depression on a plateau will not necessarily feed into a fluvial system and could be classified as a water sink, whereas a depression on a slope, in close proximity to a stream or connected to a seep, would provide a water source to a nearby river (and flood attenuation). An examination of the literature suggests that this type of research approach is also limited across wetland complexes and in ephemeral versus permanent systems (Leibowitz and Nadeau 2003). Thus, to appropriately define and manage wetland functioning, the different scales and wetland types need to be considered (Brinson 1996). The basis of this approach would be to establish whether there are specific important environmental variables and species assemblages for each HGM type or within a wetland complex.

Some of the wetland processes that are reflected in the abiotic and biotic characteristics of a wetland and, consequently, their functioning, have led to the development of wetland inundation models. These models, such as those described by Euliss *et al.* (2004) and Pyke (2004), reflect some of the functional responses of a wetland to climatic events, primarily through the input of water into a system, thereby indicating the importance of the length, timing and frequency of inundation.

Different abiotic and biotic indicators are evident in an ephemeral wetland system. Euliss *et al.* (2004) provides a detailed conceptual model on the biotic changes that occur during a wetland inundation cycle and the associated relationship with groundwater (that affects inundation periodicity). This model highlights the importance of identifying where a wetland is positioned on both axes of the continuum proposed to best understand the biological community structure of the system at a particular time as well as how biological data can be interpreted as communities shift in accordance with changes in atmospheric (surface) water and ground water levels (Euliss *et al.* 2004). These dynamic community shifts illustrate the complexity of ephemeral systems that are identified. Sampling strategies need to be carefully considered to ensure that appropriate conclusions can be drawn from the biological data that is based on the timing (when in the inundation cycle) and type (amount of detail, or sampling sessions) of data collected. In addition, Pyke (2004) also illustrated the importance of the timing and amount of precipitation on the hydroregime of a vernal pool (precipitation-dominated depression wetland). This hydroregime is also affected by local environmental conditions, which can result in non-linear and more complex responses in the wetland (Pyke 2004). Similarly, this non-linear and complex response can occur in other wetland types in other locations.

Ephemeral wetlands generally have more variability in their physico-chemical characteristics than do permanent systems (Hancock and Timms 2002). Desiccation of a wetland reduces water depth which results in an increase in temperature, conductivity and (sometimes) turbidity of the water, as well as an increase in nutrients due to decomposition and concentration of material (Meintjes *et al.* 1994, Hancock and Timms 2002). Oxygen levels tend to decrease, together with an increase in the biological oxygen demand associated with a drop in water level (Meintjes *et al.* 1994). Therefore, both faunal and floral communities have adapted to these fluctuating abiotic conditions, resulting in community compositions that differ from those of more permanent systems. Table 2-11 provides an outline of how wetland indicators might change or develop according to the inundation and saturation period of wetlands in NMBM.

2.11. WETLAND POSITION IN THE LANDSCAPE: GEOGRAPHICAL ISOLATION AND CONNECTIVITY

The surrounding landscape plays a critical role in wetland formation, maintenance and function (Rossi *et al.* 2014, Kobayashi *et al.* 2015). Some of the landscape processes associated with wetland function are: water, sediment, nutrients and energy movements, as well as faunal and floral distribution patterns (Granger *et al.* 2005, Cook and Hauer 2007). It is important to identify which parts of the landscape provide these key environmental processes that affect wetland function (Leibowitz and Nadeau 2003, Granger *et al.* 2005). In addition, the interaction of environmental processes across different spatial scales within the landscape plays an important role in structural and functional relationships between wetland systems. Wetland geographical isolation and connectivity occurs on a spectrum across these different scales.

Geographically isolated wetlands lack a surface water connection to other water bodies (Leibowitz 2003, Tiner 2003b). However, intermittent hydrological connections can occur during times of flooding or through sub-surface and groundwater flows (Leibowitz 2003, Meyer *et al.* 2003). This “connection” or relative geographic isolation occurs at different spatial and temporal scales. In this study local isolation refers to the physical distance between wetlands, while longitudinal isolation refers to distances between a wetland and the nearest fluvial system.

Table 2-11 Possible changes in the five wetland indicators in the NMBM by inundation periodicity. Only key characteristics are displayed. FW = Facultative wetland; OW = Obligate wetland; Spp. = species; WA = Wetland-associated.

Indicator	Dry (non-wetland)	Ephemeral (< 3 months/annum)	Seasonal (> 3 months/annum)	Permanent (or semi-permanent)	
Mottles in the soil	None	Some	Lots	Few (or none)	DWAF (2005)
Soil colour (driven primarily by saturation periodicity)	Red & light brown soils	Darker brown with some grey (chroma 0-3)	Dark brown with black grey (chroma 0-2)	Black & grey soils (chroma 0-1)	DWAF (2005)
Vegetation	No wetland plants, maybe some WA species	Generally, grasses, FW & WA species	Dominated by FW & WA species, maybe some OW species such as sedges	OW, FW & WA species. Dominated by emergent, floating or submerged aquatic plants	Euliss *et al.* (2004), DWAF (2005), Drinkard *et al.* (2011)
Macroinvertebrates	Desiccated propagules in soil. Terrestrial invertebrates	Passive dispersers. Invertebrates with a resting egg stage: Branchiopods (Anostraca, Notostraca, Conchostraca), and other zooplankton (Rotifera, Cladocera and Copepoda) with rapid life cycles and/or single generations.	Passive & active dispersers. Spp. found in ephemeral systems as well as Diptera, Coleoptera, Hemiptera & gastropods. Multi-generations & resting egg stage	Mature active dispersers. Spp. found in ephemeral & seasonal systems as well as more predator species. Community increasingly shaped by predator-prey interactions, especially with inclusion of fish as top predators	Euliss *et al.* (2004), Ferreira *et al.* (2012), O'Neill and Thorp (2014), Rouissi *et al.* (2014)
Amphibians	None	Species with short larval stages	Species with short to long larval stages and & aquatic juveniles (e.g. froglets)	Multi-generations. Species with long larval stages. Predatory species.	Euliss *et al.* (2004), O'Neill and Thorp (2014)

Biotic connectivity is the movement/dispersal of plants and animals between two habitat patches, while hydrological connectivity is the intermittent surface water connections between two water bodies (Leibowitz 2003, Leibowitz and Nadeau 2003). The degree of geographical isolation, as well as the distance between two water bodies, affects species dispersal, species richness and overall community composition (Semlitsch 2000, Leibowitz 2003). These movement patterns result in 'source-sink dynamics': a surplus of individuals in one wetland can act as a source to other systems, while other wetlands, that are drying up, result in the local population of a species dying out (the sink) (Semlitsch 2000). The ephemerality of wetland systems means that different systems are inundated at different times of the year and for different lengths of time. Therefore, a complex of wetlands (wetlands in close proximity to each other) is needed within a landscape to maintain biological interactions/connectivity over a broader scale (Gibbs 1993, Semlitsch 2000). Thus, wetland connectivity can influence the biological community structure of wetlands. This is especially important in ephemeral areas where rainfall is less predictable, as is the case in the NMBM.

Broad-scale mapping and delineation, as well as statistical analyses, can be used to assess spatial and temporal associations between wetland complexes and to determine how wetlands are linked to landscape processes. There is a need to establish how these driving forces behind the structure and interactions of ephemeral depressions in a semi-arid environment can be used to determine their function within the surrounding landscape. These concepts are expounded on in Chapters 5 and 6.

There are many names for geographically isolated wetlands worldwide. An abbreviated list of some well-known isolated wetlands is provided in Table 2-12. These systems are driven by various processes and inundation patterns, which, in turn, have shaped the abiotic and biotic characteristics of these systems. The need for this knowledge, for SA systems, was highlighted in Section 1.3. The ephemeral systems in Table 2-12 can be used to compare to similar wetlands in the NMBM.

Table 2-12 Examples of geographically isolated ephemeral wetlands found in different regions around the world. The main processes that drive their formation and inundation are highlighted. * Sinkholes occur in karst regions worldwide.

Type	Location	Formation & Structure	Hydrology & Connectivity	References
Carolina Bay wetlands	South Atlantic Coastal Plain	Shallow, elliptical depressions with a sandy rim due to aeolian processes in dune systems	Intermittent connections with other wetland systems and indirectly to streams/rivers. Precipitation & evapotranspiration driven	11, 13
Endorheic Pans	Southern Africa as well as other semi-arid regions around the world	Closed depressions found in dryland regions which form as a result of salt weathering and aeolian deflation. Can be associated with calcrete or silcrete	Found in areas where mean annual precipitation is less than 500 mm Can be groundwater and/or surface water driven	1, 5, 12
Gilgais	Worldwide, especially Australia	Argilliturbation (repeated swelling & shrinking of clay). Perched systems on hard clay layer	Precipitation & evapotranspiration driven during the wet season (winter/spring)	3, 4
Playa lakes	South-west USA	Wind, wave and dissolution processes	Seasonal precipitation driven depressions via snowmelt &/or rainfall	2, 9, 14
Pocosins	South Atlantic Coastal Plain	Interfluves between rivers	Precipitation driven. Intermittent connectivity with other systems	9, 14
Prarie potholes (kettle holes)	Northern USA	Glacial processes	Precipitation & run-off driven	7, 9, 14
Tarns/Corrie Lochs	Australia, New Zealand	Glacial processes	Fed by surface water & precipitation	6, 14
Turloughs (sinkholes)*	Ireland & Slovenia	Karst processes – the dissolution of limestone ($CaCO_3$)	Seasonally inundated by karst groundwater. Connections can occur through groundwater	9, 10, 13
Vernal pools	USA	Various processes, including glacial. Depressions often perched systems on a bedrock or hard clay layer	Precipitation (snow and rain) driven during winter or spring. Temporary surface water connections occur.	8, 9, 14, 15

1. Allan *et al.* (1995) 2. Bartuszevige *et al.* (2012) 3. Dickson *et al.* (2014) 4. Goudie (2013) 5. Goudie and Thomas (1985) 6. Johnson and Rogers (2003) 7. Kahara *et al.* (2009) 8. Lathrop *et al.* (2005) 9. Mitsch and Gosselink (2007) 10. Proctor (2010) 11. Sharitz (2003) 12. Shaw (1988) 13. Sheehy-Skeffington *et al.* (2006) 14. Tiner (2003b) 15. Zedler (2003)

2.12. ANTHROPOGENIC IMPACTS ON WETLANDS

Anthropogenic activities influence wetland function and health. These activities could potentially result in wetland loss, where wetland areas are converted into non-wetland areas (i.e. there is a loss of function), or wetland degradation, where wetland function becomes impaired due to human activities (Maltby and Acreman 2011, Mitchell 2013).

Many wetlands have been drained or dredged for housing developments and agriculture, or even to prevent mosquitos breeding (Barbier *et al.* 1997, Maltby and Acreman 2011). Overgrazing or removal of vegetation as well as paved surfaces in urban areas increase surface run-off and lower the water table level (Arnold Jr. and Gibbons 1996, Mitchell 2013). Alien vegetation and groundwater extraction can also place a strain on the water resources (Millennium Ecosystem Assessment 2005, Junk *et al.* 2013). Pollution of ground and surface waters from urban or rural developments can severely impact the quality of water entering wetlands (Turner *et al.* 2000, Junk *et al.* 2013), which in turn could affect the overall health of the wetland system.

Unsustainable harvesting of wetland resources (for example, plants and fish) can also negatively impact wetland ecosystems (Barbier *et al.* 1997, Millennium Ecosystem Assessment 2005). Tourism and recreational activities can also have an effect on wetlands. On larger systems, power boating, off-road vehicles, fishing, hunting and abstraction of water can place a strain on wetland resources (Burger *et al.* 1995, Millennium Ecosystem Assessment 2005). On smaller systems, even small amounts of human activity can result in significant disturbances to the surrounding vegetation or fauna in the wetland (Meyer *et al.* 2003).

Wetland degradation or a change in wetland function can be associated with increased nutrient inputs (particularly phosphorus and nitrogen) into a system from agricultural, industrial or sewage sources (Rossouw *et al.* 2005, Corry 2012). This nutrient-enrichment leads to increased algal growth and reed growth, which consequently reduces the amount of available oxygen in the water column, and leads to changes in the wetland community structure (Rossouw *et al.* 2005, Corry 2012).

Another possible cause of human-induced wetland degradation is a lack of knowledge on how these complex systems function (Turner *et al.* 2000, Schuyt 2005). This effect is compounded in smaller, more ephemeral systems which are less ‘obvious’ to untrained people and are consequently seen as less important (Meyer *et al.* 2003, Blackwell and Pilgrim 2011). As a result, they tend to be encroached on or affected before their existence is known

or the impact of a particular activity is understood (Semlitsch 2000, Meyer *et al.* 2003). Consequently, this often results in the failure to predict or manage regional anthropogenic activities on the surrounding wetlands because of the lack of information on the complex spatial relationships between the ground and surface water, surrounding land use and wetland vegetation (Turner *et al.* 2000, Schuyt 2005).

To conserve and protect smaller or ephemeral systems, input and agreement is required from socio-economic, political and environmental stakeholders, at various spatial scales (Turner *et al.* 2000, Schuyt 2005). As mentioned previously, functioning wetlands provide a wide array of ecosystem services. Therefore, wetland resources need to be sustainably used to ensure that future generations will have access to the goods and services supplied the wetlands before there is an irreversible impact on wetland function (van der Duim and Henkens 2007). An important component of sustainable use is understanding the spatial and temporal scales of the anthropogenic (and ecological) stressors on a system which should be part of a spatially applicable decision-making processes (Danz *et al.* 2007, Minaya *et al.* 2013).

2.13. POTENTIAL EFFECTS OF CLIMATE CHANGE

Climate change refers to statistically quantifiable changes in the climate that persist for an extended period, and refers to both natural and human-induced changes (IPCC 2014). In SA, climate change could result in increased temperature, changing rainfall patterns (mostly a reduction in rainfall) and more extreme rainfall patterns such as droughts and floods (Mitchell 2013, IPCC 2014). These changes would result in an increased net water loss to systems, which could potentially result in a reduction in the number and/or size of ephemeral wetlands (Erwin 2009, Junk *et al.* 2013). Ephemeral ecosystem functions could be altered because the abiotic and biotic components of the system are strongly influenced by the timing of the hydrologic regime (as well as the amount of surface water input) (Erwin 2009, Junk *et al.* 2013). This is partially due to their rapid evaporation rates and their shallow depths (Erwin 2009, Johnson *et al.* 2010).

A reduction in rainfall could also result in the overall reduction of wetland areas over a landscape, thereby potentially affecting overall wetland connectivity (Erwin 2009, Johnson *et al.* 2010). These changes in rainfall patterns could also potentially result in a greater disturbance to the ecosystem structure, making them less resilient to further impacts (whether human or naturally induced) (Erwin 2009, Junk *et al.* 2013).

Climate change can potentially compound the effects of human activities on wetlands. The negative effects of overexploitation of wetland resources due to various socio-economic

factors (population growth, poverty etc.) can be exacerbated by drought (Turner *et al.* 2000, Junk *et al.* 2013). For example, freshwater availability is already limited in southern Africa, and this is expected to worsen with a reduction in precipitation and increasing population pressures for freshwater supplies (IPCC 2014). The increase in extreme weather events can put wetland systems under increased strain and possibly reduce the ability for the systems to withstand previously sustainable levels of human activity (Erwin 2009, Junk *et al.* 2013).

The effects of climate change illustrate the need for extensive wetland research that can be used to establish appropriate management strategies. This type of research begins with baseline knowledge on the number of wetlands, size, position in the landscape and the influence of surrounding anthropogenic activities. Combined with knowledge obtained on wetland functioning, the vulnerability of wetlands can also be more accurately assessed.

2.14. CONCLUSION

This review has illustrated the wide variety of wetland systems that exist globally and within SA as a result of various hydrological and geomorphological factors. Yet, the majority of wetland research has been carried out in limited areas within SA. Therefore, research in various climatic regions within SA is still needed to further understand the variety of systems that exist in the country. Until recently, little was known about the distribution, structure and function of ephemeral systems that exist in semi-arid areas of the Eastern Cape (United Nations Environmental Programme 2009), and the present CS (Ollis *et al.* 2013) had not been applied to such areas. This study will apply the CS that exists for SA, and use the main wetland indicators (hydrology, soils, and plant and macroinvertebrate communities) to determine the patterns in wetland distribution and structure, as well as ecosystem functioning of some ephemeral systems, in the NMBM. Various soil and water properties, as well as vegetation and faunal species, are unique to (or more commonly found in) wetlands than in the terrestrial environment. These indicators are, therefore, useful in determining the presence of a wetland during wet and dry periods, as well as providing insight on environmental processes occurring at a broader scale. Thus, these indicators become important when conducting wetland research in a semi-arid environment when water is not always present in a wetland system. This review has also highlighted the need to take into account anthropological and climate factors that affect wetland ecosystems at varying levels of intensities and at different scales. Therefore, wetland research needs to be conducted across different spatial and temporal scales, taking into account various wetland indicators and the different aspects (environmental and anthropogenic) of the surrounding ecosystems. This forms the foundation of this study in the NMBM.

3. STUDY AREA

3.1. INTRODUCTION

A brief introduction to the study area was described in Section 1.2. This chapter describes the prominent geographical, geological, hydrological and biological features of the NMBM. Related anthropogenic activities and conservation strategies are also outlined. Detailed, recorded knowledge on small wetlands in the Municipality has been limited until recently. These environmental and anthropogenic features associated with the NMBM are based on data obtained from the literature and from various secondary (already existing) spatial data (see Appendix B for a list of spatial data and their respective sources).

3.2. CLIMATE

The NMBM is situated along the southern edge of the Eastern Cape Province of SA, bordering the Indian Ocean (Figure 3-2). The weather of Algoa Bay is predominantly controlled by high pressure systems as well as cold fronts and coastal lows (Goschen and Schumann 1988, 2011). These fronts and coastal lows are associated with high winds and cloud cover which bring rainfall to the region (Goschen and Schumann 1988).

The Municipality is dominated by west south-westerly winds, as well as south-westerly and westerly winds throughout the year (Illenberger 1986, Goschen and Schumann 1988). Land and sea breezes constitute an important component of local winds in the bay (Beckley and McLachlan 1979, Beckley 1983). These winds, as well as the local rainfall, influence evaporation rates.

Port Elizabeth (PE) falls in the transition zone between winter and summer maximum rainfall regions which are found on the west and east coasts of SA respectively, and experiences an overall winter maximum rainfall (Stone *et al.* 1998). Weather data from the South African Weather Service (SAWS) indicates that this region receives, on average, 613 mm of rainfall per annum, which can fall at any time throughout the year (Figure 3-1). The rainfall is unevenly distributed, with the northern parts of the Municipality receiving between 364 mm and 480 mm per annum, while the southern coastline receives between 630 and 720 mm of rainfall per annum. Evapotranspiration rates are much higher at approximately 1800 mm per annum (1600 mm in the south to 2000 mm in the northwest of the NMBM). This indicates that, in general, evaporative losses are greater than precipitation gains (except during a rainy season), resulting in a nett water loss, frequently associated with dryland or semi-arid areas.

A dryland is defined by the United Nations Environmental Programme (UNEP) (2009), as areas with an aridity score of less than 0.65, which equates to MAP that is 1.5 times lower than the mean annual potential evapotranspiration rate. Consequently, the NMBM is classified as a dryland with aridity scores ranging from 0.291 in the north, to 0.569 in the south-east corner (UNEP 2009). In terms of the Köppen climate classification, only the northern half of the Municipality is categorised as semi-arid, while the southern two quaternary catchments are classified as humid sub-tropical and oceanic climates (Kottek *et al.* 2006). However, the southern part of the Municipality falls within the lower extreme of the latter two classes, with rainfall being less available and consistent (Pers. Obs.). Thus, the NMBM is better represented by the dryland definition of a semi-arid area, and it is this definition that is used in this research. In summary, the overall lack of available and reliable provision of surface water illustrates the need for extensive knowledge on water resources in the Municipality.

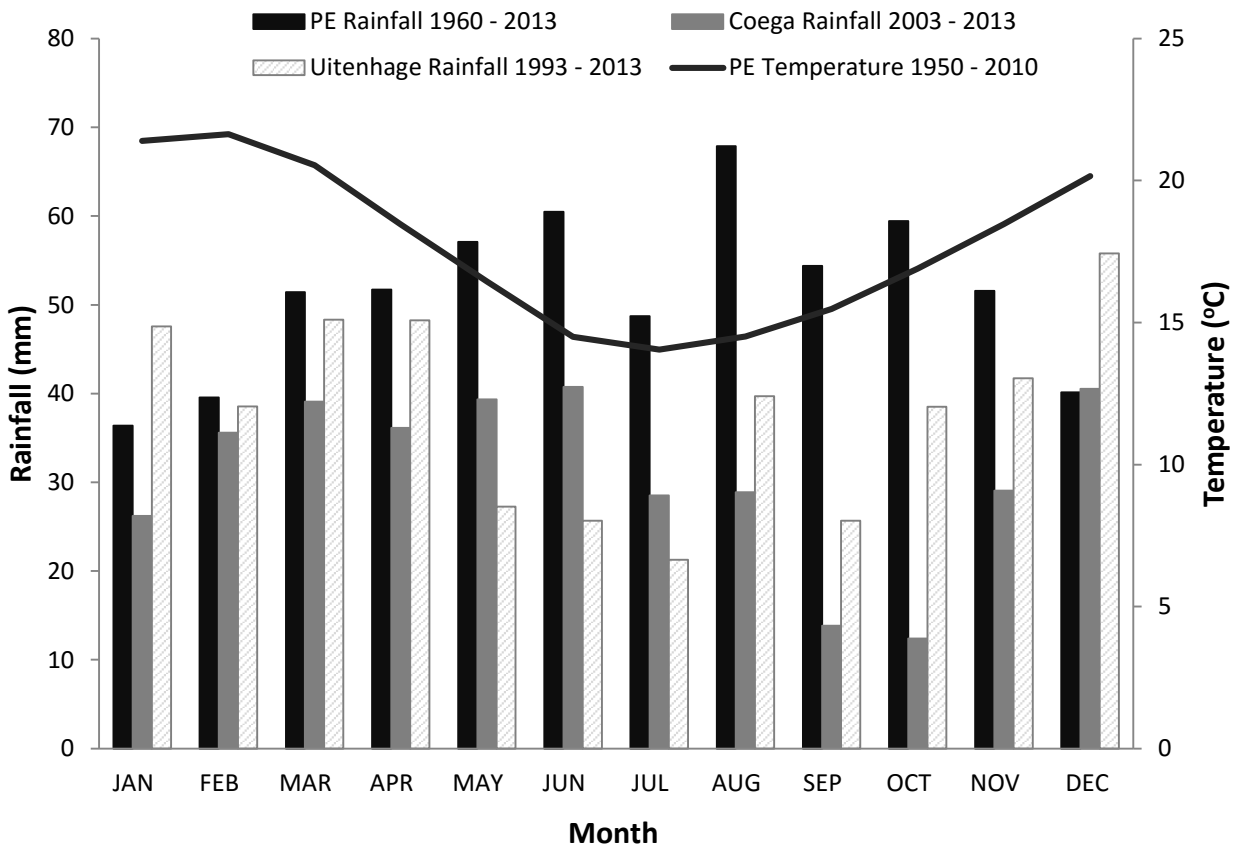

Figure 3-1 Long-term mean monthly rainfall and temperatures for Port Elizabeth (PE), Coega and Uitenhage. Timeframes of data collection for each weather station are given in the legend. See Figure 3-2 for weather station locations. Error bars have been excluded due to the large variation in monthly rainfall.

3.3. GEOMORPHOLOGICAL FEATURES

The Municipality is generally low-lying with altitudes ranging from 0 m above mean sea level along the coast to 955 m along the western edge of the Municipality (Figure 3-2). The Van Stadens Mountains lie to the south-west of the Municipality and the Winterhoek Mountains towards the north-west.

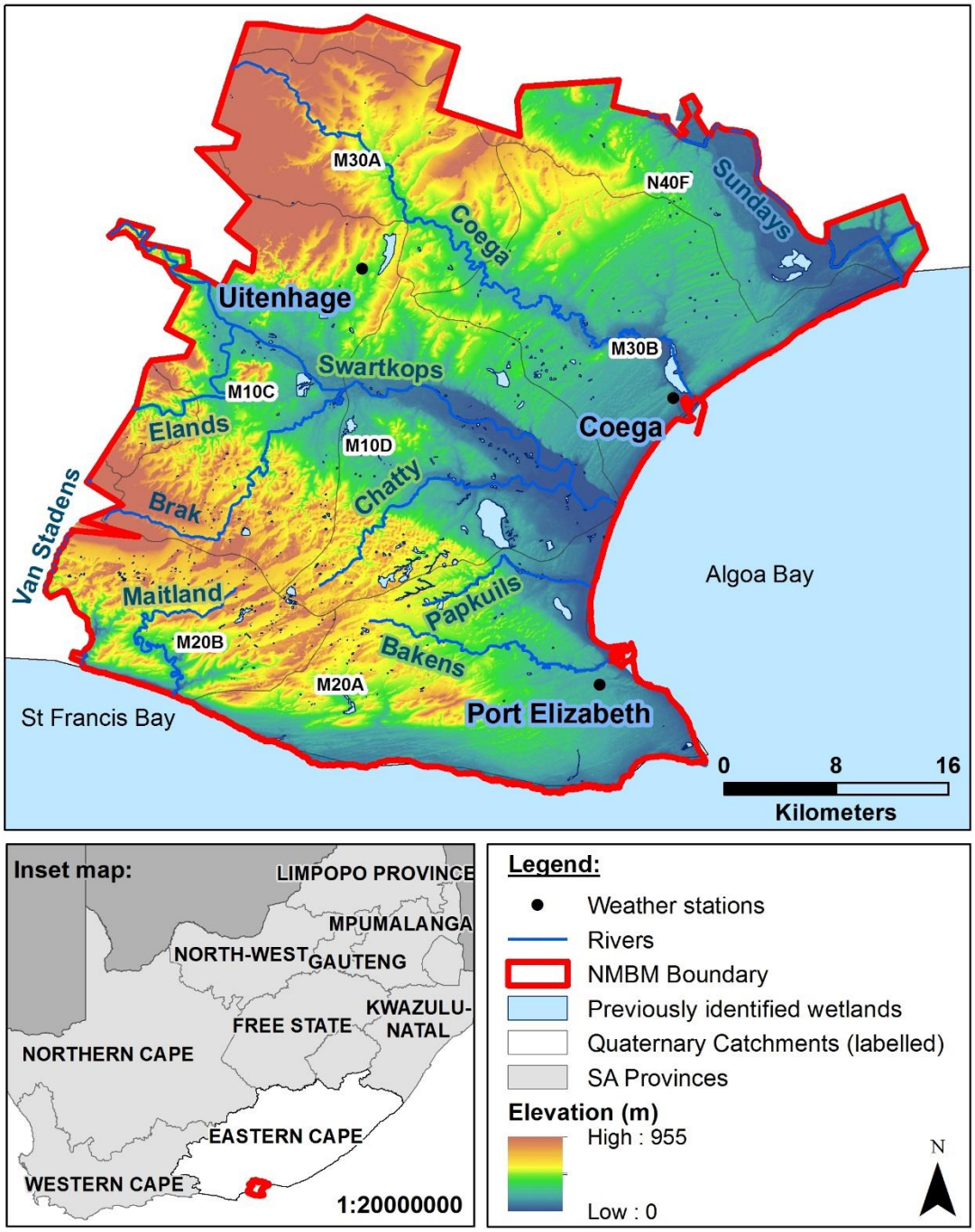

Figure 3-2 **Environmental and hydrological features of the NMBM study area situated in the Eastern Cape Province of South Africa (inset map). Data from Stewart (2008), NMBM (2011), Department of Water Affairs (2012).**

The geology of the Eastern Cape region is dominated by sedimentary rocks of the Cape and Karoo Supergroups (Maud 1998). PE forms the eastern margin of the Cape Fold Belt with Gamtoos and Table Mountain Group (TMG) deposits, superseded by various formations in the Bokkeveld and Algoa Groups (Figure 3-3). The more recent deposits from the Uitenhage group, Alexandria and Nanaga Formations (Algoa Group), and quaternary deposits, which comprise the surface geology in the NMBM (Maud 1998). The Alexandria and Nanaga Formations form part of the Post-African II erosion surface layer which has resulted in sandstone comprising a large portion of the surface geology for the NMBM (Maud 1998). Another important geological feature are the calcrete layers that have formed in many areas with these sandstones and aeolian sand deposits (Lomberg *et al.* 1996). A detailed geological map is illustrated in Figure 3-3 with further descriptions of the formations given in Appendix C.

Surface sediments and present day topography are affected by underlying geology, geomorphological and aeolian processes (Ellery *et al.* 2009). The Alexandria Dunefields lie to the north-east of the Municipality while the Cape Recife Headland-bypass Dunefields are found on the southern border of the city of PE, across the Cape Recife Headland (Illenberger and Burkinshaw 2008). These dunefields are important sand movement corridors providing a habitat for soil-specific plant communities and plant species diversity and host a number of ephemeral wetlands (Cowling *et al.* 2003, Stewart 2010). Alluvial deposits underlying the main river channels also form important sedimentary features in the NMBM (CSIR 2011).

3.4. WATER RESOURCES

As defined by Vegter (1990), the NMBM falls within two hydrogeological regions (based on lithology and climate): the Lower Gamtoos Valley along the southern part of the Municipality, and the Algoa Basin in the north. In both these basins groundwater comes from both intergranular and fractured aquifers. The Uitenhage aquifer is found within the Algoa Basin, and is one of the most well-known artesian aquifers in the country, providing around 10% of the water for the area around the town of Uitenhage (DWA 2010b). The TMG aquifer in the PE area has relatively low yields (less than 10 $m^3.h^{-1}$) and is not generally of good quality (Lomberg *et al.* 1996).

The NMBM falls within the Swartkops River Catchment (Primary Water Catchment M) and the Sundays River Catchment (Catchment N) (Haigh 2002, Institute of Water Research 2004). Ten quaternary catchments are located within the Municipality (DWAF 2012) with rivers flowing into St Francis Bay, in the south, and Algoa Bay in the east (Figure 3-2).

Riparian areas cover approximately 16% of the total area of the NMBM (Stewart 2010). However, most of these streams are intermittent, with the main perennial and non-perennial channels covering approximately 4.4% of the NMBM area, with 1.4% of this coverage now lost due to anthropogenic activities (Stewart 2010).

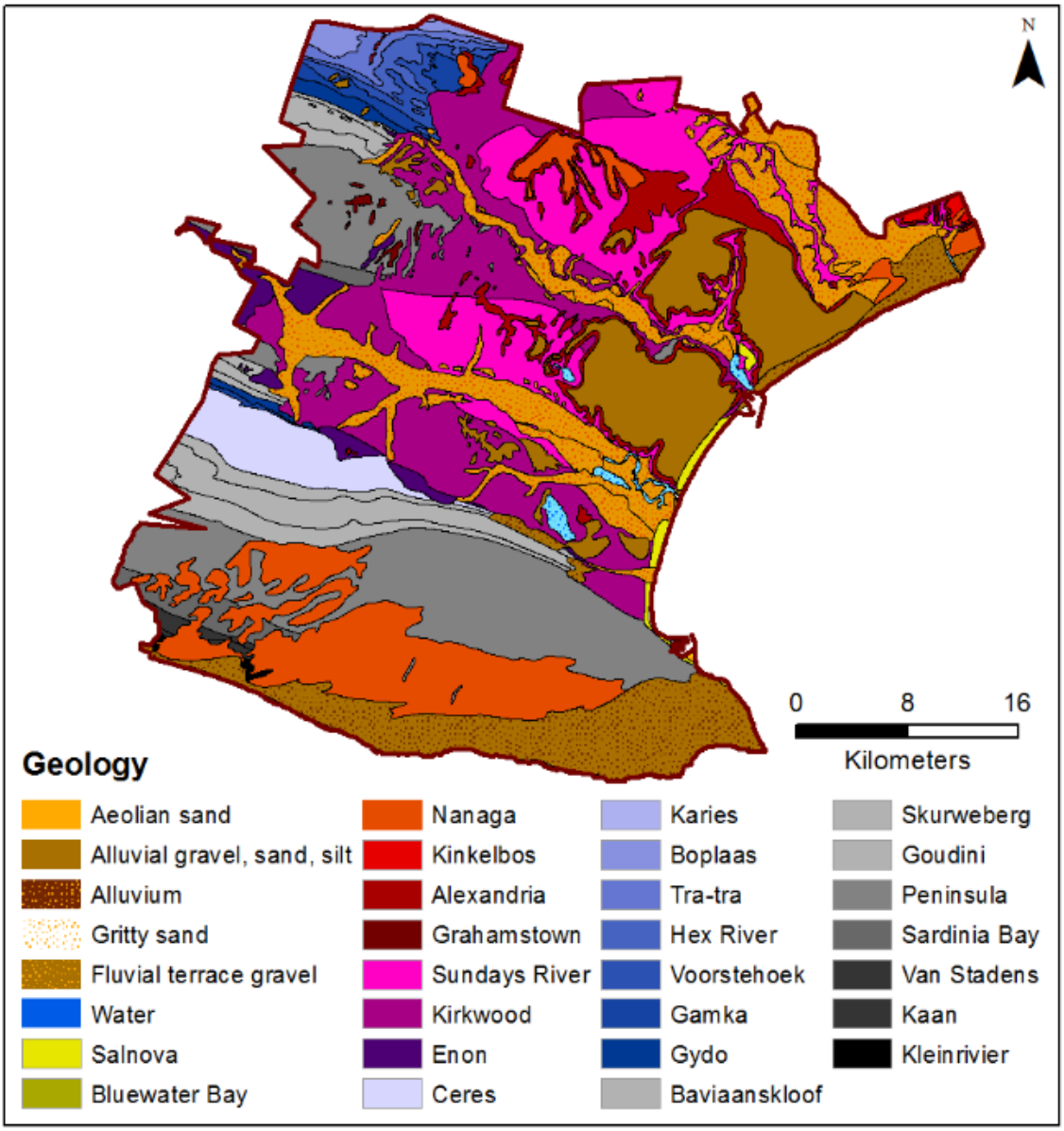

Figure 3-3 **Geological map for the NMBM with the legend depicting formations from youngest to oldest. Quaternary deposits are comprised of aeolian sand and gravels), followed by formations in the Algoa Group (shades of orange/yellow), Grahamstown Group, Uitenhage Group (shades of pink), Bokkeveld Group (shades of blue) and the Table Mountain Group (Baviaanskloof to Sardina Bay formations), with the oldest formations belonging to the Gamtoos Group (the Van Stadens, Kaan and Kleinrivier formations). Descriptions for each of the formations are given in Appendix C. Data from Council for Geosciences (N.D.).**

The Swartkops and Sundays rivers are two large perennial systems within the NMBM with permanently open estuaries draining into Algoa Bay (Figure 3-2) (Bremner 1983). The Sundays River mouth (33°43.32' S 25°50.95' E) is situated along the northern section of the NMBM border. This river and has a catchment area of approximately 20 729 km^2 and receives perennial flow through the Orange-Great Fish inter-basin transfer scheme (Whitfield 2000).

The Swartkops River (33°51.90' S 25°38.00' E) has a catchment size of approximately 1555 km^2 and is situated 10 km north-east of PE (Melville-Smith and Baird 1980). This permanently open estuary is 16 km long and several salt pans and estuarine wetlands are found within its floodplain.

The seasonal Coega River (33°47.82'S 25°41.72'E) enters Algoa Bay, supporting a salt-extraction works along the middle and lower reaches, and the Port of Ngqura (Coega Port) which is situated at the mouth of the river (Bremner 1983, Whitfield 2000). The Papkuils River (33°55.03' S 25°36.83' E) and the Baakens River (33°57.83' S 25°37.77' E) are also small non-perennial streams with canalised openings to the sea, the latter flowing into the PE Port (Bremner 1983, Whitfield 2000).

Two other rivers have temporarily open/closed estuarine openings to St Francis Bay, on the south-west corner of the NMBM. The Maitland River mouth (33°59.28' S 25°17.45' E) is situated approximately 26 km west of PE and is a small (approximately 600 m in length), shallow sandy system (Whitfield 2000, James and Harrison 2010). The Van Stadens River mouth (38°58.17' S 25°13.28' E) is a relatively undisturbed system that forms part of the western border of the NMBM and is situated approximately 32 km west of PE. This river has a catchment area of 271 km^2, and an estuarine length of about 3 km (Whitfield 2000, James and Harrison 2010).

In a conservation assessment done between 2007 and 2009 by Stewart (2010) approximately 40.5 km^2 of wetlands in the NMBM were measured; however, most of this mapped area consisted of estuaries, salt marshes and pans (Figure 3-2). Only 2.7 km^2 of the Municipality area was defined as a wetland or pan, as well as a further 4 km^2 of dams were delineated by Stewart (2010), when the estuarine systems and artificial pans were excluded. The National Wetland Map IV comprises 60.1 km^2 of wetlands in the Municipality (CSIR 2011). This wetland coverage was also primarily comprised of estuarine wetlands, salt pans and other artificial systems (e.g. salt works). Thus, the contribution of small ephemeral systems was largely underrepresented in these databases.

3.5. VEGETATION

3.5.1. Terrestrial vegetation

Vegetation in the region has been primarily shaped by the underlying geology and the semi-arid climate. The NMBM is situated in the south-eastern corner of the Cape Floristic Region (CFR) and the southern edge of the Albany Centre of Endemism (ACE), both of which are recognised centres of biodiversity including floral and faunal endemism (Van Wyk and Smith 2001, Cowling *et al.* 2004). Several reports indicate that the NMBM is an area of convergence of five of the seven biomes found in SA, namely: Fynbos, Subtropical Thicket, Forest, Nama Karoo and Grassland (Low and Rebelo 1998, Vlok and Euston-Brown 2002, Stewart 2010). Within these biomes various broad habitat units and vegetation types have been defined (Vlok and Euston-Brown 2002, Cowling *et al.* 2004, Stewart 2010). A detailed map of the distribution of terrestrial vegetation types is illustrated in Figure 3-4 with the associated key in Table 3-1. These spatial data were used for this study for site selection and data analysis across the various vegetation types.

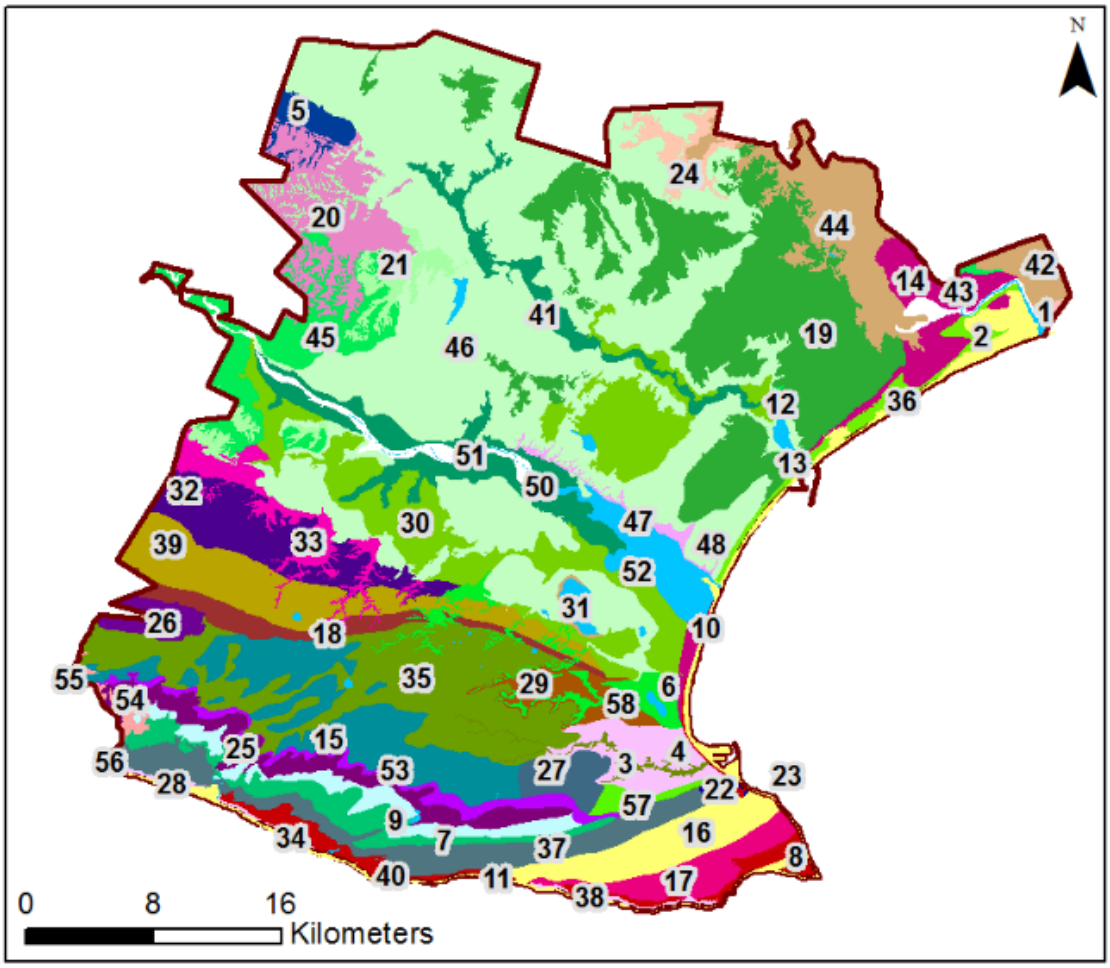

Figure 3-4 Detailed vegetation map for the NMBM. Vegetation types are listed in Table 3-1. Data from Stewart (2010).

Table 3-1 Vegetation types found in the NMBM. Distribution is illustrated in Figure 3-4. Data from Stewart (2009).

Code	Vegetation type	Code	Vegetation type
1	Albany Dune Thicket	**31**	Pan
2	Algoa Dune Thicket	**32**	Rocklands Renoster Bontveld
3	Baakens Forest Thicket	**33**	Rocklands Valley Thicket
4	Baakens Grassy Fynbos	**34**	Rocky Beach
5	Baviaans Spekboom Thicket	**35**	Rowallan Park Grassy Fynbos
6	Bethelsdorp Bontveld	**36**	Sandy Beach
7	Bushy Park Indian Ocean Forest	**37**	Sardinia Bay Forest Thicket
8	Cape Recife Bypass Dunefield	**38**	Schoenmakerskop Rocky Shelf Fynbos
9	Chelsea Forest Thicket Mosaic	**39**	Skurweberg Grassy Fynbos
10	Coastal	**40**	St Francis Dune Fynbos Thicket Mosaic
11	Coastal Hummock Dunes	**40**	Wetland
12	Coega Estuary	**41**	Sundays Doringveld Thicket
13	Coega Estuary Floodplain	**42**	Sundays River
14	Colchester Strandveld	**43**	Sundays River Floodplain
15	Colleen Glen Grassy Fynbos	**44**	Sundays Spekboom Thicket
16	Driftsands Bypass Dunefield	**45**	Sundays Thicket
17	Driftsands Dune Fynbos	**46**	Sundays Valley Thicket
18	Goudini Grassy Fynbos	**47**	Swartkops Escarpment Valley Thicket
19	Grass Ridge Bontveld	**48**	Swartkops Estuarine Floodplain
20	Groendal Fynbos	**49**	Swartkops Estuary
21	Groendal Fynbos Thicket	**50**	Swartkops River
22	Humewood Dune Fynbos	**51**	Swartkops River Floodplain
23	Intermediate Beach	**52**	Swartkops Salt Marsh
24	Koedoeskloof Karroid Thicket	**53**	Thornhill Forest and Thornveld
25	Kragga Kamma Indian Ocean Forest	**54**	Van Stadens Afromontane Indian Ocean Forest
26	Lady Slipper Mountain Fynbos	**55**	Van Stadens Forest Thicket
27	Lorraine Transitional Grassy Fynbos	**56**	Van Stadens River
28	Maitland Dunefield	**57**	Walmer Grassy Fynbos
29	Malabar Grassy Fynbos	**58**	Wetland
30	Motherwell Karroid Thicket		

The dunefields along the south-east and north-east coastline of the Municipality are comprised of aeolian sand, with limited vegetation cover. The south is comprised of Fynbos (inland and coastal) and Subtropical Thicket. A small portion of St Francis Dune Fynbos Thicket Mosaic is located along the Cape Recife headland (Figure 3-4). The northern parts of the Municipality are comprised of various Thicket and mosaic vegetation types, which are

associated with the underlying geology. These include: Dune Thicket, Sundays Valley Thicket, Motherwell Karroid Thicket, Grass Ridge Bontveld and Bethelsdorp Bontveld (Vlok and Euston-Brown 2002, Stewart 2010).

Several invasive grass and weed alien plants have been observed both within wetlands and in the surrounding ecosystems in the NMBM. Many of the invasive plant species are associated with wetland areas in the Eastern Cape, especially pioneer terrestrial species which initially occupy a wetland area that has recently dried up. Some of these invasive plants include Port Jackson (*Acacia saligna*), and several weed species (e.g. *Chenopodium album*, *Chenopodium carinatum*, *Eclipta prostrata,* and *Sonchus asper*) (Schael *et al.* 2015). These species affect the distribution and abundance of indigenous plant species (affecting biodiversity), as well as potentially affect hydrological dynamics within a catchment (Zedler and Kercher 2004).

3.5.2. Wetland vegetation

Wetlands provide a habitat for a number of specialised plant species that have adapted to either temporary or permanent wetland environments. These adaptations are a result of factors such as hydroperiod, sediment characteristics and movement, nutrient inputs, seed dispersal, and especially the ability to survive prolonged periods of soil saturation (Drinkard *et al.* 2011, Corry 2012, Raney *et al.* 2014). As a result, plant communities within a wetland tend to 'zone' according to these abiotic conditions, resulting in distinct rings of plant communities around a wetland (Keddy 2000, Corry 2012).

The CS for SA (Ollis *et al.* 2013), classifies wetlands at a broad scale according to their ecoregion or wetland vegetation group. The NMBM falls within the Southern Eastern Coastal Belt ecoregion (Kleynhans *et al.* 2005), which hosts the endemic Succulent thicket biome, as well as a number of more local, endemic species such as several *Euphorbia* spp., and the *Aloe africana* (Low and Rebelo 1998, Johnson *et al.* 1999, South African National Biodiversity Institute 2014).

Until recently, no systematic research had been done on wetland vegetation in the NMBM or across most of the Eastern Cape (Sieben 2012). Various hydrologically adapted plant species are found in wetlands and the NMBM falls within the distribution range of several of these wetland plant families. Plant families associated with small wetlands found in the Eastern Cape include those listed in Table 2-9 on page 25. Most of these families are found in the NMBM with the exception of Eriocaulaceae (eriocaulons) and Xyridaceae (yellow-eyed grasses). The distribution of these wetland plant families is given in Table 2-9, page 25. A wide variety of species with different adaptations are found within each family, with some

species having a limited distribution and others, more broadly distributed. Other plant types were also observed in the NMBM, such as geophytes and herbs/forbs.

3.6. LAND USE AND ANTHROPOGENIC ACTIVITIES

Approximately 40% of the NMBM has been modified or transformed to some extent (Figure 3-5). Urban activities are concentrated in the wetter, south-east portion of the Municipality around PE and Uitenhage (Figure 3-5). The northern areas of the Municipality are less developed, with natural cover predominating (Figure 3-5). Over 14% of the NMBM is used for agricultural activities such as cultivation and livestock farming, which predominantly occur within a wide band across the southern part of the Municipality (Figure 3-5), on the dunes of the Nanaga Formation. Approximately 5% of the NMBM is covered by high densities of alien plants (Figure 3-5). In addition, a large portion of the Municipality has been developed for urban or agricultural activities, or consists of degraded land (which is potentially restorable) (Stewart 2010).

Some of the underlying geology is also useful for construction and industrial purposes and, consequently, bears an impact on the accompanying ecosystem. Clay, quartzitic sand, quartzitic sandstone and salt are all mined in the NMBM, comprising 1.9% of the municipal area (Stewart 2010) (Figure 3-5).

Upstream activities can affect the water quality and quantity in the larger rivers. This includes: water abstraction, pollution dams and surrounding land use. This could result in a change in base flow or water quality, thereby potentially affecting the sub-surface water that infiltrates to wetlands on the surrounding floodplain. A key example of this would be the extensive Swartkops floodplain. Development (factories, roads and settlements) have resulted in this systems being highly modified both structurally and hydrologically, as well as having high levels of pollution.

The extent of anthropogenic activities in the NMBM illustrates the degree to which wetland areas are being modified or destroyed for various anthropogenic activities (such as development or irrigation).

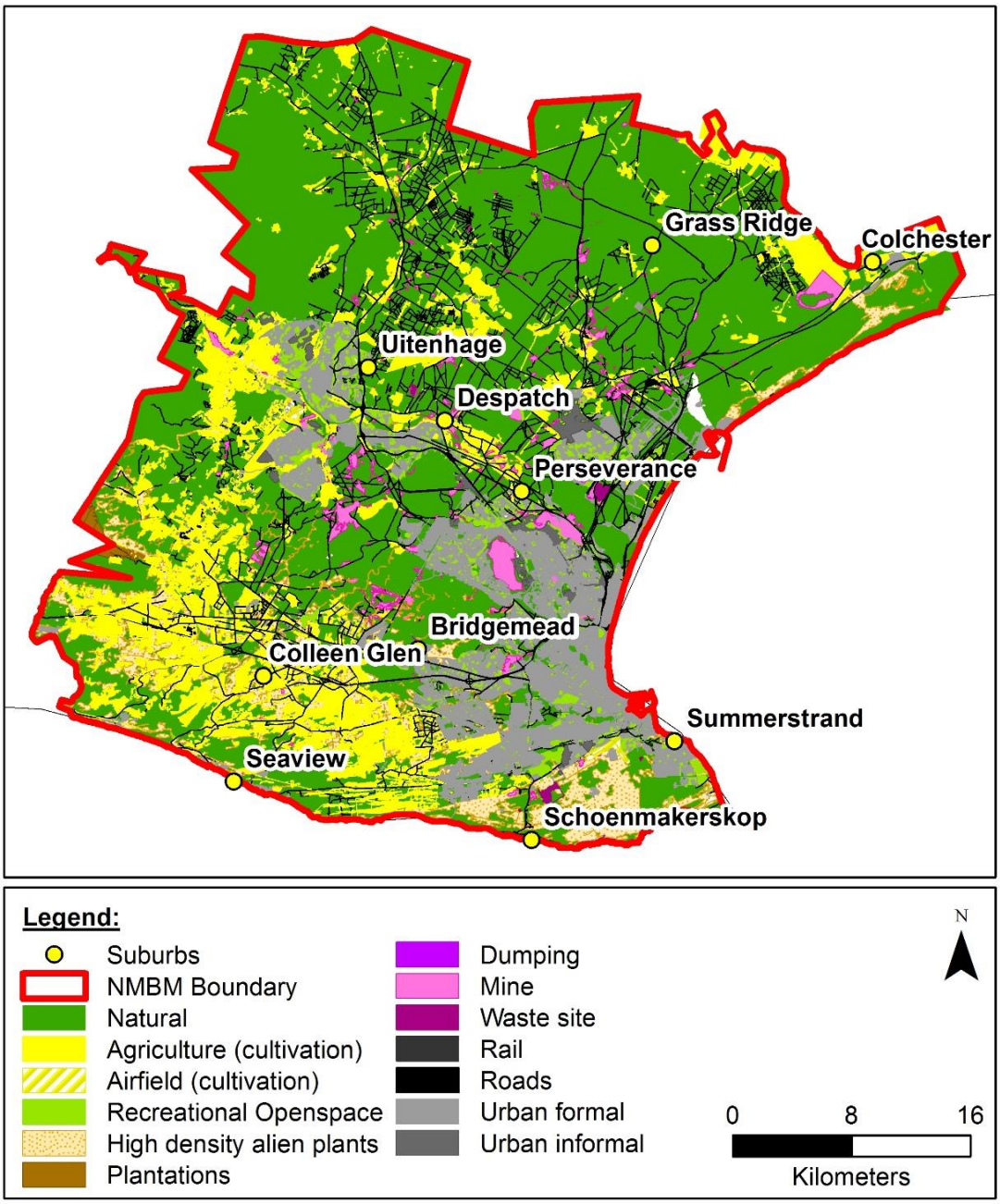

Figure 3-5. Landcover map for the NMBM with some key suburbs towns illustrated. Data from Stewart (2010).

3.7. CONSERVATION STRATEGIES FOR THE NMBM

In SA, strategic management and conservation priorities for the sustainable use of freshwater ecosystems (wetlands, rivers and estuaries) have been defined through the establishment of Freshwater Ecosystem Priority Areas (FEPAs) project by Nel (2011). The FEPAs were systematically identified and mapped using criteria such as: key/flagship ecosystem types and key areas that supply water (see CSIR (2011) for data). Wetland condition and the

presence of rare fauna and flora were important in identifying wetland FEPAs. Wetland FEPAs also consisted of wetland clusters where a number of closely-positioned wetlands are found within a relatively natural landscape and, as such, allow important ecological processes to occur (e.g. migration of faunal species). The importance of these clusters within a landscape and the role they play in the NMBM, are highlighted in Chapters 6 and 8.

Various conservation strategies have been assessed for the NMBM in order to carry out the vision for the conservation of a representative proportion of all biodiversity in the NMBM (Stewart 2010). The Coastal Management Programme (Stewart 2008) and the Conservation Assessment and Plan (Stewart 2010) for the NMBM are two such reports that provide a systematic approach to conservation planning for this Municipality.

The existing nature reserve system (protected areas) in the NMBM is about 10 482 ha (less than 0.0005% of the total municipal area). This area is comprised of both state-owned and privately-owned protected areas and only protects a small portion of the biodiversity in the region. The conservation targets for the NMBM are broken down into various Critical Biodiversity Areas (CBAs) and Critical Ecosystem Support Areas (CESAs) that are needed to ensure the sustainability of a representative proportion of ecological processes and biodiversity patterns. A number of wetlands identified in the NMBM are found within these key areas, some of which are also associated with sand movement corridors and, to a lesser extent, edaphic gradients.

A thorough description of the steps needed to achieve conservation targets in the NMBM are outlined in the aforementioned reports, as well as other conservation plans carried out at a broader scale (such as provincial and national assessments). These conservation strategies for the NMBM play a fundamental part in the current and future states of wetland systems in the Municipality.

3.8. CONCLUSION

Within an area of approximately 2000 km^2, the NMBM has a diverse range of geographical, geological and botanical features. This unique setting is also influenced by a variety anthropogenic activities that influence the ecosystems within, highlighting the importance of conducting research in the area. These landscape features are the foundation of the work undertaken in this study and they also provide the necessary data for multi-scalar data analysis.

4. METHODS

4.1. RESEARCH METHODS AND DESIGN

This research primarily takes the form of quantitative empirical research using a combination of exploratory, descriptive and explanatory methods. To address the research aims described in Chapter 1, a multi-disciplinary and multi-scale approach was taken, from landscape to fine habitat scales. A range of desktop, field and laboratory methods was used to address the knowledge gap on wetland systems in terms of their location and ecological diversity and, consequently, wetland function. Rivers were excluded in this study as they have been well demarcated in the area. The focus of this research was on the remaining six wetland HGM types that are defined at Level 4 of the CS (Ollis *et al.* 2013).

A digital database of inland wetland systems was created and ground-truthed to confirm and modify information to the maps and provide added detail to the classification of selected sites. A subset of field sites was chosen across the NMBM for a once-off site visit. These wetlands were unchannelled, small (generally less than 200 m in diameter) and predominantly ephemeral in nature (either seasonally or intermittently inundated). Sites were selected to represent the range of rainfall and terrestrial vegetation areas across the Municipality, as well as to provide a broad spatial coverage of wetlands. A total of 46 sites were sampled between 2012 and 2013. The development of the database and the results of the site visits have been presented as part of a WRC report by Schael *et al.* (2015). However, the analyses carried out and presented in the chapters are the author's own work.

The Department of Economic Development, Environmental Affairs and Tourism (DEDEAT) granted permission to collect plant samples in the Cacadu (now Sarah Baartman) region (Permit CRO 56/12CR). NMMU also provided animal ethics clearance (A12-SCI-BOT-001) for the collection of animal samples.

4.2. DATA PREPARATION AND DEVELOPMENT OF THE WETLAND DATABASE

The hierarchical CS levels, described in the Literature Review (Section 2.3, page 11), were used in the initial phase of this research. The first four levels of the hierarchy are considered primary descriptors and were determined using GIS techniques. All wetlands considered in this project are part of the inland wetland systems, therefore estuary and marine systems were not included. At Level 2 of the CS, the Ecoregion for the NMBM is the South Eastern

Coastal Belt. Levels 3 and 4 were determined using GIS, with additional site level data used in conjunction with the desktop exercise, where possible. The degree to which a system has been modified by anthropogenic activities was also recorded. Three classes were defined: natural, if the wetland illustrated no signs of man-made structures and was (relatively non-disturbed); modified, if the wetland illustrated some signs of man-made structures (e.g. a berm) or has some anthropogenic/animal impacts; and artificial, for wetlands that are highly modified (e.g. dams) such that it is not possible to determine whether these wetlands existed before man-made structures were implemented. The metadata file of the wetland database created, with details of the attribute data within, is in Appendix Table D-2.

Many regional GIS delineations map wetlands at various scales from 1:25 000 to 1:10 000 (Miller *et al.* 2001, Machmer 2004, Macfarlane *et al.* 2009, Qamer *et al.* 2009). Broad and meso scale digitising have major restrictions in terms of capturing smaller wetland features (Murphy *et al.* 2007, Qamer *et al.* 2009). Visual interpretation of aerial photography has been used to map various wetlands types globally. However, many authors agree that it is increasingly difficult to detect wetlands less than 1 ha in size when using coarser scales (Machmer 2004, Murphy *et al.* 2007). As this research focused on smaller, ephemeral wetlands, the study area was scanned methodically from east to west at a 1: 2500 scale to improve the probability of accurately detecting a wetland. Wetlands were then digitised at a scale of 1: 2000 to ensure that the boundary was accurately delineated.

ArcGIS 10.2.2 and 10.3 for Desktop (ESRI 2014), were used for spatial analysis. In order to locate, delineate and classify wetlands to Level 4a of the CS, a variety of data sources was used, and are listed in Appendix B. Wetlands within the NMBM were digitised using 2009 aerial photos, obtained from the NMBM Environmental Sciences Division, as well as existing shape files from the National Wetland Map IV. Rivers and 2 m contours were overlaid on the map as guidelines for identifying wetlands. Wetlands were digitised for the NMBM in a vector format as discrete polygon units with associated attribute data. Wetlands were digitised if water was observed or vegetation/contour indicators were present, with varying degrees of certainty. The map was updated throughout the study and Google Earth imagery was also used to help confirm wetland sites. Details of the attribute data assigned to the shape file as well as the metadata are given in Appendix D: Table D-1 and Table D-2.

From the results of the desktop study, a range of wetland types was chosen for ground-truthing to confirm or modify conclusions made from the maps and classification. The mapped wetlands as well as preliminary site visits were used to select study sites for field sampling.

The South African Weather Service (SAWS) recorded above average rainfall in 2011 and 2012 (742 mm and 960 mm respectively). Due to extremely high rainfall in 2012, any potential

wetland sites that were not inundated (or did not have wetland indicators present) at the time of inspection were removed from the database. Likewise, areas that were not previously classified as wetlands that had wetland indicators (such as wetland soils or vegetation – see Sections 2.5 to 0), were included in the GIS database. The coordinates of these sites were captured with a handheld Trimble GPS.

4.2.1. The NMBM wetland inventory

The National Freshwater Ecosystem Priority Areas (NFEPA) wetland dataset (CSIR 2011) was used to compare to the results recorded in the NMBM. This dataset is a combination of many datasets that have been collected at different spatial and temporal scales as well as using different methods. Although the dataset needs to be refined to check for accuracy, it can still be used to infer broad patterns in distribution. Thus, a broad analysis of wetland density for each of the SA provinces was illustrated graphically. Wetland densities were separated into two classes, artificial (man-made) and natural (as defined by NFEPA as any naturally occurring wetland) systems, to make the data more comparable.

Wetlands were digitised in ArcMap 10.3 using existing data from the National Wetland Map IV and high resolution aerial photos. Of particular importance were the number of wetlands at Levels 3 (Landscape Unit) and 4 (HGM) of the CS, as well as the level of modification (see Section 4.2) and the areas of the different wetland types. These data were used to describe the distribution and types of wetland systems in the NMBM. The data were also used to create a wetland occurrence model for the NMBM (Chapter 5).

Wetlands were digitised with different levels of certainty, depending on the amount of indicators present on the aerial photograph:

“1” indicated a possible wetland (contours and/or vegetation indicate the possible presence of a system), certainly = Low;

“2” strong vegetation and contour indicators of a wetland but no surface water evident, certainly = Medium; and

“3” the presence of water as well as vegetation and contour indicators, certainly = High.

Where low certainty scores were assigned, historical Google Earth DigitalGlobe Imagery (from different dates) were used to ascertain whether sites could be classified as a wetland. A subset of systems that still had low certainty scores were then verified in the field as per methods outlined in Ollis *et al.* (2013). These field trips were also used to determine which sites could be used for data collection (see Section 4.3).

4.2.2. Wetlands and the surrounding environment

Available environmental (abiotic) spatial data were used to compare characteristic differences across HGM types. These data included: elevation, slope aspect and gradient, solar radiation, evapotranspiration, MAP, underlying geology, broad-scale soil characteristics (e.g. depth, clay, calcareous), land use, annual heat units (HU), flow accumulation and direction, groundwater occurrence. HU pertains to the amount of accumulated heat within a day above a threshold temperature of 10 ^{o}C (Schulze and Maharaj 2007). Flow direction and accumulation values are derived from digital elevation models, using ArcGIS, and provide an indication of the surface water flow direction and the amount of water that could potentially accumulate which is the result of the length and steepness of slope. Groundwater occurrence represents the borehole yield ($L.s^{-1}$) coverage based on the 1:500 000 hydrogeological map series of SA. A list of the data sources and data resolution is listed in Appendix B.

4.3. SITE SELECTION AND SITE METHODS

A variety of sites was selected for once-off data collection to represent the diversity of wetlands found in the NMBM. The criteria for selection included location (covering the different regions), level of modification/disturbance (systems that have been significantly altered/disturbed were avoided), site accessibility and size (generally less than 1 ha). This wetland size threshold was chosen as it represented over 85% of the wetlands in the study area. The wetlands chosen within each quaternary catchment were based on the broad terrestrial vegetation type, underlying geology, and various combinations of Level 3 (Landscape forms) and Level 4 (HGM types) of the CS sites to obtain a representation of the wetland types in the NMBM. Wetlands selected were limited to all ephemeral sites (i.e. could be seasonally or intermittently inundated). Only seeps, depressions and wetland flats (Level 4 of the CS) within the various landscape forms were considered for data collection as these were the most common wetland types across all landscape units and geographical areas within the NMBM.

A field sampling session was designed to obtain an overview of the abiotic and biotic nature of the wetland. A total of 46 sites was assessed across six quaternary catchments within the NMBM. Sampling was conducted in 2012 and 2013 and, where possible, was done across the different catchments in both years. The majority of sites were also sampled in spring/early summer (September to December). At each site Levels 3 and 4 of the CS were confirmed (from the desktop analysis) and the site was then classified to Level 6 of the CS, as per methods outlined in Ollis *et al.* (2013). Level 5 addresses soil inundation and saturation, while

Level 6 looks at the habitat unit and vegetation cover of the wetland, both of which can be measured and recorded only in the field (see Section 2.3 for more details on the different levels of the CS). Final site distribution is illustrated in Figure 4-1.

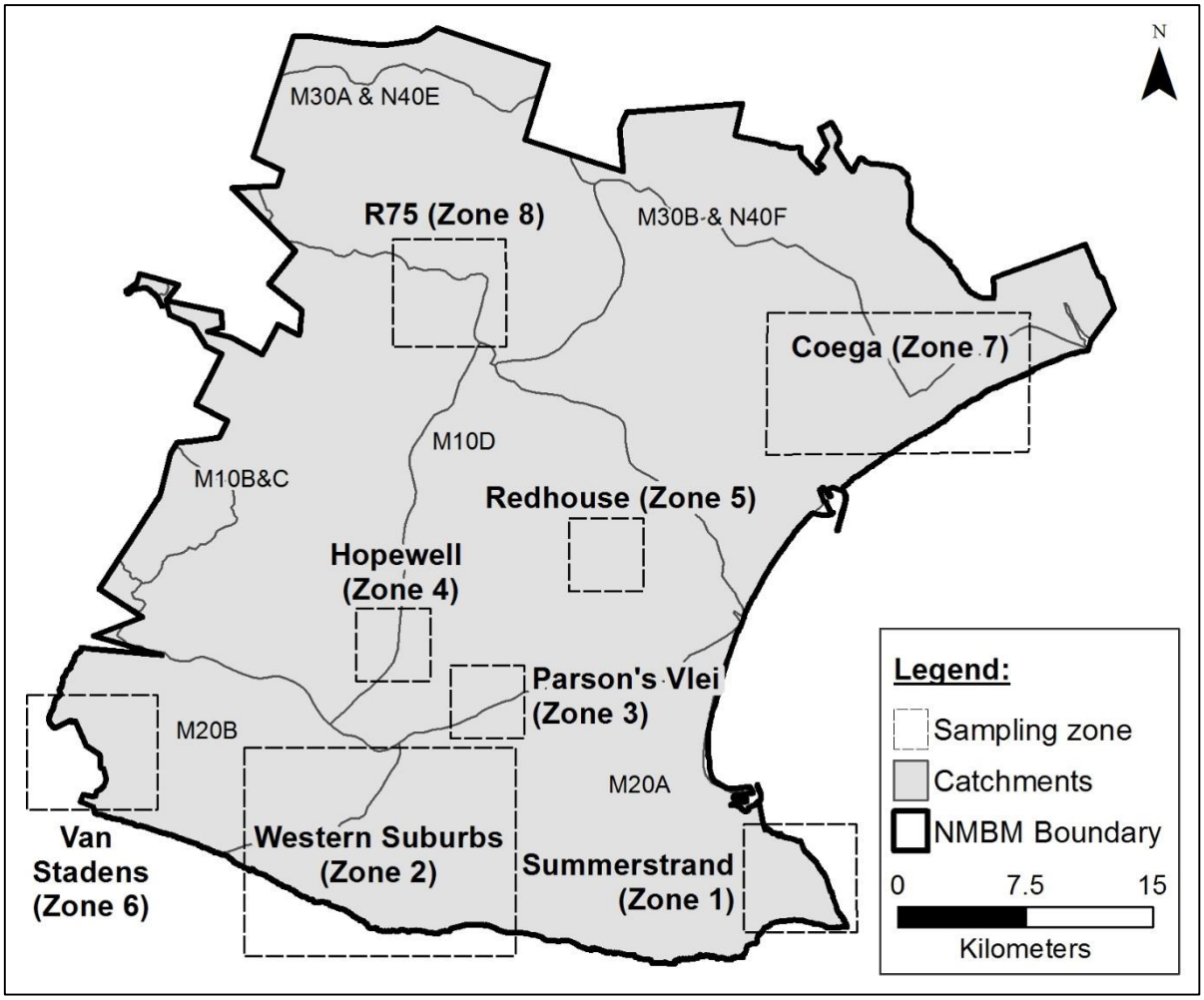

Figure 4-1 Map of the eight sampling areas (labelled 1 to 8) for wetland sites in the NMBM. General names of the surrounding area of the sampling zone are also given. Site positions are illustrated in Chapter 7. A detailed list of sites is in Appendix F.

A datasheet was constructed to record the overall site description, based on information from several sources (DWAF 2005, Ewart-Smith *et al.* 2006, Job 2009, Kotze *et al.* 2009b, Ollis *et al.* 2013). Data recorded included the surrounding terrestrial vegetation type, the presence of disturbances (e.g. alien vegetation and grazing), general habitat description, the position of the wetland in the landscape, and a sketch map delineating important features/HGM units and sample points. The perimeter of the wetland was recorded using a GPS when water was present. At dry sites, a variety of cues was used to demarcate the wetland perimeter, such as: soil morphology, slope, plant cover and species, water marks, etc.

4.4. ABIOTIC CHARACTERISTICS: SOILS

4.4.1. Soil sample collection

Two consolidated soil samples were collected from each of the sites using a soil auger of approximately 1.3 m in length. Each of the consolidated soil samples were comprised of soil collected at three cores along one of two the vegetation transects that was taken at depths of 10 cm to 50 cm (Figure 4-2). Therefore, a total of six cores was evaluated. Each core was assessed at 10 cm intervals, recording colour (Munsell colour), texture and various wetland soil indicators (DWAF 2005, Ewart-Smith *et al.* 2006, Job 2009). As most wetland soil indicators were detected within the top 50 cm of the soil, augering was limited to a maximum of 1 m, or to bedrock. Indicators of a wetland soil recorded in the field included high organic content in the surface soil layer, a low chroma (< 2), mottles, concretions, oxidised root channels, organic streaking, a gleyed matrix, and/or a sulfurous odour. The depth of soil saturation and to sub-surface water were also recorded. The two soil samples were sealed and kept refrigerated until further analyses were run.

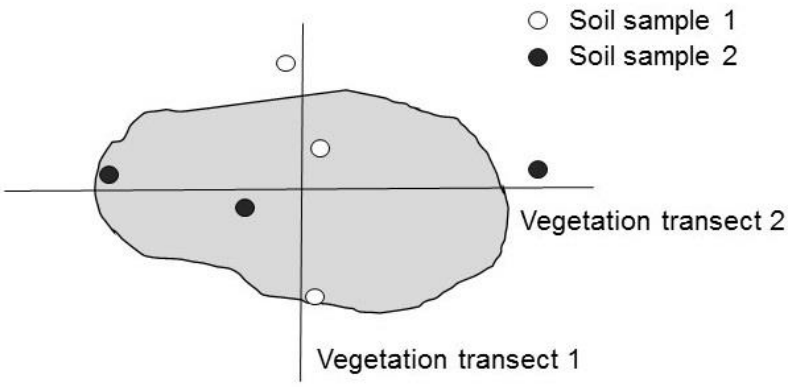

Figure 4-2 Diagram of a generic wetland illustrating general soil core positions with reference to the two perpendicular vegetation transects. Grey area indicates the seasonal wetland inundation zone.

A Field Scout TDR 300 Soil Moisture Meter was used to measure surface soil moisture in the field. This meter measured the volumetric water content (VWC) using the standard mode with two 12 cm long rods attached. The top 10 cm of the soil was sampled at each soil core sample site and in each vegetation quadrat.

The soil samples were analysed for moisture content, organic content, pH and EC (Robbins and Wiegand 1990, Sparks *et al.* 1996, Carter and Gregorich 2008). These are described below.

4.4.2. Soil moisture and organic matter content

Soil moisture content was analysed using the method by Black (1965). Each of the two collated soil samples was mixed well before sub-sampling for analysis. Three sub-samples of 10 to 15 g were weighed and placed in an oven at 40 ^{o}C for 48 h. The samples were then re-weighed to determine the percentage moisture content using the following equation:

$$\left(\frac{Mw - Md}{Mw}\right) * 100$$

Where: *Mw* is the initial mass of the soil (wet) and *Md* is the mass after drying.

The dried soil samples used to determine soil moisture were then used for the percentage organic matter, which was calculated using the loss-on-ignition method (ashing) (Smith and Atkinson 1975, Briggs 1977). The crucibles containing the soil samples were placed in a muffle furnace at 550 ^{o}C for at least 6 h, and then left inside the furnace to cool overnight. The samples were then placed in a desiccator containing anhydrous silica crystals until they were cool enough to handle and weigh. The percentage organic matter was then calculated using the following equation:

$$\left(\frac{Md - Ma}{Md}\right) * 100$$

Where: *Md* is the initial dry mass and *Ma* is the mass after ashing.

4.4.3. Soil texture

The particle size distribution (PSD) provides important information on the physical properties of a soil. There are various methods for determining particle size fractions. Mechanical sieving, sieve-pipetting and sedimentation are well known methods (Foth 1990, The Non-Affiliated Soil Analysis Work Committee 1990, Eshel *et al.* 2004). However, these methods are also time consuming and difficult to replicate with accuracy. Eshel *et al.* (2004), Konert and Vandenberghe (1997), Beuselinck *et al.* (1998), and Eshel *et al.* (2014) discuss the advantages and disadvantages of these methods in comparison to the laser diffraction method.

Numerous sources provide a full explanation on how laser diffraction (LD) works (e.g. Beuselinck *et al.* 1998, Eshel *et al.* 2004, Stojanovic and Markovic 2012). The benefit of LD is that it can produce accurate results in less time and with a smaller sample than other methods (Beuselinck *et al.* 1998, Eshel *et al.* 2004). LD also provides data on a wide range of size fractions which can be divided up into particle size groups compared to the sieving and sedimentation methods that are limited to sieve mesh sizes and proportions of sand, silt

and clay respectively. Furthermore, it is acknowledged that LD data are not as comparable as the two classical methods, as its application to analysing soils is relatively new (Eshel *et al.* 2004). As LD would provide the most consistent data, this method was used for particles smaller than 1 mm in size.

Approximately 50 g to 100 g of soil was taken from each of the two sample bags and dried at room temperature for PSD analysis. A pestle and mortar was used to grind the sample to separate the particles and clumps. Any material greater than 4 mm in diameter (coarse gravel and cobbles) was removed and weighed separately. Particle size was then measured using dry sieving method (Foth 1990, The Non-Affiliated Soil Analysis Work Committee 1990). The size of the sieves used is outlined in Table 4-1, with the particle size class given according to the Wentworth Scale. Size fractions smaller than 1 mm were collected in the sieve tray for further sampling using LD. The total sediment weight in each of the sieves was weighed separately and recorded. The remainder of the sample was then weighed and stored until the LD analysis could be conducted.

The Malvern Instrument Mastersizer (Malvern Instruments Ltd, Worcestershire, England) with Mastersizer-S v2.18 software was used to determine particle sizes ranging from 0.02 µm to 878.7 µm. The average density was set before each analysis for each respective site using the following equation:

$$D_p = \frac{oven\ dry\ weight\ (g)}{volume\ of\ soil\ solids\ (cm^3)}$$

Where: D_p is the particle density of soil, a value approximately 2.65 g/cm^3 (the density of silica) (Foth 1990, Brady and Weil 1999, Blake 2008).

Each of the sediment samples were dispersed using sodium hexametaphosphate with 2-3 drops of Triton X165 solution. An ultrasonic bath was filled with water and the lasers initialised before the sample was slowly added to the bath. Three measurements were performed for each sample once the turbidity had settled.

The following parameters were used:

Pump speed:	2000 rpm
Ultrasound:	60% (on during analysis)
Sensitivity:	Normal
Measurement time:	20 sec
Obscuration:	20 – 30%

The data were extracted from the Mastersizer software and stored in Excel (Table 4-1). The proportion of sample occurring in each predestined class was then calculated in proportion to the larger size classes that was calculated using sieving.

Six samples were analysed using the Saturn digitizer 5200 due to equipment malfunction. The same parameters were used (where possible). Extra parameters defined: beam at 15°, three rinse cycles, and a flow rate of 16 L.min^{-1}. No statistical significant difference was found with samples measured using both digitisers.

Table 4-1 Particle size class and methods used for particle size analysis. Scale according to Wentworth (1922).

Particle diameter (mm)	Particle size class	Method of analysis
> 2	Fine gravels (and larger)	Sieve
1 – 2	Very coarse sand	Sieve
0.5 – 1	Coarse sand	Sieve tray & Laser diffraction
0.25 – 0.5	Medium sand	Sieve tray & Laser diffraction
0.125 – 0.25	Fine sand	Sieve tray & Laser diffraction
0.063 – 0.125	Very fine sand	Sieve tray & Laser diffraction
0.031 – 0.063	Coarse silt	Sieve tray & Laser diffraction
0.016 – 0.031	Medium silt	Sieve tray & Laser diffraction
0.008 – 0.016	Fine silt	Sieve tray & Laser diffraction
0.002 – 0.008	Very fine silt	Sieve tray & Laser diffraction
0.001 – 0.002	Clay	Sieve tray & Laser diffraction

4.4.4. Soil electrical conductivity and pH

Electrical Conductivity (EC) was measured, as an indicator of salinity, using the methods described in The Non-Affiliated Soil Analysis Work Committee (1990).

Soil samples were air dried. De-ionised water was added to 250 g of soil until a saturated paste was formed. The amount of de-ionised water added was noted and the paste was left to stand for at least one hour before filtering. The sample was periodically tested for properties of a saturated paste, and extra water added, if necessary. The sample was then filtered through a Whatman no. 1 filter paper using air suction through a Buchner funnel. The filtrate was collected in a test tube and measured using a hand held Crison Conductivity Meter 524. The solution was also used to measure the pH of the extracted solution using a RE 357 Microprocessor pH meter calibrated to 4.7, 7 and 10.

4.5. ABIOTIC CHARACTERISTICS: HYDROLOGY

Several hydrological parameters were recorded in the field, including the absence or presence of channelled inflows and outflows (Level 4B of the CS) and connections to other HGM types (Table 4-2).

When surface water was present, water depth was measured every 3 m along each transect, in conjunction with the vegetation data collection. Estimates of the annual maximum depth of inundation were also recorded, by looking at the surrounding morphology and vegetation of the wetland. Water samples collected in the field were stored in an ice box until the samples could be filtered.

Table 4-2 Abiotic data collection, *in situ* measurements and sample collection for laboratory processing. N/A = not applicable; TSS = total suspended solids; SRP = soluble reactive phosphorus; TP = total phosphorus. Levels of accuracy (indicated in brackets) for the instruments are given where applicable.

Parameter	Measured *in situ*			Laboratory Processing	
					Units (accuracy)
Soils	Colour			Organic content	%
	Texture			Moisture content	%
	Mottles			Particle size	mm
	Saturation			EC	mS/cm (±0.001)
	Profile			pH	units (±0.2)
		Units (accuracy)			**Units**
Surface and sub-surface water	Depth	cm	(±0.5)	Nutrients	µg/L
	Temperature	^{o}C	(±0.15)	Total Nitrogen	
	pH	units	(±0.2)	Nitrate	
	EC	mS/cm	(±0.001)	Nitrite	
	Salinity	ppt	(±0.1)	Ammonium	
	DO	mg/L	(±0.2)	TP	
	TDS	g/L	(accuracy not given)	SRP	
				Silica	
				TSS (surface water)	mg/L

4.5.1. *In situ* water measurements

Water colour, transparency and smell (algae, sulphur dioxide etc.) were evaluated and recorded on site. Physico-chemical properties were also measured and recorded *in situ* using a YSI hand-held multi-probe (556 MPS) and Crison Conductivity Meter 524. These properties included: water temperature (°C), pH, EC (µS/cm), salinity (ppt), total dissolved solids (TDS) (mg/L), and dissolved oxygen (DO) (mg/L). The physico-chemical measurements were taken at three points within the wetland: one at the deepest point, one within the marginal vegetation (if present) and at a third randomly selected point. The physico-chemical properties of sub-surface water was also measured at two random points next to the wetland, one of which was 'upstream' of the surface water. Holes were dug in the ground and left to fill up with water before measurements were taken.

4.5.2. Total suspended solids

Two surface water samples were collected to measure total suspended solids (TSS) at inundated sites. TSS measures the amount of suspended solid or dissolved impurities (greater than 2 µm) in a water sample and is an indicator of water quality. TSS samples were measured using the standard oven drying method (Bartram and Ballance 1996). Approximately 250 ml of a well-mixed water sample was filtered through a pre-dried 0.45 µm membrane filter paper. The total amount of TSS (mg/L) was calculated by determining the amount of solids left on the filter paper after filtration and desiccation. The following equation was used:

$$\left(\frac{Ma - Mb}{Fa}\right) * 1000$$

Where: *Ma* is the mass (g) of the filter paper after filtering, *Mb* is the mass of the filter paper before filtering and *Fa* is the amount filtered in ml.

4.5.3. Nutrient analysis

Two surface water samples and two sub-surface water samples were collected for nutrient analysis. Nutrient data were obtained from the WRC project K5/2181 (Schael *et al.* 2015). Full details of the processing methods are explained in that report. Surface and sub-surface water samples were filtered through 0.45 µm GFC filters and stored in 100 ml plastic acid-stripped containers. Nitrates, nitrites, total nitrogen, ammonium, soluble reactive phosphorus, total phosphorus and silica were analysed using methods described by Solorzano (1969), Strickland and Parsons (1972), Bate and Heelas (1975), and Wetzel and Likens (1991). Samples were filtered and frozen on the same day of collection, to preserve the sample until

laboratory processing could be done. These samples were used in multivariate analyses to look at species assemblages (see details in Section 4.7.2).

4.6. BIOTIC PARAMETERS

At each wetland site, data on several different biotic parameters were collected (see: Schael *et al.* 2015). Biological data used in this thesis include: phytoplankton biomass (in terms of Chl *a*), vegetation species composition, aquatic macroinvertebrates and tadpoles. Species identification for the different taxa was done with expert assistance. Collection methods and the data analysis process are described below.

4.6.1. Water column biomass

Phytoplankton biomass was measured using Chl *a* analysis, by filtering three replicate samples using 1.6 µm glass fibre filters (GF/C). Filters were either frozen in foil until extraction within 3-4 days from day of sampling, or immediately placed in Ethanol for extraction and processing within 24 h (Lorenzen 1967). The filtrate was read using a spectrophotometer at a wavelength of 665 nm, before and after 1 N hydrochloric acid was added, and the resultant absorbance was converted to Chl *a* in µg/L using the following equation:

$$Chl\ a = \frac{26.7\ X\ (665_b - 665_a)\ X\ V_1}{V_2\ X\ l}$$

Where: $665_b - 665_a$ is the absorbance value before and after acidification, V_1 is the volume of extract in ml, V_2 is the volume of the sample in L and *l* is the light path of the cuvette in cm.

4.6.2. Vegetation

An interrupted belt-transect method was used to determine plant diversity, cover, community patterns and zonation within a wetland (Eckhardt *et al.* 1993, Sieben 2011). Two vegetation transects were placed perpendicular to each other along the longest and shortest axis of the wetland, and extended to the edge of the terrestrial zone on either side of the wetland. A 1 m^2 quadrat was used every 3 m along each transect to determine the number of individual and relative cover of each plant species. This protocol was used as wetlands in the region tend to have heterogeneous vegetation and, consequently, quadrats need to be small (1 m^2 to 4 m^2), and sampled frequently along a transect, to incorporate changes in species composition within a small area (wetlands were typically less than 1 ha in size) (Corry 2012).

Cover was estimated using the Braun-Blanquet cover-abundance scale (Braun-Blanquet 1932) (Table 4-3). The sum of the Braun-Blanquet covers for each species in a particular

wetland was used to provide an indication of the relative abundance for that species (Sieben 2012, Ballantyne and Pickering 2015). The height of the dominant plant species was recorded. Where present, filamentous algae and macro-algae were noted.

Table 4-3 Braun-Blanquet scale used for vegetation transects (Braun-Blanquet 1932).

Braun-Blanquet scale	Cover (%)	Midpoint value (%)
r	<1	0.5
1	1 – 5	2.5
2a	6 – 12	8.5
2b	13 – 25	18.5
3	26 – 50	37.5
4	51 – 75	62.5
5	76 – 100	87.5

Where plant species were unknown, a sample was collected, photographed and pressed for further identification. Herbarium resources and a number of references and guides were used to identify unknown plants, these included: Vanderplank (1998), Van Oudtshoorn (1999), Vanderplank (1999), Manning (2001), Cook (2004), Manning (2009), Bromilow (2010), Vlok and Schutter-Vlok (2010), van Ginkel *et al.* (2011), Dorrat-Haaksma and Linder (2012). Unidentified wetland plants were also taken to wetland vegetation experts for further identification or confirmation (see acknowledgements).

Ancillary data were added to the plant species list. This included information on the IUCN Red List status, endemism, alien or indigenous and the plant indicator category (hydric status) (Table 2-8, page 25). The South African National Biodiversity Institute (2014) provided most of the information, along with the various plant identification guides. Where necessary, field experience was used to define the indicator category for a species.

For vegetation data analyses the midpoint value for each Braun-Blanquet cover class was used for each quadrat (Table 4-3). For each wetland, the total value for each species was enumerated, and divided by the number of quadrats to provide a relative abundance for a species in a wetland. As the resultant matrix was highly skewed, with a large number of zeros, the data were fourth root transformed for further analysis (Quinn and Keough 2002).

4.6.3. Aquatic fauna

Macroinvertebrate data can be used to further illustrate biotic and abiotic connections. Like vegetation data, invertebrate data also provides a snap-shot picture of a wetland. However, the time-scale of the community shift is much quicker with invertebrates, due to the shorter life-span of some species.

Aquatic invertebrate samples were collected in both shallow (less than 20 cm and/or emergent vegetation zone) and deeper inundated sections (greater than 25 cm and/or open water zone) of inundated wetland sites. A kick-net with 900 µm mesh was dragged through all layers of the water column throughout the wetland. Two sweeps were done for each habitat type for 1 min and 1.5 min respectively. Samples were preserved in 70% Ethanol. The list of identified species was obtained from Schael *et al.* (2015).

Incidental data were collected on tadpoles (order: Anura) during invertebrate sweeps (see above). Any tadpoles or froglets found within the sample were separated and enumerated separately. Identification was done by Denise Schael (Botany NMMU) and John Measey (Stellenbosch University) using the South African frog guide (Carruthers and du Preez 2011). As the sampling was not aimed at tadpoles, no statistics were conducted on the data.

4.7. GENERAL DATA MANAGEMENT AND STATISTICAL ANALYSIS

All field and laboratory data were captured in MS Excel spreadsheets for ease of access and manipulation. A combination of data analysis techniques was used to analyse the collected data. Both non-parametric and parametric statistical analyses were done using the following different statistical computer packages: Statistica 13 (Dell Inc. 2015), R (The R Foundation for Statistical Computing 2010), Primer 6.0 (PRIMER-E Ltd 2009), and ARC GIS 10.3 for Desktop Advanced (ESRI 2014).

The data collected from the wetland sites were used to provide an indication of the type and geographical distribution of wetlands in the NMBM. The wetland structure can be used to determine the relationship between HGM units (landscape setting and geographic classification) to the different abiotic and biotic variables, in accordance with the aims and objectives of this thesis (specifically Objectives 2 and 3). Data analyses pertaining to the research questions are explained in the relevant chapters. Standard statistical assumptions were checked for each statistical analysis using standard testing procedures (Rawlings *et al.* 1998, Quinn and Keough 2002).

4.7.1. GIS analysis

All GIS analyses were conducted using ArcGIS, with the following extensions: Spatial Analyst, 3D Analyst and Geostatistical Analyst and Xtools. GIS techniques were used to display spatial trends while statistical analyses and models were used to expound on the relationship of the different wetland types to the surrounding environment. The spatial reference used was Transverse Mercator central meridian 25 and the Hartebeesthoek 94 datum.

The Spatial Join function (Analysis Tools) was used to join available environmental datasets to the NMBM wetland database. An extensive list of the datasets obtained as well as the scale at which they were created and their respective sources, is found in Appendix B. Slope gradient and slope aspects were derived from a 20 m Digital Elevation Model (DEM) using the Surface Tool in Spatial Analyst. The Extraction Tool in Spatial Analyst was used to derive the slope gradient and aspect for each respective wetland.

4.7.2. Statistical data analysis

A variety of statistical analyses were conducted in this study. The more general statistics are described below and those that pertain to specific sections of work are described in their respective chapters.

Various methods were used to compare HGM types to the environmental variables. Boxplots were initially created in R to visualise the data. One-way ANOVAs were done on the various datasets to establish significant differences in the means of these variables among predetermined groups. If a significant difference was found, a post-hoc Tukey HSD test was conducted to indicate the level of significance between two HGM types. Care was taken to ensure the statistical assumptions were met (see: Quinn and Keough 2002, Townend 2003, McKillup 2006).

A Bray-Curtis similarity resemblance analysis was conducted in Primer. Both dendrograms and non-metric Multi-Dimensional Scaling (MDS) plots were used to determine distribution of patterns in vegetation or macroinvertebrate communities at the sample sites. A distance-based redundancy analysis (dbRDA) was then done in PERMANOVA+ (an extension of Primer) to establish which set of variables best explain the dissimilarity between predetermined groups (e.g. HGM type and catchments). Combinations of the input variables were used to establish which variables were more prominent with different sample data, including: water and nutrient variables, sediment and position in landscape characteristics, and a combination of all these variables. Only key variables were displayed graphically.

SIMPER (similarity of percentages) analyses identified which variables (such as particle size classes, HGM type etc.) contributed to the observed pattern of similarity in a predetermined group (CS Level 4). A cumulative percentage total of approximately 50% was used. A Bray-Curtis similarity was used for vegetation and macroinvertebrates, and Euclidean distance for environmental variables. When needed, BIOENV was used to determine which environmental variables best explain the vegetation or macroinvertebrate community patterns. BIOENV finds a subset of environmental variables that best explain plant or macroinvertebrate community dissimilarities.

4.8. CONCLUSION

As presented in this chapter, a variety of methods were used in this study, such as: broad-scale desktop delineation and analysis, the physical, chemical and biological parameters of 46 sites, and laboratory processing for data analysis. Specific data analyses were conducted to meet certain objectives in the project, and they are described in detail in the relevant Chapters (Chapters 5 to 7). The methods of data capture and analyses applied in this study were used to bring new understanding on the types and functioning of wetlands in this region. This includes understanding the interactions between the physical structure, and the biological communities in wetlands.

5. MAPPING WETLANDS: MANUAL DIGITISATION AND LOGISTIC REGRESSION MODELLING

5.1. INTRODUCTION

The aim of this chapter is to ascertain wetland distribution and structure within the NMBM through identifying wetlands using visual interpretation of aerial photographs and by building a wetland occurrence model (Objective 1). As highlighted in Chapters 1 and 2, wetlands need to be identified and classified for conservation and management purposes. To address Objective 1, wetlands were identified by extensively scanning high resolution aerial photography to demarcate all wetlands (see Section 4.2). Following this, a number of site visits were conducted to verify wetlands that had been identified. A wetland model was also created to estimate the probability of wetland occurrence using logistic regression (LR) techniques (Section 5.2), to meet Objective 2 of this thesis. In addition, various LR models were run to determine whether variable deletion order impacts final model accuracy. This information forms the foundation for subsequent data chapters that describe ephemeral wetland distribution in terms of environmental factors, and the resultant wetland functions within a landscape.

5.1.1. Determining wetland numbers: collecting inventory data

Basic inventory data on wetland distribution are needed to protect and conserve existing wetlands and prevent further loss or degradation (Taylor *et al.* 1995, Day and Malan 2010, Malan 2010). However, in many areas across SA, fundamental knowledge on the structure and location of wetland systems is unknown (Rossouw *et al.* 2005, Day *et al.* 2010, Malan 2010), as discussed in Chapters 1 and 3.

The National Wetland Map (IV) has 596 wetlands delineated within the NMBM, 50% of which were modified or artificial (CSIR 2011). Many of the naturally occurring systems fall within the urban boundary and have consequently been impacted by surrounding anthropogenic activities. The size of these systems range from 0.01 ha to 45.1 ha (CSIR 2011). However, no study has focused on the smaller, geographically isolated wetlands in the study area, until a recent Water Research Commission Project by Schael *et al.* (2015).

Wetland inventories can be done at multiple spatial scales, with varying levels of precision, and using different data capturing methods (Qamer *et al.* 2009, Monfils *et al.* 2012). There

are three methods commonly used in inventories of this nature, which are outlined in Table 5-1 below. This chapter describes the outputs of two of these methods that were applied in the NMBM, namely, manual heads-up digitising (on aerial photographs in a GIS) and a LR model that estimates wetland occurrence.

Table 5-1 Advantages and disadvantages of three methods used to develop wetland distribution databases.

Model type	Advantages	Disadvantages	References
Visual interpretation of aerial photographs	Cost effective Data more easily available Small, ephemeral systems can be identified Can determine spatial scale of data capture	Small area covered Labour intensive Date of aerial photo: more difficult to identify wetlands from photos taken in drier years versus wetter years	Taylor *et al.* (1995), Barrette *et al.* (2000), Miller *et al.* (2001), Machmer (2004), Qamer *et al.* (2009)
Wetland occurrence models	Presence/absence can be modelled beyond surveyed area Can predict changes in wetland occurrence (e.g. locations of previous wetlands that have been lost)	Size and type of wetland not estimated Scale dependent on resolution of data	Houhoulis and Michener (2000), Koneff and Royle (2004), Bai *et al.* (2010), Hiestermann and Rivers-Moore (2015)
Other remote sensing techniques (semi-automated to automated)	Time efficient Potentially covers a large area	Availability of suitable satellite imagery (high resolution) at suitable time intervals Expense of imagery Cannot identify small systems (less than one pixel in size) Misclassification of pixels	Taylor *et al.* (1995) Ozesmi and Bauer (2002), Raptis *et al.* (2003), , Roshier and Rumbachs (2004), Murphy *et al.* (2007), , Rebelo *et al.* (2009), Martin *et al.* (2012)

Visual interpretation of aerial photography by means of heads-up digitising, using geographical information systems (GIS), and it is a well-established method used to create and maintain wetland inventories. It can be performed using data captured and observed at various spatial scales, depending on the size of the study area and the resources available (Taylor *et al.* 1995, Barrette *et al.* 2000, Machmer 2004). Although time consuming, GIS provides an appropriate tool for establishing wetland inventories within a confined research area (Taylor *et al.* 1995, Tiner *et al.* 2002, Environmental Research & Services 2014). This is

especially relevant in the NMBM as it is associated with an expanding urban and peri-urban area that requires accurate boundaries for the different land types/uses, for management and conservation.

Broad-scale wetland inventories also commonly use automated remote sensing (RS) techniques (Ozesmi and Bauer 2002, Roshier and Rumbachs 2004, Frohn *et al.* 2009). Automated RS provides a relatively cost-effective way of mapping systems over a large area, if high resolution images are available (FGDC, 1992, Roshier and Rumbachs 2004). However, there are several problems with using this technique. As with manual digitising, automated RS techniques are often unable to accurately identify smaller, more ephemeral or isolated systems (FGDC, 1992, Frohn *et al.* 2009). The Federal Geographic Data Committee (FGDC) (1992) estimated that only 22% of wetlands smaller than 0.77 ha were recognised. The results improved with wetland systems larger than 2 ha having more than 90% chance of being recorded (FGDC, 1992).

High-resolution satellite data such as Landsat Thematic Mapper can yield slightly better results for broad-scale mapping, especially when combined with other datasets such as topography, geology, soils and vegetation (FGDC, 1992, Taylor *et al.* 1995). However, the size of systems is still a limiting factor. This is problematic in a semi-arid region, such as the NMBM, where wetlands tend to be small and mostly ephemeral.

Logistic regression models have been applied to many different environmental management fields, including: landslide susceptibility, species habitat preferences, land cover change detection, and likelihood of occurrence modelling (Houhoulis and Michener 2000, Marquínez *et al.* 2003, Mathew *et al.* 2009, Bai *et al.* 2010, Monfils *et al.* 2012). To a lesser degree, LR models have also been used to predict wetland occurrence over large study areas, for example: along the US Atlantic Coast and in KwaZulu-Natal (KZN), and on the east coast of SA (Koneff and Royle 2004, Grant 2005, Hiestermann and Rivers-Moore 2015). Limiting factors to LR models is that they cannot indicate the spatial coverage of wetlands, but, merely the likelihood of a wetland being present or absent, and they require an existing inventory of wetland types to build the model.

In conjunction with inventory techniques, various ancillary data are used to improve accuracy and certainty of wetland identification. These attribute data include environmental variables captured at different resolutions, and from many sources. With visual interpretation of aerial photographs, attribute data are used to increase the certainty of identifying a wetland. LR models wetland occurrence in relation to the most suitable environmental data. Consequently, a wide variety of spatial environmental data are needed for wetland identification.

5.2. METHODS

Two methods were used to derive wetland distribution data for the NMBM. The first method was the creation of a wetland map using heads-up digitising of aerial photographs was described in Chapter 4 (Section 4.2.1). A second method to determine wetland distribution, using logistic regression (LR) techniques, is described below. An outline of the process described in this section is illustrated in Figure 5-1. The main outcomes were two maps: one of wetlands that were manually delineated and another probability map of wetland occurrence. The wetland database created formed the foundation for the remainder of the chapters in this thesis.

Wetlands were digitised on ArcGIS using existing data from the National Wetland Map IV (CSIR 2011) and high resolution aerial photos, as per methods outlined in Chapter 4. Of particular importance in this chapter were the number of wetlands at Levels 3 (Landscape Unit) and 4 (HGM) of the CS, the level of modification, and the surface areas of the wetlands. This was described in detail in Section 4.3, page 52. These data were used to describe the distribution and types of wetland systems in the NMBM.

5.2.1. Wetland occurrence modelling

A point dataset was created with wetland presence/absence locations and associated environmental variables (Figure 5-1). The wetland presence data were taken from the NMBM wetland layer that was created. Absence data were created using the genrandompnts tool in the Geospatial Modelling Environment (GME) (Beyer 2010), which generates a sample of random points within the parameters given. Absence points were created in proportion to the number of wetlands found within a catchment, with a total of 2000 points. Points did not overlap with existing presence data and were a minimum of 150 m apart to ensure the same wetland would not be detected twice.

Both the presence and absence data were then divided into training and test datasets to avoid overfitting the model (Aguilera *et al.* 2011, Hiestermann and Rivers-Moore, Maldonado *et al.* 2015). The r.sample tool in GME was used to randomly select 70% of the presence and absence data points for the training dataset (Figure 5-1). The remainder of the points (30%) were used to test the model (Figure 5-1).

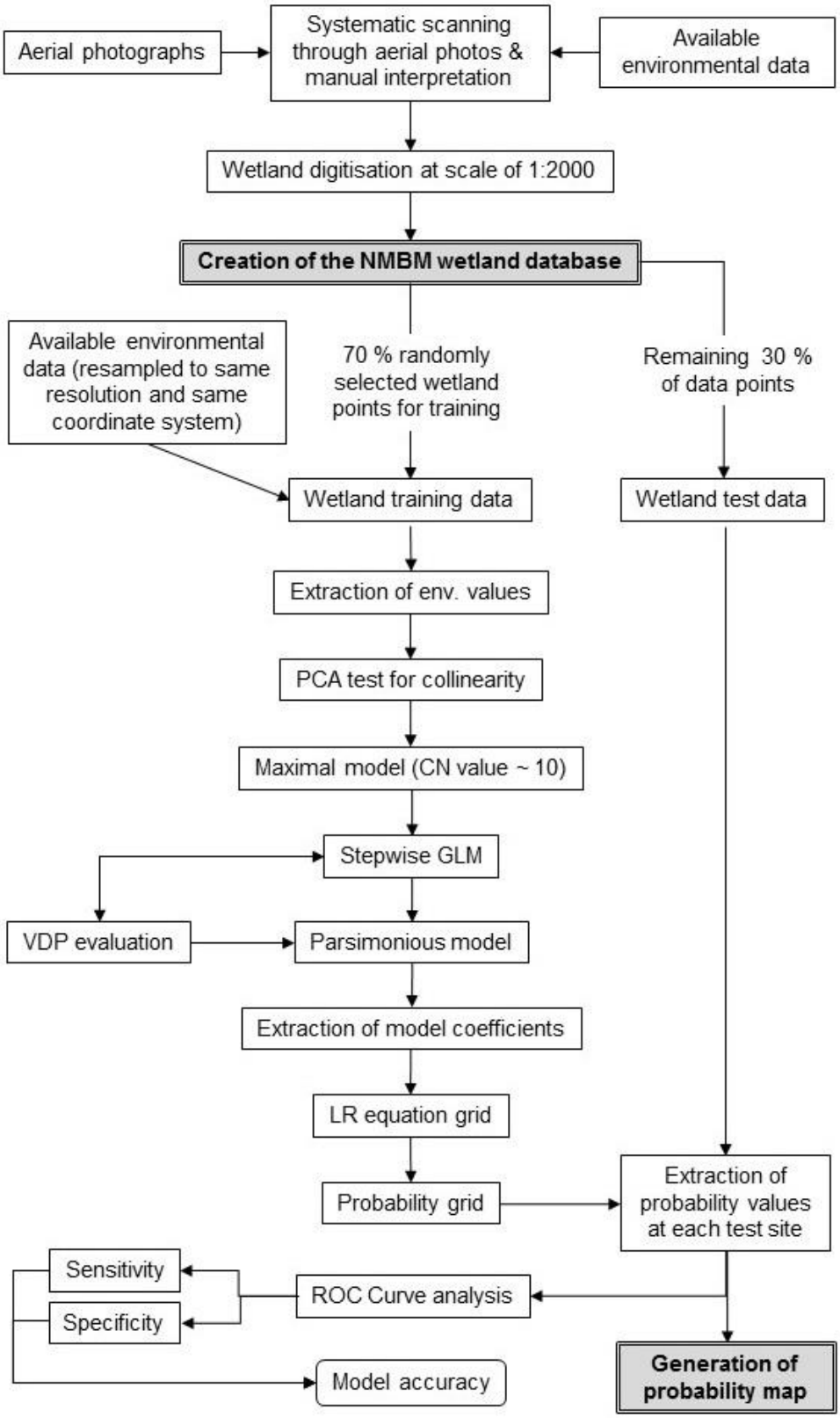

Figure 5-1 Outline of the process used for mapping wetland occurrence and wetland probability (highlighted in the grey boxes). CN = Condition Number; GLM = Generalised Linear Model; LR = Logistic Regression; PCA = Principal Components Analysis; ROC = Receiver Operator Characteristic; VDP = Variance Decomposition Proportion.

A variety of environmental spatial data was used to build the model (Table 5-2). The NMBM digital elevation model (DEM) was used to calculate the slope gradient (in degrees) and slope aspect of wetlands in the NMBM, using the Surface Tool (Spatial Analyst Tools: ArcMap 10.3). Slope aspect was defined by the eight compass points as well as a value for “flat” areas (no aspect). The flow direction and accumulation were also derived from the DEM. Initially, the Fill function (Hydrology Tools in Spatial Analyst: ArcMap 10.3) was used to remove small sinks and data errors. This raster was used to create the flow direction raster which was, consequently, used to create the flow accumulation raster (using the Hydrology Tools). The cell values of the raster were joined to a point feature dataset of the NMBM wetlands using the Extraction tool in Spatial Analyst.

Table 5-2 Input variables used in the wetland occurrence model. Some variables represent similar data which were deleted during the variable deletion process. See Section 4.2.2 for further information on the variables). N/A = no units defined, DEM = Digital Elevation Model. Abbreviations are those used in the multivariate analyses in Chapter 7.

Theme	Variable	Abbreviation	Data class	Units
Climate	Solar radiation	Sol.rad	Continuous	$MJ.m^{-2}.day^{-1}$
	Mean annual temperature	Temp	Continuous	ºC
	Summer heat units	Hu.summer	Continuous	º days
	Winter heat units	Hu.winter	Continuous	º days
	Annual heat units	Hu.annual	Continuous	º days
Hydrological	Mean annual precipitation	MAP	Continuous	mm
	APan evaporation	APan.evap	Continuous	mm
	Evapotranspiration	eto	Continuous	mm
	Groundwater occurrence	gw	Categorical	$l.s^{-1}$
Environment	Soil clay content	Clay.cont	Categorical	%
	Soil rock content	Rock.cont	Categorical	%
	Soil depth	Soil.depth	Categorical	N/A
DEM derived	Elevation	elev	Continuous	m
	Slope (gradient)	slope	Continuous	degrees
	Aspect	aspect	Continuous	degrees
	Flow accumulation	Flow.accum	Continuous	N/A
	Flow direction	Flow.dir	Continuous	degrees

All environmental data were standardised as the data were from different sources, with various projections, resolutions and spatial extent. Data were projected to The World Geodetic System 1984; Universal Transverse Mercator Zone 35 ^{o}S (WGS 84 UTM Zone 35S) for ease of resampling. Raster layers were resampled using the raster processing tool to a resolution of 20 m (the resolution of the DEM for the NMBM). Different resampling techniques were used for the various data types: nearest neighbour resampling technique for categorical data, cubic convolution for continuous data and bilinear for DEM and DEM derived data. Once the data were in the same resolution and format, the environmental variables were extracted using the presence/absence points to create an Excel database with all the environmental variables.

Model development

The wetland occurrence probability model was developed in ArcGIS and R. Two methods were used to investigate whether there were collinearities among the variables which would reduce the effectiveness of the model. Collinearity is a measure of the degree to which two variables that almost lie on the same line, i.e., are not independent from each other (Belsley *et al.* 1980, Booth *et al.* 1994). This, in turn, makes it more difficult to separate the influence of the explanatory variables on the response variable (Belsley *et al.* 1980, Booth *et al.* 1994).

A Principal Components Analysis (PCA) was run and the eigenvalues were used to check collinearities among the continuous variables (Belsley *et al.* 1980, Wetherill 1987, Manel *et al.* 1999, Quinn and Keough 2002). The PCA calculates which set of input variables would result in the greatest predictive power, while keeping collinearity to a minimum (Wetherill 1987, Quinn and Keough 2002). An overall Condition Number (CN) is one way to assess collinearity and is defined by:

$$CN = \sqrt{\frac{\lambda_{max}}{\lambda_{min}}}$$

Where λ is the eigenvalue from the PCA being assessed (Belsley *et al.* 1980, Wetherill 1987, Quinn and Keough 2002, Dormann *et al.* 2013). The variable with the smallest variable loading was subsequently removed and the PCA re-run until the CN was below 10 (Belsley *et al.* 1980, Douglass *et al.* 2003). Care was taken to ensure that the potential importance of the environmental variables to a wetland and the interaction with other variables, were considered. The final selection of continuous variables, along with the ordinal data, formed the maximal model that would be used to fit the LR model (Manel *et al.* 1999, Crawley 2012).

A further method to test for collinearity is variance decomposition proportions (VDP), where the variance of each regression coefficient is decomposed into a contribution from each principal component. The VDP was defined by:

$$Var(\hat{\beta}_j) = \sigma^2 \sum_k \left(\frac{u_{jk}^2}{\lambda_k}\right)$$

Where u_{jk} is the jth element of the k_{th} eigenvector. Each contribution is calculated using the square of the ratio of an element, j, from the kth eigenvector, u_{jk}, to the singular value $1/\lambda_k$ (Rawlings *et al.* 1998, Liao and Valliant 2012).

The VDP method establishes which variables are contributing to collinearity, with eigenvalues larger than 0.5 being the source of near dependency between variables (Belsley *et al.* 1980, Dormann *et al.* 2013). The VDP method was run using the *Colldiag* function in the package 'perturb' in R (Hendrickx 2012). The use of the CN and the VDP together measures the degree to which the collinearity has degraded the corresponding regression estimate. *Colldiag* measures the condition indices of a matrix using the regression collinearity diagnostic procedures. The output table can be used to establish which variables are contributing to any large VDPs.

A Generalised Linear Model (GLM) determines which variables should be included in the final wetland occurrence model. GLMs are an extension of linear models with greater flexibility (Nelder and Wedderburn 1972, Quinn and Keough 2002). In GLMs, the linear model is related to the response variable, y, via a link function, $\eta(.)$, and is modelled as a sum of the explanatory variables ($x_1, x_2, \ldots x_p$), each corresponding to a linear coefficient ($\beta_1, \beta_2, \ldots \beta_k$), such that:

$$\eta(y) = \mu = \alpha + \sum_{i=l}^{k} \beta_i x_i$$

Where the link function was defined as:

$$\mu = log\left[\frac{\mu}{1-\mu}\right]$$

In GLMs the coefficients are estimated by minimising the appropriate log-likelihood function, ln L. Akaike's Information Criterion (AIC: Akaike 1973). The AIC was used in the GLMs as the basis for selecting the parsimonious model that explained the most variance with the fewest number of parameters, using *a posteriori* stepwise backward variable selection procedure (Manel *et al.* 1999, Quinn and Keough 2002, Crawley 2012). The most parsimonious model

had the lowest AIC. The GLM was run in R using a binomial distribution (for presence and absence data) and a (logit-link) function (Quinn and Keough 2002, Crawley 2012).

The significant variables in the final GLM were used to create the LR model. The LR models wetland presence (binary data) using both continuous and discrete environmental variables (predictors) from the GLM, and the maximum likelihood estimation (McCullagh and Nelder 1989, Manel *et al.* 1999, Quinn and Keough 2002, Bai *et al.* 2010). An advantage of the LR model is that it does not rely on the data being normally distributed, and variables can be continuous and categorical (McCullagh and Nelder 1989). The LR model for wetland occurrence was defined as:

$$\pi(x) = \frac{e^{\beta_o + \beta_1 x}}{1 + e^{\beta_o + \beta_1 x}}$$

Where β_o and β_1 are the environmental parameters to be estimated. $\Pi(x)$ is the probability that a wetland is present for a given x_1 (ratio of presence to absence), which varies from 0 to 1. The intercept (constant) is β_o, and the regression coefficient is β_1 (Manel *et al.* 1999, Quinn and Keough 2002, Mahiny and Turner 2003).

The LR model was built in ArcGIS 10.3. The rasters corresponding to the variables in the final GLM output were multiplied by the respective coefficient in the GLM, to form a new raster layer. Each new raster layer was added together, according to the above GLM equation, to form an equation grid, using the Raster Calculator Tool (Spatial Analyst: ArcMap 10.3). The value of the constant was the intercept of the coefficients. From the equation grid, a probability grid for the LR model was created, using the following equation:

$$Probability\ grid\ (P) = \frac{e^{equation\ grid}}{1 + e^{equation\ grid}}$$

The test wetland dataset (presence and absence data) was used to extract values from the probability grid. The data were analysed in MedCalc (MedCalc Statistical Software 2015). The area under the Receiver Operator Characteristic (ROC) curve (AUC), was used to determine the accuracy of the predictive distribution model (DeLong *et al.* 1988, Fawcett 2006, Hiestermann and Rivers-Moore). ROC curve values range from 0.5 to 1, with higher values indicating increased accuracy or discrimination (Fawcett 2006, Bai *et al.* 2010, Hajian-Tilaki 2013). The final probability layer was based on the model with the highest levels of sensitivity, specificity and accuracy (Fawcett 2006, Bai *et al.* 2010, Hiestermann and Rivers-Moore). Sensitivity is a measure of the number of wetlands accurately identified, i.e. “True Positives” (TP). Specificity is a measure of how many non-wetlands were accurately

identified, i.e. “True Negatives” (TN). Accuracy indicates the overall success of the probability layer. These measures are defined as:

$$Sensitivity = \frac{TP}{TP + FN}$$

$$Specificity = 1 - Sensitivity = \frac{TN}{FP + TN}$$

$$Accuracy = \frac{TP + TN}{P + N}$$

Where, P is positive, N is negative, FP are False Positives, and FN are False Negatives (Fawcett 2006, Zhu 2011, Hiestermann and Rivers-Moore).

5.3. RESULTS

5.3.1. Wetland GIS database

A total of 1712 wetlands was digitised in the NMBM (Figure 5-2). Rivers, estuaries, and floodplains with direct connectivity to a river or estuary were excluded from the delineation exercise (as per methods). Site visits verified over 80% of the wetlands, with a similar number of systems being both added and removed to the wetland dataset. A summary of the number of identified wetlands in each HGM Unit (Level 4 of the CS) by the Landscape Level Unit (Level 3 of the CS) is given in Table 5-3.

The valley floor was the most diverse landscape unit, with all HGM types present; the total number of wetlands was lower than other landscape units, however (Table 5-3). Slopes and benches were less diverse, with only four HGM types, but overall they had more wetlands, with 660 and 487 wetlands respectively (Table 5-3). Over 80% of the wetlands in the NMBM were depressions, seeps and wetland flats, most of which were located on benches and slopes (Table 5-3).

The 1712 wetlands digitised in the NMBM had a total coverage of 17.88 km^2 (1788 ha) (Figure 5-3). This is approximately 1% of the total area in the NMBM, and about 26% of the riparian areas and wetland areas combined. The three predominant HGM units (depressions, seeps and wetland flats) contributed to approximately 50% of this total wetland area (Figure 5-3).

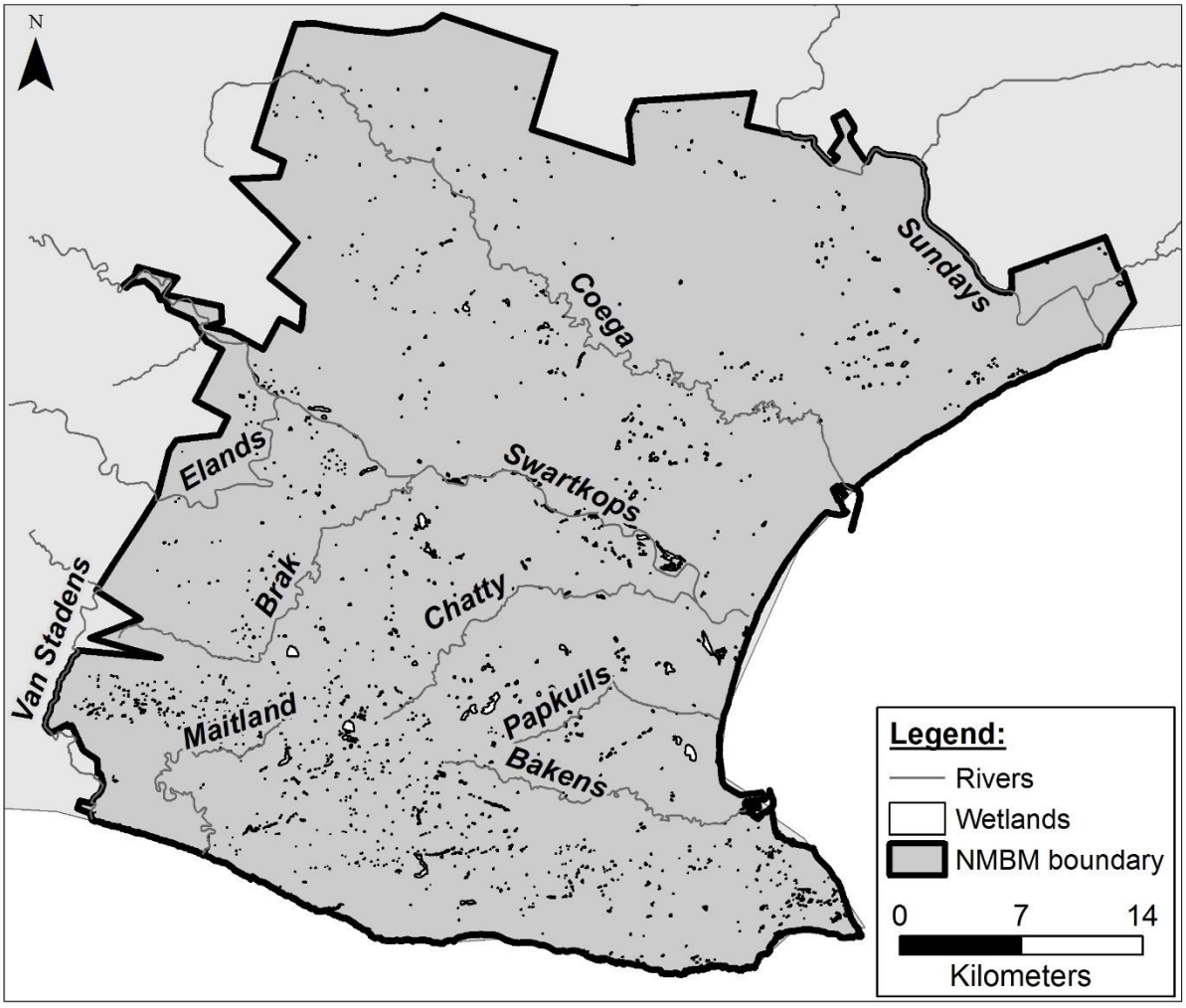

Figure 5-2 **Map of the wetlands delineated in the NMBM showing the major rivers and quaternary catchments.**

Table 5-3 **Number of wetlands at Levels 3 and 4 (landscape and HGM units respectively) of the CS. CVB = channelled valley bottom, UCVB = unchannelled valley bottom, FP = floodplain.**

	HGM						
Landscape Unit	**Depression**	**Seep**	**Wetland flat**	**CVB**	**UCVB**	**FP**	**Total**
Bench	207		275	1	4		**487**
Plain	22	1	89				**112**
Slope	183	444	14	19			**660**
Valley floor	106	26	10	103	130	78	**453**
Total	**518**	**471**	**388**	**123**	**134**	**78**	**1712**

Wetland size ranged from a modified slope seep of 0.002 ha to a natural floodplain wetland along the valley floor of the Swartkops River of 57.06 ha, and an artificial pan used for Salt Works of 214.86 ha. A total of 86% of the wetlands digitised in the NMBM were less than 1 ha in area. Only 38 wetlands were larger than 5 ha, and four of these were greater than 50 ha. There was a significant correlation between wetland size and latitude, with larger wetlands associated with the southern parts of the study area (Pearson's statistic = 0.1961, p-value < 0.0001).

When examining proportions of HGMs, depressions were dominant by both total number (518) and area (568 ha) (Figure 5-3). By contrast, floodplains were the least common HGM type (Figure 5-3), but had a relatively large total area of 402 ha (Figure 5-3). Unchannelled valley bottom wetlands also covered a large area of 390 ha, compared to their relatively low overall numbers (Figure 5-3). The contribution to total wetland area by seeps, wetland flats and channelled valley bottoms was much lower than that of the other three HGM units (Figure 5-3).

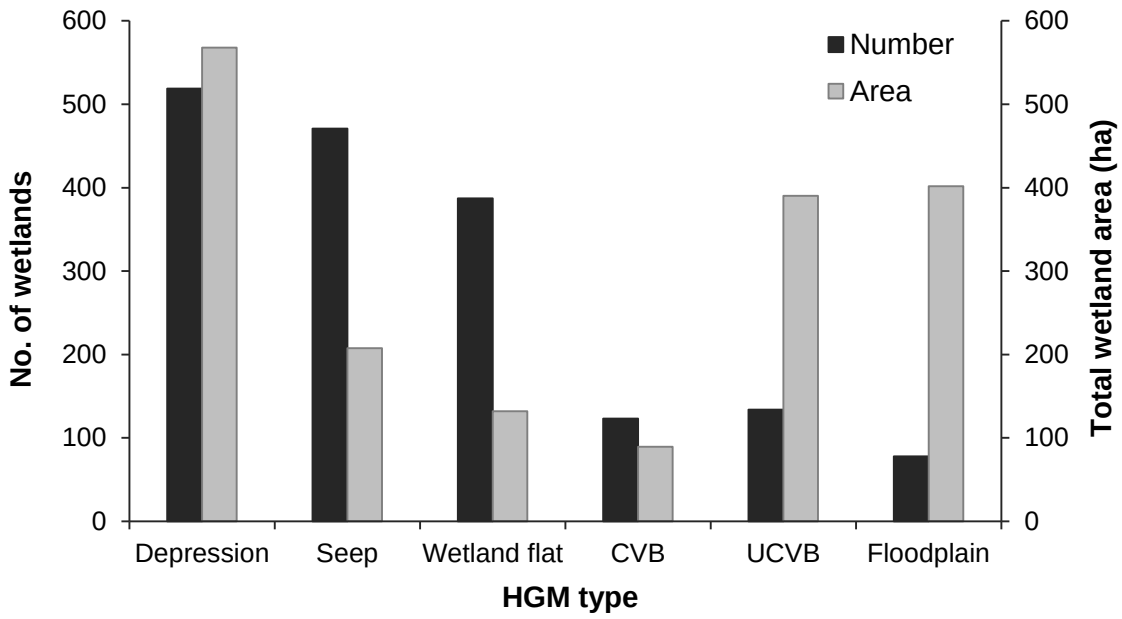

Figure 5-3 Wetland area and number of wetlands per HGM type. CVB = channelled valley bottom, UCVB = unchannelled valley bottom.

Wetlands on slopes and valley floors were larger than wetlands on benches and plains, with mean areas of 1.39 ha (SE ± 0.44), 1.08 ha (SE ± 0.19), 0.67 ha (SE ± 0.09) and 0.49 ha (SE ± 0.16) respectively (Figure 5-4). However, these difference in areas among the different landscape units were not statistically significant (ANOVA: $F_{3, 1708} = 1.109$, $p = 0.344$). The

larger wetland areas on slopes and valley floors were due to the presence of floodplain wetlands and unchannelled valley bottom wetlands which were, in general, much larger than the other HGMs (Figure 5-5). These two HGMs had mean areas of 5.15 ha and 2.91 ha respectively. The smallest HGM types were mostly seeps and wetland flats with mean areas of 0.034 ha and 0.044 ha respectively. Overall, there were highly significant differences in the areas among the different HGMs (ANOVA: $F_{5, 1706} = 7.994$, $p < 0.0001$).

Approximately 66% of the wetlands in the NMBM were natural (with unaltered morphology), 27% having some level of modification (a degree of modification or disturbance by anthropogenic activities) and the remaining 7%, artificial. Natural wetland systems were significantly smaller than artificial and modified systems with a total area of over 1045 ha and an average area of 0.92 ha (SE ± 0.10) (ANOVA: $F_{2, 1709} = 12.02$, $p < 0.0001$). Although artificial systems contributed the lowest number of wetlands, in terms of area, these systems were much larger than natural and modified systems, with a mean area 4.12 ha (SE ± 2.28) (Post-hoc Tukey: $p < 0.0001$). Most of the artificial systems were farm dams and reservoirs. Both artificial and modified wetland systems were situated on relatively undisturbed lands, land that is used for agricultural activities or within the urban boundary. In comparison, the majority of natural systems were found on land that is currently in a natural condition.

Floodplain wetlands and depressions were mostly unmodified, with 97.4% and 74.4% classed as “natural” respectively. In contrast, 13.8% of channelled valley bottoms and 9% of wetland flats had been modified to such an extent that they were classified as “artificial” as there was an apparent total loss of natural, pre-existing functions. Approximately 40% of channelled valley bottoms and 35% of seeps were classed as modified.

Wetland distribution

Almost all HGM types were found within all nine quaternary catchments, with the exception of floodplain wetlands which were limited to larger river and estuarine systems (Figure 5-6). Figure 5-6 and Table 5-4 illustrate the increase in the total number of wetlands in each catchment, which coincides with the increase in annual rainfall from the north of the Municipality (Catchments M30A & B, N40E & F) towards the south (Catchments M20A & B). This north-to-south increase in wetlands was especially prominent in seeps and wetland flats. Depressions were the exception as their numbers varied across catchments, as such, these systems represented a larger proportion of the total number of wetlands in the north of the Municipality. For example, 77% of the wetlands in catchment M30B (a “dry” catchment) were depressions. In comparison, depressions in the wettest catchment (M20A) represented only 13% of the total wetland density. These results are explained further in Chapters 6 and 7.

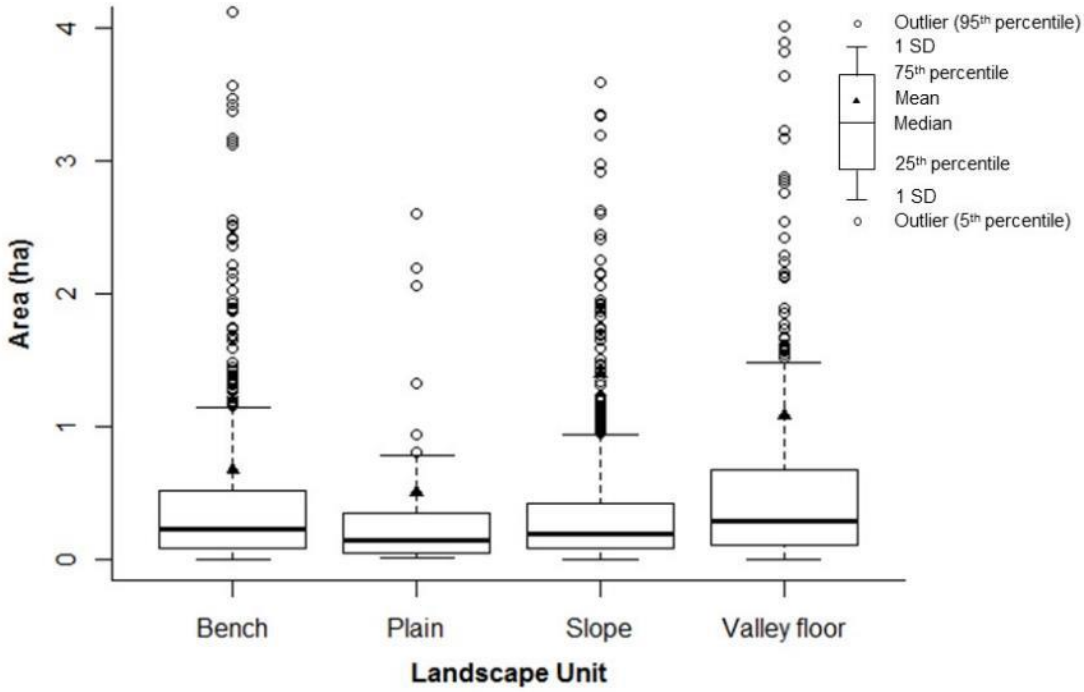

Figure 5-4 **Median area (ha) and standard deviation for the four landscape units. The key given is standard for all boxplots. Outliers extending beyond 4 ha were not shown.**

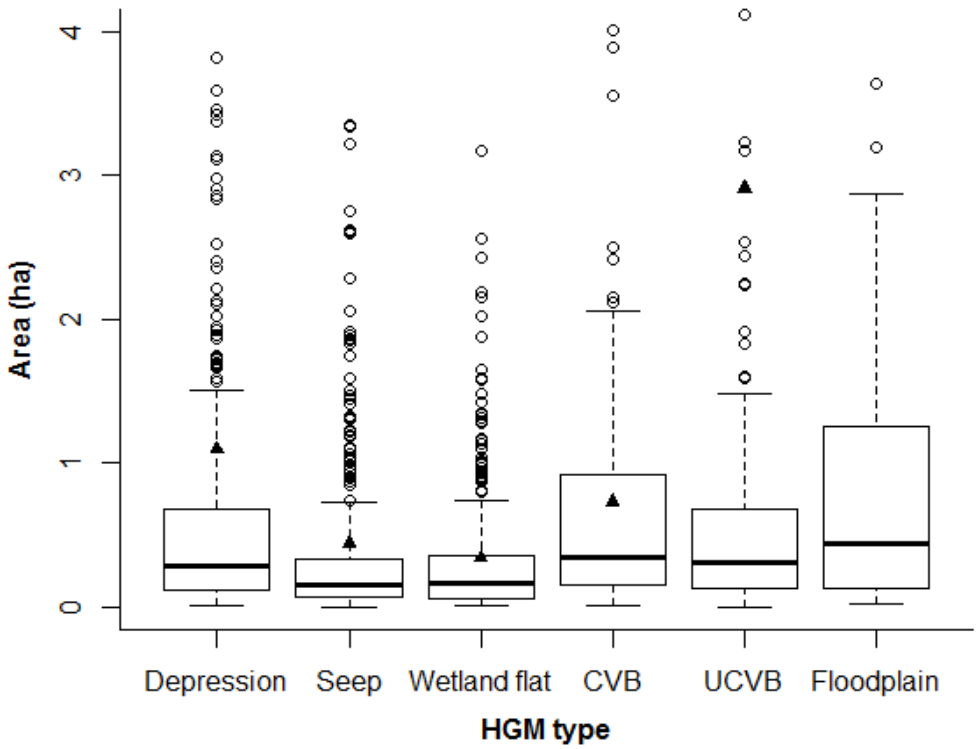

Figure 5-5 **Median area (ha) and standard deviation for the six HGM types. See Figure 5-5 for boxplot key. Outliers extending beyond 4 ha were not shown.**

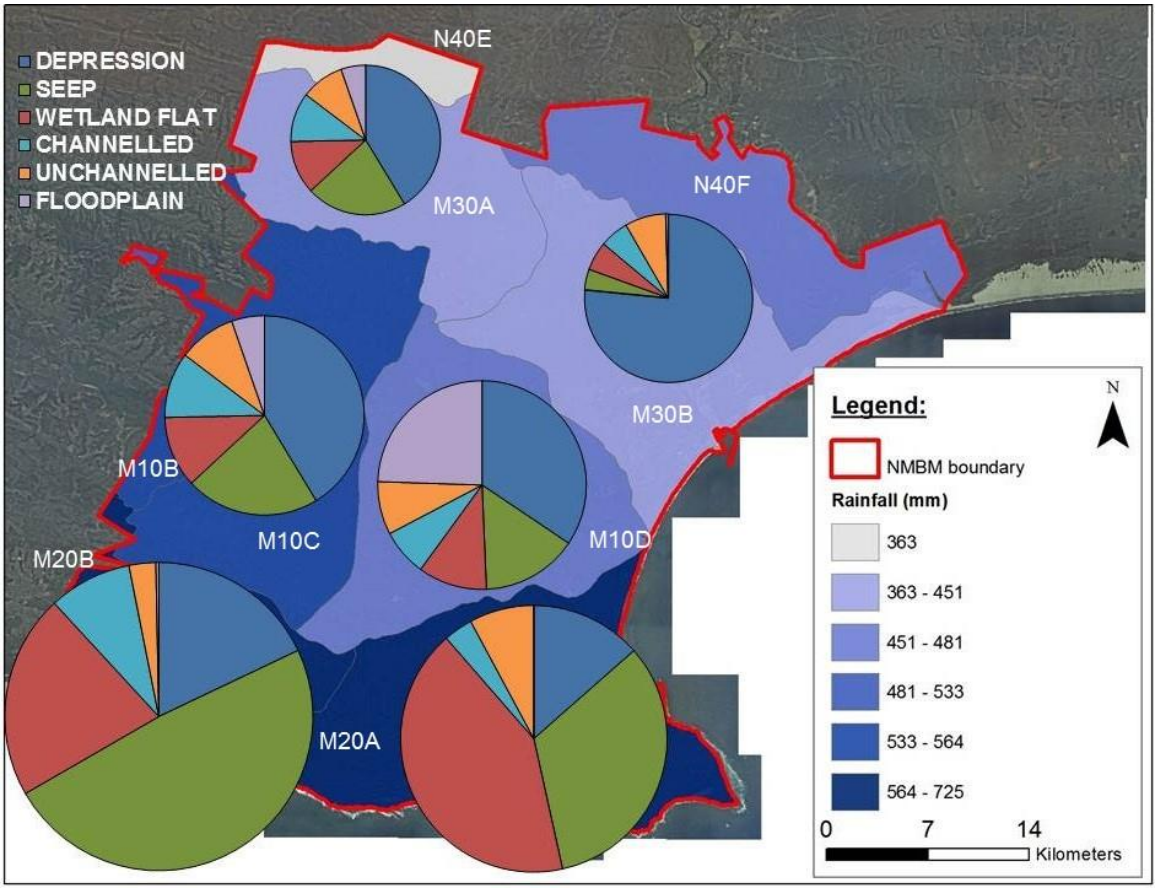

Figure 5-6 **HGM units identified within each quaternary catchment. Background shading illustrates annual rainfall (mm) in each catchment (Data from WRC (1990)). Size of pie charts indicate the relative overall number of wetlands in a catchment compared to other catchments.**

Table 5-4 **Total number of wetlands (per km^2) found within each quaternary catchment.**

Catchment	Number of wetlands per km^2
M30A & N40E	0.36
M30B & N40F	0.82
M10C & M10B	0.86
M10D	1.01
M20A	2.26
M20B	1.22
AVERAGE	0.88

The NMBM and the National Wetland Map IV

Overall wetland density (excluding rivers) for each of the nine provinces, based on the National Wetland Map IV map, is displayed in Figure 5-7. This map is a combination of datasets collected at different spatial and temporal scales, therefore, the data must be analysed with caution. However, general patterns can be observed. The overall density of 8.77 wetlands per 10 km^2 in the NMBM (from the high resolution data collected in this study) was higher than for the rest of the Eastern Cape and for SA as a whole. Fewer wetlands were found in the drier provinces, in the northern parts of the country (Figure 5-7), and larger wetland densities were recorded in the Free State, Gauteng and the Eastern Cape, due to a high proportions of dams (artificial systems) (Figure 5-7).

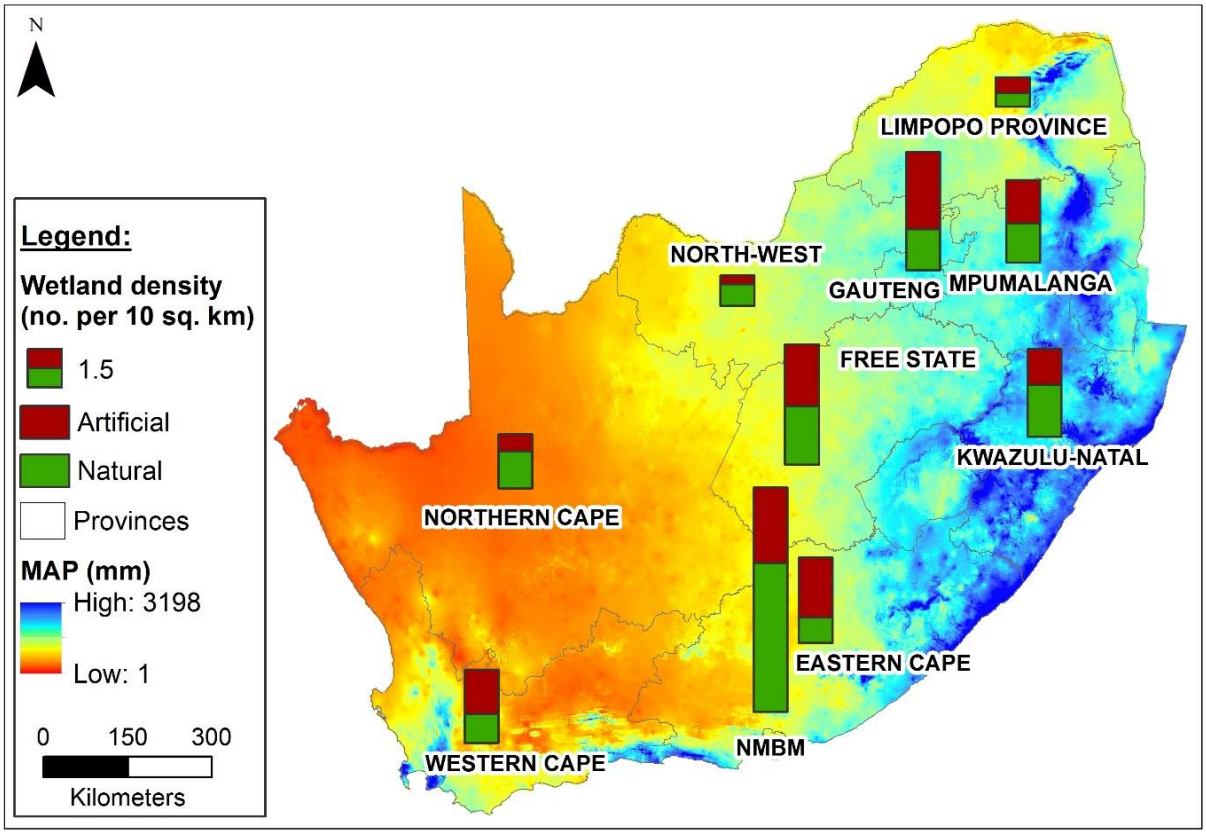

Figure 5-7 **South African rainfall map with histograms illustrating the average wetland density (average number of wetlands per 10 km^2) for each of the nine provinces in South Africa. Red and green colours represent the proportion of the overall wetland density that is artificial or natural. Data are from the National Wetland Map IV and artificial (man-made) wetlands and natural wetlands have been separated. Wetland density for the NMBM is also displayed for comparison. MAP = mean annual precipitation.**

5.3.2. Results for the logistic regression (LR) model

A total of 19 input variables was used to develop the wetland occurrence model, of these, 13 were continuous variables (Table 5-2). The training dataset comprised 1198 wetland data points and 2000 non-wetland points. Some known wetland sites and non-wetland sites were excluded as the raster images did not cover the full extent of the study area. The resultant values for known sites and random points was roughly equal.

Variables selected using PCA and the Condition Number

High collinearities between some of the ordinal variables resulted in five variables being deleted from the model: temperature, summer and winter heat units, APan evaporation, and solar radiation. The remainder of the variables had a Condition Number (CN) score of 9.928. Annual heat units had the highest contribution on the first principal component, followed by MAP and elevation, with a total of 38% of the variance being accounted for by the variables on the first axis (Table 5-5). The latter two variables also contributed consistently to the second and third axes, indicating the important influence of these two variables (Table 5-5).

Table 5-5 Eigenvector scores for the first three axes for the ordinal variables with a total Condition Number of less than 10.

PCA variable loadings	PC1	PC2	PC3
Elevation	-0.306	0.229	-0.558
Flow accumulation	-0.003	-0.018	-0.019
Flow direction	-0.004	-0.010	0.003
Aspect	0.010	-0.883	-0.464
Slope gradient	0.000	-0.013	0.002
Evapotranspiration (eto)	0.172	0.151	-0.270
Mean annual precipitation (MAP)	-0.523	-0.344	0.585
Annual heat units (hu.annual)	0.776	-0.164	0.241
Standard deviation	139.792	104.112	101.901
Proportion of variance	0.38	0.21	0.20
Cumulative proportion of variance	0.38	0.59	0.79

A GLM was fitted to the remaining continuous and categorical data. The final parsimonious model included seven variables, all of which were significant where $p < 0.001$, with an AIC

value of 3283.9 (Table 5-8). Note that both groundwater occurrence and the categorical rainfall variable (pe.rnfl) had high standard errors than the other five variables. The coefficients from the output in Table 5-6 was used to fit the LR in ArcGIS. These coefficients indicate that the largest contribution to the presence of a wetland was groundwater occurrence and rainfall; however, both of these variables also had large standard errors. The result of the LR model (LR 1) was an AUC value of 0.683. A p-value of less than 0.0001 indicates that the model performed well and that a wetland area versus a non-wetland area were significantly different.

Table 5-6 Coefficients and standard errors for the significant variables used in the first logistic regression model. P-values are all significant at a 0.05 level.

	Coefficient	Std. error	P- value
(Intercept)	-13.28000	2.21300	< 0.0001
Elevation	-0.00290	0.00047	< 0.0001
Flow accumulation	-0.00933	0.00358	0.0090
Flow direction	0.00842	0.00147	< 0.0001
Evapotranspiration (eto)	0.00658	0.00146	< 0.0001
Mean annual precipitation (MAP)	0.00439	0.00078	< 0.0001
Groundwater occurrence	0.50740	0.07649	< 0.0001
PE rainfall (pe.rnfl)	0.32660	0.08858	0.0002

Variables selected using the condition number and variance decomposition proportion

The output of the GLM was also tested for collinearity among the significant variables using the C*olldiag* function. A variance decomposition proportion (VDP) of 177.276 was computed for the first GLM, with evapotranspiration being the main contributing variable to the high VDP. Evapotranspiration was subsequently removed from the GLM and a step-wise GLM was re-run. The final output is displayed in Table 5-7. The AIC value of 3302.2, was slightly higher than for the previous model (Table 5-8); the overall effect on the model was minimal, however.

The coefficients from the output (Table 5-7) were used to fit a second LR (LR 2) in ArcGIS. The result of the second LR model was an AUC value of 0.685 ($p < 0.001$) (Table 5-8). The two LRs performed similarly, with only a slight model improvement with the exclusion of evapotranspiration and the resultant changes to the GLM. Thus, the *a priori* collinearity test was sufficient for the LR.

Two more LR models were run to validate the level of accuracy achieved. A new training and test dataset was selected using the same guidelines as discussed in Section 5.2.1. Different combinations of variables were removed to achieve low VDP values that met the LR model criteria. The coefficients for the two additional GLM outputs are included in Appendix E: Table E-1 and Table E-2. Although there were differences in some of the variables that were used in the output, this did not appear to affect the model output in either model, with AUC values of approximately 0.68 and an accuracy of approximately 66% (Table 5-8).

Table 5-7 Coefficients and standard errors for the significant variables used in the second logistic regression model. See Table 5-2 for acronyms. P-values are highly significant at a 0.5 level.

	Coefficient	Std. error	P- value
(Intercept)	-11.59000	2.73500	< 0.0001
elevation	-0.00144	0.00050	0.0045
flow.accum	-0.00985	0.00359	0.0060
flow.dir	0.00829	0.00147	< 0.0001
map	0.00376	0.00076	< 0.0001
temp	0.42370	0.14080	0.0026
gw	0.49120	0.07624	< 0.0001
pe.rnfl	0.29750	0.08784	0.0007

Table 5-8 Comparison among the logistic regression (LR) models on estimating the probability of wetland occurrence. AIC = Akaike's Information Criterion, GLM = Generalised Linear Model, VPD = Variance Decomposition Proportion.

	LR 1	LR 2	LR 3	LR 4
No. of variables	7	7	6	5
AIC value of GLM	3283.9	3302.2	3295.6	3308.1
VDP score	177.28	24.17	160.57	15.47
Area under the ROC curve (AUC)	0.68	0.69	0.68	0.68
Std. error	0.02	0.02	0.02	0.02
Sensitivity (%)	54.23	58.14	56.08	58.12
Specificity (%)	75.30	72.52	74.09	71.75
Accuracy (%)	**65.66**	**65.94**	**65.85**	**65.47**

Figure 5-8 illustrates the outcome of the LR 2 model for the NMBM (model with the highest accuracy). Distinct areas of high and low probabilities can be seen in different areas of the Municipality. Two areas with a generally high wetland probability of occurrence are observed in the southern area of the Municipality, and a band south of the Coega River. This corresponds with a general increase in the number of wetlands that have been recorded in these areas (marked on the map). Low probability areas lie around the Swartkops River and towards the northern part of the Municipality.

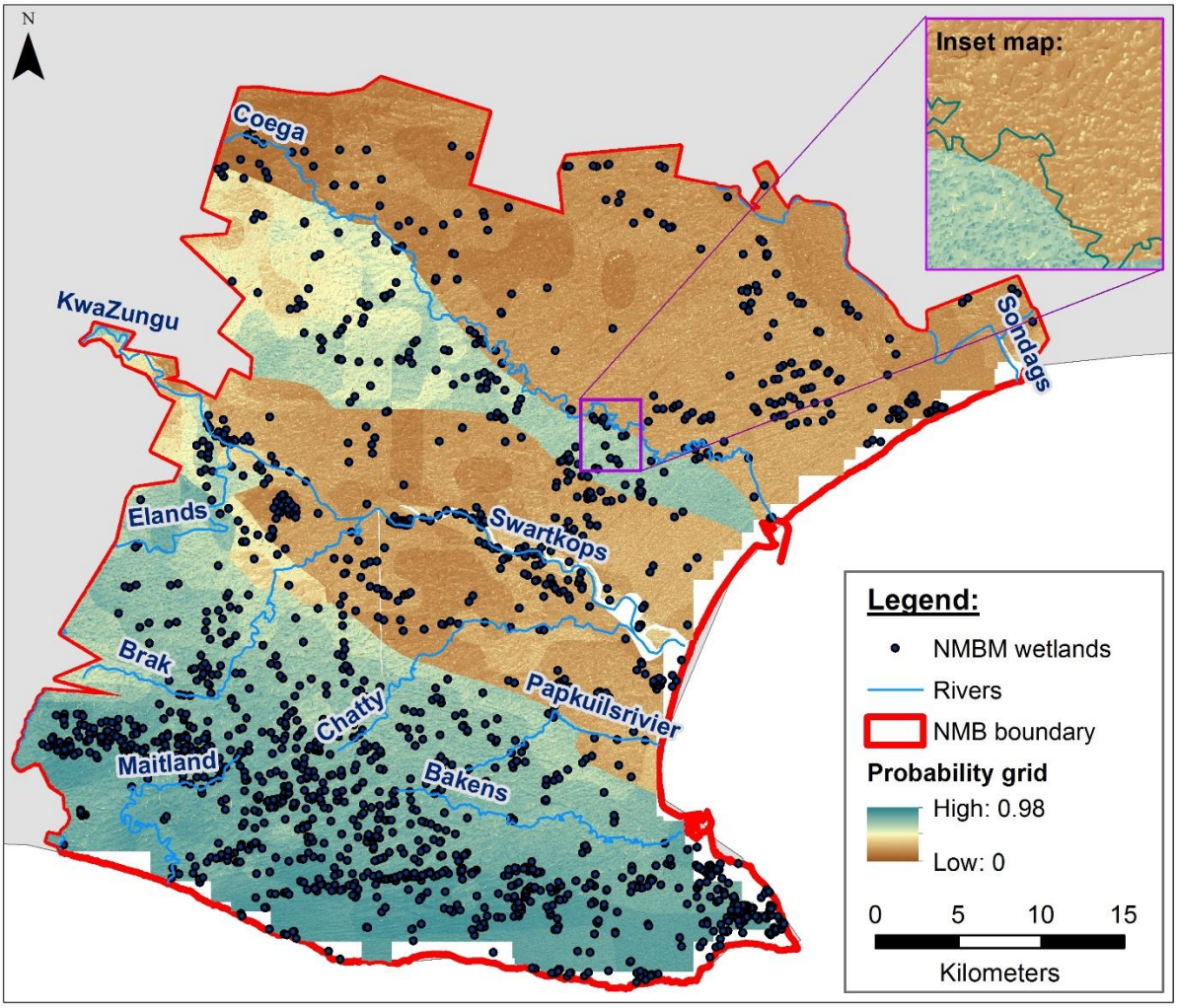

Figure 5-8 Logistic regression probability grid for wetland occurrence in the NMBM. Wetlands identified using aerial photos are also illustrated. White areas indicate "No Data". Inset map (top right) illustrates the variability at a finer scale.

The inset map in Figure 5-8 also illustrates the variation in probabilities that can occur within a relatively small area, even though it cannot be readily seen at a broader scale. There was also significant variability in the model prediction for the different HGM types (ANOVA: $F_{5, 1580} = 126.74$, $p < 0.001$) (Table 5-9). Seeps and wetland flats had the highest average probability

score, and were best detected by the model, while unchannelled valley bottom wetlands and floodplain wetlands were poorly predicted by the LR model, followed by depressions (Table 5-9). Average probability scores were significantly correlated to wetland size (see Figure 5-5 for wetlands areas by HGM type) (Pearson's statistic = -0.2222, p-value < 0.0001).

Table 5-9 Average probability scores for each HGM type based on the outcome of the final logistic regression model. Score ranges from 0 to 1.

HGM type	Average probability score
Depression	0.46
Seep	0.73
Wetland flat	0.68
Channelled valley bottom	0.58
Unchannelled valley bottom	0.39
Floodplain wetland	0.29
Average	**0.58**

5.4. DISCUSSION

5.4.1. The NMBM GIS database

The 2009 aerial photographs used in the study were the latest data available when the bulk of the digitising occurred for this study. Between 2007 and 2010 SAWS recorded drought conditions, which would have a negative effect on the ability to detect ephemeral/cryptic systems as there would be less surface water cues. It was for this reason that the dataset had to be revisited several times as experience was gained during fieldwork, and during the wetter conditions experienced during the study. Thus, Google Earth imagery proved to be an additional invaluable tool to accurately identify and delineate wetlands.

The desktop delineation of wetlands in the NMBM made a significant contribution to the previous wetland database, with more than 1000 wetlands being newly identified. Some of these wetlands were known to exist; but, the data had not been recorded before the work of Schael *et al*. (2015). The 1712 wetlands identified in the NMBM comprised a total wetland area of approximately 17.88 km^2. The national wetland database previously indicated approximately 596 systems in the NMBM, most of which were larger, more permanent wetlands and farm dams with a total area of approximately 14.7 km^2 (CSIR 2011). A land

cover study conducted in 2007 indicated approximately 4 km^2 of dams (Stewart 2010), a similar coverage than the total area of artificial systems digitised (approximately 5 km^2). Both of these studies, however, illustrate that although the overall percentage land cover is not vastly different, the total number of wetland systems was underestimated. As a result of this study, the updated National Wetland Map for wetlands in SA will include wetlands that have been identified in this study.

Wetland numbers have not only been underestimated in the NMBM, but also at a national level. The overall wetland density for the NMBM was disproportionately high compared to other provincial numbers based on the National Wetland Map. A large portion of this difference can be attributed to the coarse resolution and variability of data sources of the national dataset compared to the high resolution of data collected in the NMBM. Despite the variation in numbers, even compared to the whole of the Eastern Cape, the data illustrates the value of conducting fine-scale studies across all regions.

A paper by Semlitsch (2000), titled “Size does matter: the value of small isolated wetlands”, reiterates the value of having identified numerous small wetland systems in the NMBM, of less than 1 ha. The identification of these systems can be attributed to manual aerial photograph interpretation at a fine scale. Various other studies have also shown the value and importance of fine-scale manual aerial photographic interpretation, particularly for regions where wetlands are smaller than 1 ha (Grant 2005, Lathrop *et al.* 2005). However, the probability of identifying a small, highly ephemeral system would be improved by using aerial imagery from different seasons and over different years that captures both wet and dry cycles. This is especially important in areas that receive highly variable rainfall, both spatially (within a small area) and temporarily, as is the case in the NMBM.

The total number of small (< 1 ha) wetlands in the NMBM illustrates the importance of these systems to water resources in the area (Semlitsch 2000). Various semi-arid areas have recorded the extent and importance of smaller systems, such as, on the High Plains in Kansas (USA), almost 95% of the wetlands were less than 5 ha in size (Bowen *et al.* 2010), 64% of the wetlands were less than 1 ha in size, and 17% were less than 0.2 ha in size. In Mallorca, Spain, the majority of wetlands were less than 10 m in length (ca. < 0.01 ha), with a few relatively larger wetlands of approximately 0.1 ha in size (Mutaner *et al.* 2013). This pattern is more pronounced in the NMBM where 89% of the wetlands are smaller than 1 ha, and 48% of the wetlands fell below most detection limits of 0.2 ha. Small, ephemeral wetlands can also contribute to water resources in wetter areas. For example, on the south eastern Atlantic Coastal Plain (USA), where 46% of the Carolina Bay wetlands were less than 1.2 ha, and the large majority were less than 4 ha (Semlitsch and Bodie 1998), and in north central

Minnesota, ephemeral wetlands ranged in size from 0.01 ha to 0.25 ha (Palik *et al.* 2003). Semlitsch and Bodie (1998) and Semlitsch (2000) emphasise that size is imperative to biodiversity maintenance. The prevalence of these small wetland systems is expounded on in Chapter 6 and in Chapter 8.

Depressions were the most ubiquitous HGM type, found across all rainfall zones and landform types in the NMBM. In contrast, other semi-arid regions in SA tend to be dominated by ephemeral wetland flats, seeps and channelled valley bottom wetlands (e.g. Nieuwoudtville and Kamieskroon in the semi-arid region of the Northern Cape) (CSIR 2011). In regions of North America, there is also a prevalence of small, isolated depressions, albeit formed by different processes (Winter and Rosenberry 1995, Meyer *et al.* 2003, Tiner 2003b, Johnson *et al.* 2005). For example, the prairie pothole region that extends from Canada down along the western parts of North and South Dakota have depressions formed by glaciers (Winter and Rosenberry 1995, LaBaugh *et al.* 1998). Another example are playa wetlands that are found in semi-arid and arid states such as Colorado, Wyoming and Montana that have formed as a result of wind and dissolution (Johnson *et al.* 2005). An outline of the formation and inundation characteristics of these wetland types can be found in Section 2.9.

Wetland flats are also common in plains and interfluves, where precipitation is dominant (Hauer *et al.* 2002, Tiner 2003b), a feature that was observed in the study area. Seeps were predominant on the slopes, associated with areas where there is interflow, and where the sub-surface water surfaces that occur at a break-point on a slope (Richardson 1995, Ollis *et al.* 2013). Thus, the prevalence of these three HGM types can be attributed to the abiotic factors described above. The importance of these landscape factors will be discussed in Chapter 7.

The total area covered by wetlands indicates the potential contribution to water resources in the NMBM. One quarter of the surface water area exists as a result of these small geographically isolated systems (when all wetland and riparian systems are inundated). Thus, their overall contribution becomes an increasingly important contribution to the total water surface area, on a larger landscape level, even though these systems are small and would be missed in most surveys.

A study on wetland distribution in SA found that there was approximately 16 800 km^2 of inland wetlands distributed throughout the country, comprising approximately 0.4% of the land area (including both natural and artificial systems) (van Deventer *et al.* 2016). Considering the uneven distribution of rainfall in SA, most of the natural wetland systems are located in areas that have a higher MAP (generally greater than 600 mm per annum) and lower

evapotranspiration rates, compared to the drier areas that had fewer systems (Schulze 2007, CSIR 2011). A similar pattern was also observed in the NMBM. Although, the southern parts of the Municipality only receive about 100 mm more of rainfall per year compared to the northern parts, there is a significantly higher number of wetlands per unit area compared to the national average calculated by Taylor *et al.* (1995). The high density of wetlands within the relatively small study area illustrates the importance and potential impact of the surrounding climate, underlying geology and elevation as some of the key environmental features that shape the distribution and abundance of wetlands in semi-arid areas.

Several authors (for example: Semlitsch and Bodie 1998, Leibowitz 2003, Meyer *et al.* 2003, Zedler 2003, Lathrop *et al.* 2005, Tooth and McCarthy 2007) recognise the function and contribution of these small, ephemeral wetlands in semi-arid to arid areas. These small systems are important for maintaining biodiversity of the associated aquatic fauna and flora, by allowing connectivity to occur at a landscape level (Semlitsch and Bodie 1998, Zedler 2003). Connectivity between wetlands and the biodiversity of ephemeral systems in the NMBM is discussed in Chapters 6 and 7 respectively.

The majority of these systems would not be inundated during extended dry periods. This includes larger and deeper systems which were fully inundated during a flood season and dried after only one year of low rainfall (Pers. Obs.). For example, a large near-natural depression had a wetted area of approximately 16 ha in November 2012. By March 2014 the same wetland had dried up, with no evidence of sub-surface water (Pers. Obs.). Thus, research needs to take into consideration the large fluctuations in surface water in semi-arid areas with smaller, more ephemeral systems to avoid further wetland loss.

A large (unexpected) number of floodplain wetlands classed as natural in the wetland database. This is likely to be due to the extreme modification of some areas of the extended floodplain of the Swartkops Estuary, resulting in these wetlands being classified as modified in another HGM type, thereby leaving the remaining systems classed as natural. Overall, two thirds of the wetlands are currently classed as natural in the NMBM. Although it is not known how many systems have already been lost, the majority of the remaining systems appears to be minimally impacted by direct anthropogenic activities. Indirect influences on the hydrology (e.g. changes in the water table due to catchment activities) are not known. In comparison, over 50% of wetlands in some developed regions have been modified by direct anthropogenic activities (Roshier *et al.* 2001). The NMBM still has the potential to develop good conservation actions. These natural wetlands also contribute to a large portion of the surface water in the NMBM. These results suggest that there is a good network of wetlands that are still functioning ecologically and contributing to resources at a landscape level.

5.4.2. The logistic regression (LR) Model

The LR model had an accuracy of 66%. This level of accuracy is comparable to the outcome of a LR wetland occurrence model carried out in Massachusetts, USA, where the occurrence 64.8% of the vernal pools were accurately predicted (Grant 2005). However, the accuracy is much lower than occurrence models in KwaZulu-Natal (KZN), SA, where an accuracy of 89% and 86% was achieved for LR and Bayesian Network models respectively (Hiestermann and Rivers-Moore 2015).

The poorer performance of the NMBM dataset compared to KZN could be due to the quality and availability of data for the NMBM; for example, hydromorphic soils, which was used in the model by Hiestermann and Rivers-Moore (2015). Martin *et al.* (2012) achieved a similar high accuracy using hydric soils. Accordingly, in-depth soils data are possibly a key factor contributing towards the success of a model. The resolution of the data also has an impact on model performance. In both LR models in this study, the categorical variables with a coarse resolution (groundwater occurrence and rainfall) were highly correlated with wetland occurrence. Although, both these variables also had large standard errors which further emphasises the importance of the resolution of data. These variables were still kept in the model as these variables, along with the other variables in the model, represent the complexity of environmental interactions that occur and result in potential wetland formation.

Another factor potentially influencing the success of a wetland occurrence model is the nature of the region. The LR model used by Hiestermann and Rivers-Moore (2015) was based on wetlands in an area that receives a high mean annual rainfall of approximately 1000 mm (ranging from 600 mm to 1330 mm), which predominantly falls during summer and has relatively low evapotranspiration rates in comparison (950 mm to 1550 mm per annum) (Schulze 2007). This is in contrast to the NMBM where there is a stronger negative relationship between rainfall and evapotranspiration, resulting in a higher portion of ephemeral systems. Rainfall patterns in the NMBM are highly variable, which also makes it more difficult to predict and estimate the presence of surface water in a landscape at any particular point in time. Consequently, various datasets would either provide a snapshot picture of the environment at a particular time, or provide an overall average, which is not indicative of the conditions that facilitate a wetland forming at a particular time.

The average size of the wetlands would also influence the probability of identifying a wetland. The higher rainfall in KZN would result in larger, more seasonal or permanent wetlands compared to the present study area, which had many small wetlands (less than 1 ha in size), that were highly intermittent in nature. Difficulty in estimating the number and size of smaller,

ephemeral systems through modelling has also been recorded in semi-arid regions of Australia and the USA (Roshier and Rumbachs 2004, Grant 2005, Lathrop *et al.* 2005).

Certain HGM types were more accurately identified by the model. Seeps, wetland flats and channelled valley bottom wetlands had high average probability scores, indicating that the environmental variables used in the model were well suited to these HGM types. Wetlands in these three HGM types were, on average, also the smallest in size. In contrast, unchannelled valley bottom wetlands and floodplain wetlands had low mean probability scores, suggesting that these two HGM types were closely associated with fluvial systems (see Chapter 6) and were also significantly larger than the other HGM types, which would have influenced the model. It would seem more likely to have higher probability scores with larger systems than smaller systems; however, there is a possible explanation as to why this was not the case. Although there are general areas where wetland probabilities are higher and lower (Figure 5-8), the model output consists of a mosaic of pixel values that can lie adjacent to each other (for examples see the inset map in Figure 5-8). Only one data point (the centroid) is used per system and, in larger systems, this might result in the point falling on a lower probability cell. A similar observation was made by Hiestermann and Rivers-Moore (2015) in KZN.

Depressions were a further exception as they would be expected to have similar probability values to seeps and wetland flats (due to their size and general abundance); but their scores were much lower. The low probability values are possibly a result of the relative geographical isolation of these systems in the landscape compared to seeps and wetland flats, as well as the diverse nature of these systems, both of which would make it more difficult to train the model to predict a wetland based on a certain set of conditions. The complexity and diversity of the depressions are described more in Chapters 6 and 7 and summarised in Section 8.1.1.

The variability in the model results can be attributed to wetland size and HGM type, with the exception of depressions. If a LR model was performed on a subset of HGM types, the accuracy of the model might improve. A further influence on model accuracy is that large areas have been built up in the NMBM, and some wetlands are no longer recognisable within the urban boundary. Thus, the model will have a lower accuracy in these areas due to the lack of wetland sites to “train” the model or confirm wetland presence. However, even though the accuracy of the NMBM model was not as high as in KZN, it is still above the threshold for predictive occurrence models, and it was statistically significant (Grant 2005, Mathew *et al.* 2009). The model, therefore, could be used to estimate the likelihood of wetland occurrence in other regions with similar geographical features, such as along the southern Cape, or in areas/countries with a Mediterranean and/or semi-arid climate.

LR modelling can be used to improve land cover datasets; although, validation techniques would be needed to verify wetland occurrence, or to map sites that had not been identified. Outputs from these models can be used to indicate previous wetland sites in areas that have been transformed, as the models can be built independently of land cover (McCauley and Jenkins 2005, Hiestermann and Rivers-Moore 2015). A limiting factor is that these models do not provide an indication of the spatial aerial coverage of wetlands, merely the likelihood of their presence or absence within a landscape.

5.5. CONCLUSIONS

A number of wetlands were newly identified in this study (Objective 1), which has made a significant contribution to the National Wetland Map and the data is now being used by the NMBM. The total number of wetlands identified and the dominance of depressions, wetland flats and seeps, were not expected given the semi-arid climate. Wetlands as small as 0.002 ha were recorded using aerial photographs, and 86% of the wetlands were less than 1 ha, most of these were classed as natural. The prevalence of smaller, ephemeral systems is similar to studies located in similar climatic settings. In the NMBM, wetlands cover up to a quarter of the maximum surface water cover throughout the Municipality and, therefore, the overall contribution of these small systems only becomes evident at a broader scale. The abundance of wetlands in the NMBM illustrates the need to conduct in-depth studies, as cryptic wetlands can be more prominent in drier environments than expected. As was discussed in Chapter 2 Section 2.4, this type of finding is important as these systems have a greater threat of being lost/damaged due to their size. Thus, wetland numbers need to be accurate to ensure that these ecosystems can be managed or conserved appropriately.

The LR model successfully modelled the likelihood of wetland occurrence in the NMBM, despite the variable climate and quality of some of the spatial data. As a result, both manual digitising and LR modelling are useful tools for understanding wetland distribution in semi-arid environments, which addresses Objective 2 of this thesis. This modelling tool can now be used in other data scarce areas of the Eastern Cape to improve inventory data. The variables that were significant in the model (precipitation, evapotranspiration, temperature, flow accumulation and groundwater occurrence) also provide an indication of some of the important abiotic factors that might influence wetland functioning at a site and broad, catchment scale. This knowledge can also be transferred to other data scarce areas in the region. Chapter 7 address whether the environmental variables are apparent at different spatial scales and what other data are needed to describe any community patterns.

6. SPATIAL PATTERNS IN WETLAND DISTRIBUTION

6.1. INTRODUCTION

Chapter 5 described the occurrence of wetlands of 1712 wetlands within the NMBM. The logistic regression (LR) model also highlighted potential key environmental variables that correlated with wetland distribution. After establishing the wetland distribution and structure, wetland systems can be further understood at a finer scale, in terms of their connectivity or relative geographical isolation to other wetland systems, by incorporating concepts from landscape ecology. This chapter addresses wetland occurrence at this finer scale (compared to Chapter 5), and evaluates spatial patterns in wetlands and wetland complexes in different areas of the Municipality. Spatial statistics and distance metrics are used to quantify the link between broader distribution patterns across a landscape, and what is observed within a catchment and/or at an individual site. This is an important step for understanding the scale at which these systems operate and "interact", as well as for conservation and management strategies.

This chapter uses statistical analyses to describe the environmental relationships that occur within wetland mosaics and complexes in the NMBM, and how different environmental variables are associated with the occurrence of different-sized wetlands (as per Objective 3). One of the main factors influencing the spatial pattern of wetlands is surrounding land use. Land use can indirectly or directly impact the vegetation, water quantity and quality (as was discussed in detail in Section 2.11, page 30). As a result, this chapter also illustrates the distribution of wetlands within transformed areas within the NMBM and establishes the impact of both the environment and anthropogenic activities on wetland distribution (Objective 4). The conservation and management implications of these spatial patterns are later discussed in Chapter 8.

6.1.1. The wetland landscape structure

Chapter 2 introduced the concept of landscape ecology (Section 2.1, page 9), and the importance of understanding the spatial relationships among wetlands as the structure of the landscape affects associated abiotic and biotic processes (Turner *et al.* 2003, Schröder and Seppelt 2006). The bio-physical relationships between wetlands, can be better understood with reference to wetland geographical isolation and connectivity, which were briefly introduced in Section 2.9 (page 27), with reference to movements of organisms between

wetlands at different temporal and spatial scales (Amezaga *et al.* 2002, Euliss *et al.* 2004, Amat *et al.* 2005). Besides biological (functional) aspects, connectivity can refer to the geographical arrangement of wetlands within the landscape independent of the biota; this is often termed “structural” connectivity or “landscape structure” (Tischendorf and Fahrig 2000, Kahara *et al.* 2009, Morris 2012). However, structural connectivity does not always equate to functional connectivity, and functional connectivity is also dependent on the species observed (Tischendorf and Fahrig 2000, Rudnick *et al.* 2012). Therefore, it is important to understand the landscape structure before addressing the biotic component. Understanding how these systems operate at this scale is also important for conservation and research as it is easier to conduct research and apply the knowledge across similar systems rather than managing individual, unique systems.

Groups of wetlands that are in close proximity to each other are known as wetland complexes or mosaics (Brinson and Malvárez 2002, Martin *et al.* 2012). These wetland complexes have been well described in the USA and Europe in terms of their connectivity through groundwater and various faunal and floral species (e.g. Rosenberry and Winter 1997, Euliss *et al.* 2004, Cook and Hauer 2007). However, none of these authors quantifiably addresses the spatial proximity between wetlands apart from temporal hydrological connectivity. The foundation of this connectivity is the relative position of the wetlands within the landscape. Any spatial patterns that emerge on the physical habitat provides key insight on the range of spatial scales that these systems operate and are influenced by their surrounding environment, which is relevant to conservation, research and management.

6.2. METHODS

General methods have been described in Chapter 4. Additional spatial statistical methods regarding the distribution of wetlands in the study area are outlined below. Several large artificial salt works were excluded from spatial and density statistics, as these systems significantly skewed the data. However, natural salt pans that occurred within the NMBM, as well as small farm dams, were used in the statistics, except where wetland size parameters were outliers.

6.2.1. Landscape structure

Wetland clustering can be statistically examined using several spatial statistics. The patterns examined included: spatial clustering, spatial autocorrelation and a hotspot analysis. The analyses were run using all known wetlands the exception of contiguous HGM units where

only one was selected. Spatial clustering of the wetlands was calculated using an Average Nearest Neighbour ratio (ANN) (Spatial Statistics Tools: ArcMap 10.3). This tool calculates the Euclidean distance from each wetland to the next nearest wetland. ANN measures the extent to which wetlands deviate from a random distribution within the study area at various predetermined spatial scales (that can be automated using the programme), and then averages all the nearest neighbour distances (Clark and Evans 1954). The ANN ratio is defined by Clark and Evans (1954) as:

$$ANN = \frac{\bar{D}_O}{\bar{D}_E}$$

where: D_o is the observed mean distance between a wetland and its nearest neighbour and D_e is the expected mean distances between wetlands in a random pattern such that:

$$\bar{D}_O = \frac{\sum_{i=1}^{n} d_i}{n}$$

and

$$\bar{D}_E = \frac{0.5}{\sqrt{n/A}}$$

A spline interpolation technique was then used to create a smoothed wetland cluster surface (Spatial Analyst Tools: ArcMap 10.3). A z-score was then used to evaluate whether wetlands were clustered (z-score of less than -1.96) or dispersed (z-score greater than 1.96). A z-score close to zero denotes a random distribution. The z-score calculates deviations from the mean and is defined as:

$$z = \frac{y_i - \mu}{\sigma}$$

Where: y_i is the observed mean distance, μ is the expected mean, and σ is the standard deviation (Quinn and Keough 2002). The distance to the nearest wetland was used as the z-value to highlight which areas showed more clustering of wetlands than others.

Hotspot analyses are often used in the social sciences to, for example, map crime, vehicle accidents or disease risk (Goodchild *et al.* 2000, Chainey and Ratcliffe 2013). In this study, an Optimised Hotspot Analysis (Spatial Statistics Tools: ArcMap 10.3) was used to establish which areas have statistically high densities of wetlands. The analysis was used to create a fishnet (grid) map of significant hotspots and coldspots using the Getis-Ord Gi* statistic using the ANN values as a proxy. Standard settings were used to weight each feature (wetland) at the appropriate scale. The Getis-Ord Gi* statistic, like the other spatial statistics, records significance using a z-score and p-value. Significant negative z-scores indicate coldspots, areas with uniformly large distances between wetlands, while hotspots are areas where many

wetlands are in close proximity to each other. The statistic is calculated using the following equation:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j} \right)^2 \right]}{n-1}}}$$

where: $w_{i,j}$ is the spatial weight between two features, *i* and *j*, x_j is the attributed value for feature *j*, and n is the total number of features (wetlands) (Getis and Ord 1992, Zhang *et al.* 2014).

A Moran's I statistic (Spatial Statistics Tools: ArcMap 10.3) was used to calculate whether wetlands of similar sizes were more clustered or dispersed in relation to other size classes within a mosaic. If systems were of similar sizes (i.e. spatially autocorrelated), this could have an impact on the ecosystem functioning of these systems, such as vegetation zonation patterns. The Moran's I statistic is given as:

$$I = \frac{n}{\sum_{i=1}^{i=n} \sum_{j=1}^{j=n} W_{ij}} \bullet \frac{\sum_{i=1}^{i=n} \sum_{j=1}^{j=n} W_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{i=n} (x_i - \bar{x})^2}$$

where: n is the total number of features, w_{ij} is the spatial weight between *i* and *j*, and z_i is the deviation of an attribute for feature I (Getis and Ord 1992, Zhang *et al.* 2014). Values around -1 indicated that wetlands of similar sizes were more dispersed, and values closer to 1 indicated that similar sized wetlands clustered together.

Wetland density was illustrated at a quinary (sub-quaternary) catchment level. This was done in two ways, firstly by determining the number of wetlands within the quinary catchment, and secondly, as a percentage of the total wetland area within the associated quinary catchment area. These two density maps, the spline interpolation map, and the standard wetland occurrence map were all compared to establish whether there were connectivity patterns that were apparent even though different wetland spatial associations were used.

In summary, the ANN was used to find out if there is spatial clustering. The Getis-Ord Gi* was used to determine where these clusters were located (hotspots), or not (coldspots). Lastly,

the Moran's I was used to determine whether clusters tended to have wetlands of similar sizes within a cluster.

Further information is needed on the spatial dynamics of wetland complexes. Waterkeyn *et al.* (2008) suggested using a 100 m radius to establish how many wetlands are in a complex. However, based on field observations and knowledge of the study area, this distance was thought to be too small for the study area where groups of wetlands were evident in the landscape with slightly larger distances between systems. A study by Kahara *et al.* (2009) defined "cohesion" as the number of wetlands that fell within a 200 m radius. Although cohesion was not measured, this does provide an indication of distance thresholds that should be used for ascertaining clusters. As a result, four distances were used as a measure of proximity: 50 m, 100 m, 150 m and 200 m, to ascertain which distance would provide the most applicable data for the mostly small and ephemeral systems found in the NMBM. Larger proximities (e.g. 500 m to 1 km) would be relevant in areas where larger systems are located, but have been excluded for the purposes of this study.

The Generate Near Table tool was used to calculate the number of wetlands that occur within each of the four distances mentioned above (Analysis Tools: ArcMap 10.3). This tool calculates the shortest path between two features on a spheroid (geodesic). The position (XY coordinates) and distance to the wetland are given for each system that falls within the search radius. Thus, the total number of wetlands within a complex could also be established. Average distances were also compared across HGM types and different size classes. The same exercise was repeated for connections to river and stream networks to determine the potential connectivity of a wetland to fluvial processes.

6.2.2. Landscape suitability for wetland presence

One of the outputs in Chapter 5 was a wetland occurrence model. This analysis indicated which environmental features, operating at a landscape scale, could be associated with wetland occurrence. The analysis described below uses a different approach and determines the potential connectivity between wetlands. This is based on a least-cost analysis which refer to the ability of organisms to move between two patches on a path of least resistance (Beier *et al.* 2009, Rudnick *et al.* 2012, Weber and Norman 2015). The analysis determines whether certain environmental and anthropogenic features would resist or promote wetland occurrence and the formation of wetland clusters. If wetlands occur as a result of the landscape around them, then these systems would be located in areas that had suitable conditions (i.e. had a lower cost).

The landscape suitability analysis was run as an exercise to determine whether the output would provide suitable data at a broader management scale (at a quinary catchment level). In this study, the initial steps used in a least-cost analysis were applied to determine whether environmental and anthropogenic features would resist or promote wetland occurrence. Further research would then apply the outputs to faunal and floral species movements between wetland systems, and whether certain landscape features would hinder the connectivity between systems.

Several datasets were used for the analysis (data sources are listed in the Appendix B). Land cover data were the only anthropogenic variable and it was converted to a raster format for the analysis (Conversion Tools: ArcMap 10.3). Several further variables were used in this series of analyses: the DEM derived slope and flow accumulation, evapotranspiration, mean annual precipitation (MAP) and annual heat units. These variables were used as they were important in wetland occurrence (Section 5.3.2, page 81), and covered the basic environmental and anthropogenic features in the landscape, as well as the data being available. In addition, similar environmental and anthropogenic variables have been used in other least-cost analysis studies (Beier *et al.* 2009, Rudnick *et al.* 2012, Weber and Norman 2015). Chapter 5 explains how these files were resampled for the analysis.

The six raster layers (the environmental variables) were then reclassified into categories with an associated "Landscape Suitability Score" using the Reclassify function with bilinear interpolation in Spatial Analyst Tools (ArcMap 10.3) (Table 6-1). Higher scores are associated with less suitable conditions. Flow accumulation is typically assigned higher scores with higher values because it is used to model an increase in flood risk with an increase in flow accumulation. Although, in the context of abiotic and biotic connections between wetlands, this variable is seen as a promoter of wetland functioning and connectivity, with higher flow accumulation values improving connectivity.

There was only one data layer associated with anthropogenic activities for the Landscape Suitability analysis (Table 6-1) and, accordingly, there were higher values associated with increased anthropogenic impact. These higher values were used to compensate for the overall weighting of the five other environmental variables, such that the high scoring anthropogenic activity (e.g. urban activities) could still significantly increase the cell value, thereby indicating less suitable conditions.

The reclassified raster layers were then summed together using the Raster Calculator (Spatial Analyst Tools: ArcMap 10.3). The raster values were extracted for each of the random non-wetland points (see Chapter 5) and known wetland points. The results were compared using

a standard t-test to ascertain whether wetlands were located on areas with a lower score than non-wetlands.

An example of how the Resistance Score is applied is as follows. A suitable position for a wetland would be in: natural vegetation (score 10), on a gentle gradient slope (score 100), in an area with a flow accumulation of 600 000 (score 100), low evaporation rate of 1600 mm per annum (score 10), a high rainfall of 650 mm per annum (score 100) and an overall annual heat unit of 2600 °days (score 100) – giving a total score of 420. In contrast, a similar region can have the same climate, but if it is located on a steep slope (score 1000) with alien vegetation (score 1000), the location would have a higher resistance score of 2310. Therefore, the latter area would be less suitable for wetland development and persistence (survival).

Table 6-1 Classes assigned to the raster files for the landscape suitability analysis, with the associated Resistance Score. Classes defined using standard intervals except for flow accumulation which was defined using quartiles. MAP = mean annual precipitation, N/A = not applicable.

Resistance Score	Land cover	Slope (%)	Flow accumulation per 1000 cells	Evaporation (mm per annum)	MAP (mm per annum)	Heat Units (° days)
1	Dams					
10	Natural	0 – 3	100 – 1240	1593 – 1700	700 – 803	2108 – 2500
100	Airfields, recreational open spaces	3 – 9	30 – 100	1700 – 1800	600 – 700	2500 – 2700
500	N/A	9 – 15	15 – 30	N/A	N/A	2700 – 2800
1000	Plantations, high density alien plants	15 – 30	10 – 15	1800 – 1900	500 – 600	2800 – 2900
5000	N/A	30 – 60	5 – 10	1900 – 2000	400 – 500	2900 – 3000
10000	Dumps, mines	60 +	0 – 5	2000 – 2036	378 – 400	3000 – 3140
100000	Roads, urban areas	N/A	N/A	N/A	N/A	N/A

Potential areas of wetland vulnerability were calculated by combining the Resistance Scores and the values from the wetland occurrence probability map (see Chapter 5). Wetlands would be vulnerable if they were located in areas that were not highly suited to wetland occurrence due to environmental and/or anthropogenic variables. The output resistance grid was reclassified into five categories 1 (high suitability) to 5 (low suitability). The occurrence probability raster was also reclassified into five categories from 1 (high probability) to 5 (low probability). The implication is that a wetland that is situated on a low probability cell (5) (a low value in the LR model) and a low suitability cell (5) (a high overall resistance value), is more vulnerable to environmental and anthropogenic changes (total of 10). Thus, the two reclassified grids were added together such that a low overall number indicated a suitable area.

6.2.3. Wetlands within the NMBM conservation priority areas

Stewart (2010) defines several key conservation areas for the NMBM that should be conserved or protected to maintain biodiversity. These areas should be used in conjunction with vulnerable wetland areas (Section 6.2.2 above) to create and implement appropriate management and conservation strategies for wetlands in the NMBM (discussed further in Chapter 8). Several categories form part of this NMBM conservation network, as defined by Stewart (2010):

- Critical ecological processes: corridors and habitats that are needed to maintain biodiversity and ecosystem sustainability;
- Critical Biodiversity Areas (CBA): Critically Endangered and Endangered habitats, ecological processes and habitats for Species of Special Concern;
- Ecological Support Areas (ESA): ESA 1 comprises of agricultural land that has an important role in ecosystem functioning and ESA 2 areas are severely disturbed/destroyed areas by human activities and need to be restored; and
- Existing and pending Protected Areas (PA 1 and 2 respectively): National Parks and Nature Reserves.

The outcome of the number of systems identified in each of these conservation categories is illustrated in this chapter. These categories were then used to establish which areas should be given higher priority for management, research and conservation strategies in the NMBM, which is discussed in detail in Section 8.4, page 194.

6.3. RESULTS

6.3.1. Wetlands associated with anthropogenic activities in the NMBM

Surrounding land use influences wetland structure and function. Figure 3-5 on page 47 illustrated the spatial distribution of these transformed areas and the impact of anthropogenic activities on wetland structure and function was further explained in the context of the NMBM in Section 3.6 on page 46.

A large number of wetlands were located on cultivated areas, as well as disturbed areas within the NMBM (Figure 6-1). Wetlands were found, to a lesser extent, in the urban and natural areas (formal and informal), although, there was still a high occurrence in these areas (in relation to the size of the zone) (Figure 6-1). These results explain some of the degree of modification seen in wetlands in the NMBM (as indicated in Section 5.3.1). Similar patterns were observed across the different HGM types, with the highest proportion located on cultivation zones. An exception was floodplain wetlands which were more evenly distributed across the different transformed areas (Figure 6-1).

Figure 6-2 illustrates the number of wetlands per HGM type associated with the various critical biodiversity area categories, all of which should be conserved or protected, according to Municipal regulations. These categories are defined in Section 6.2.3. Of the total number of wetlands digitised in the NMBM, 35% are located on areas that are considered critical for biodiversity in the NMBM (Stewart 2010). Over 350 wetlands are located on CBAs and 41 wetlands on ESAs. A total of 100 wetlands are in established Protected Areas. The NMMU South Campus Reserve contained 47% of the wetlands that were associated with existing Nature Reserves within the whole study area; the majority of these were depressions and wetland flats. The implications for these wetlands being associated with these priority areas is discussed in Chapter 8 (Section 8.4.2).

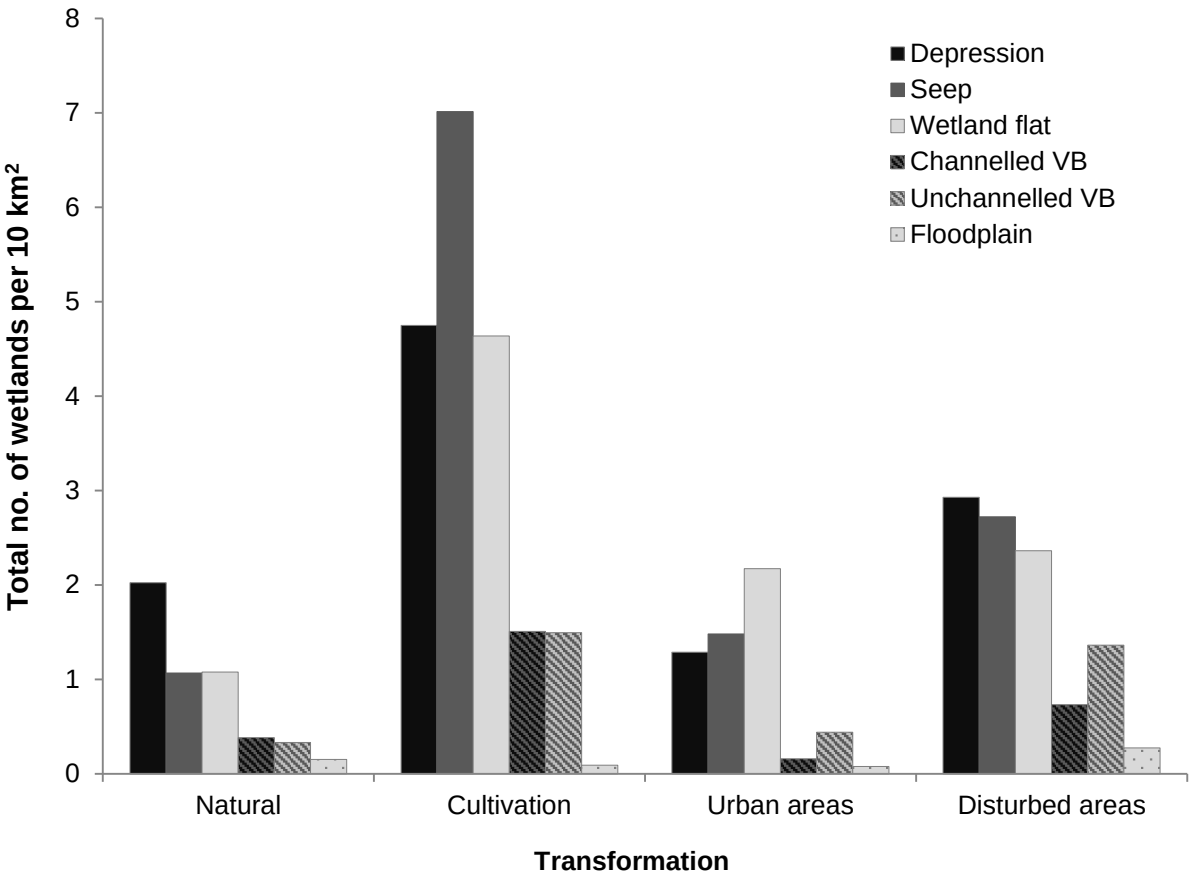

Figure 6-1 **HGM types found in different transformation zones within the NMBM (corrected for total area of the zone). Natural lands are any areas where there are very low levels of anthropogenic activities. Cultivation comprises of agriculture and airfields; urban areas, both formal and informal; and disturbed areas includes those infested with alien plants, waste sites and mines. VB = valley bottom. Land cover data from Stewart (2010).**

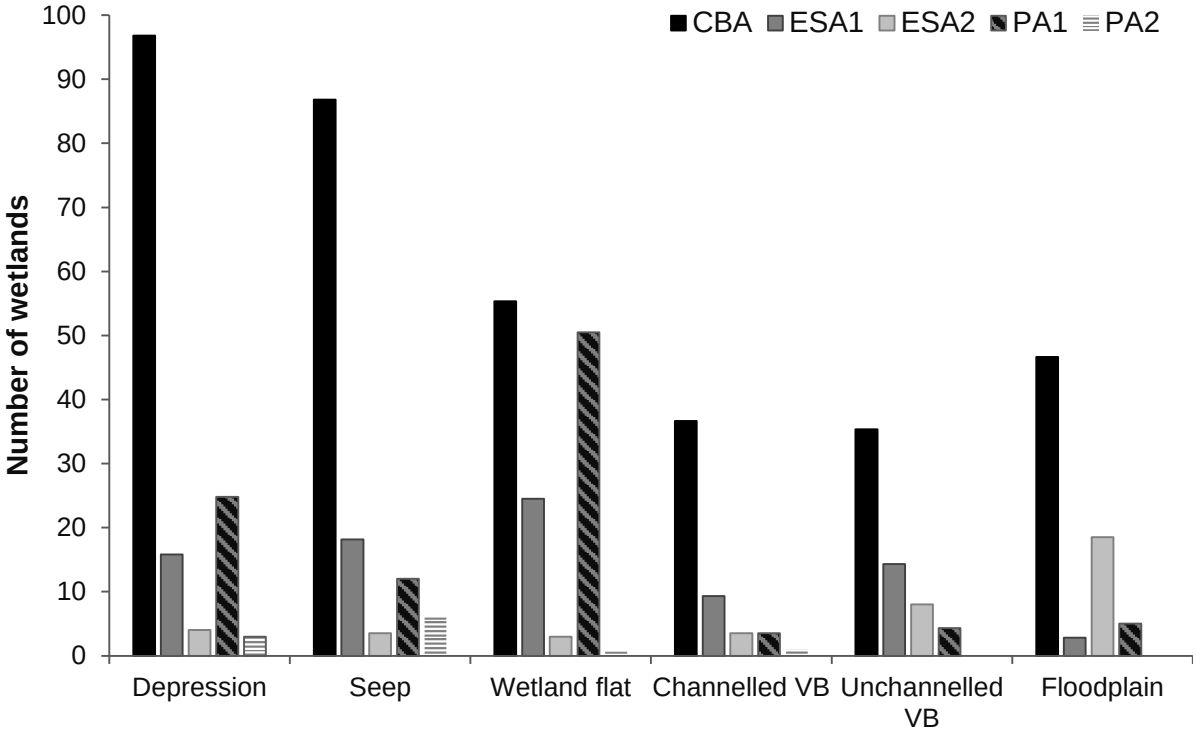

Figure 6-2 Wetlands of conservation concern associated with the HGM units. Critical biodiversity areas (CBAs) are critically endangered habitats, Ecosystem Support Area (ESA)1 comprises agricultural land that has an important role in ecosystem functioning, ESA2 is an area that is severely disturbed/destroyed by human activities and is needing to be restored, PA1 is a declared Protected Area, PA2 are protected areas pending declaration. Biodiversity data from Stewart (2010).

6.3.2. Landscape structure

Chapter 5 described the range of wetland sizes in the study area (Section 5.3.1). Figure 6-3 illustrates the variability in wetland size associated with changes in average nearest neighbour (ANN) distances. The ANN indicated that wetlands in the NMBM were significantly clustered (ANN statistic, p-value < 0.0001) (Table 6-2). This analysis was re-run under different scenarios where smaller wetlands were removed from the analysis (as smaller systems tend to be impacted on or lost first). This analysis was run three times, with only the smallest wetlands being removed in the first one (less than 0.5 ha) (Table 6-2). In the third run, all wetlands less than 1.2 ha in size were removed from the analysis, such that only the 184 larger wetlands were left (Table 6-2). When the minimum wetland size is increased, the ANN distance increases, but far fewer wetlands remained (Table 6-2 and Figure 6-3).

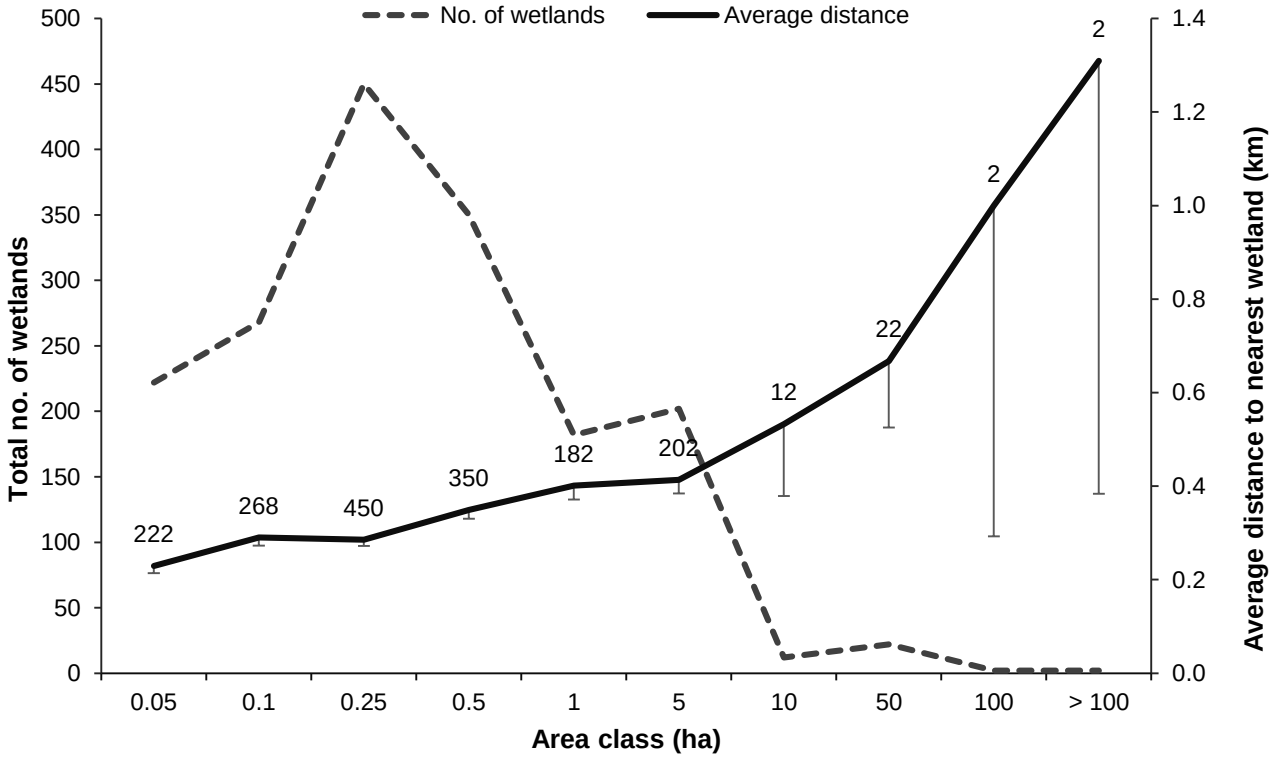

Figure 6-3 **Number of wetlands (left axis) and the mean nearest neighbour distances between wetlands (right axis) observed in each area class (with negative SE shown to illustrate variability). Note: x-axis classes are not uniform as numbers were highly irregular. Numbers given denote sample size for the respective area class.**

Table 6-2 **Outcomes for the various spatial statistics. * represents the number of wetlands remaining in the NMBM if all wetlands were lost below the associated size class (0.2, 0.5 or 1.2 ha). Z-scores below -1.96 and greater than 1.96 are significant. P-values are significant at a 0.05 level.**

Index	No. of wetlands	Observed mean distance (m)	Expected mean distance (m)	Z-score	P-value
Average nearest neighbour (ANN)	1701	328.27	617.16	-36.93	0.0000
ANN with wetlands < 0.2 ha removed	883*	513.90	847.17	-22.36	0.0000
ANN with wetlands < 0.5 ha removed	417*	776.55	1244.97	-14.79	0.0000
ANN with wetlands < 1.2 ha removed	184*	955.27	1597.45	-12.01	0.0000
Moran's I Index	-	0.01	-0.00	1.71	0.0880
Getis-Ord General Gi*	-	0.00	0.00	-0.56	0.5766

The log of wetland size and the distance to the nearest wetland were significantly positively correlated (Pearson's statistic = 0.142, p-value < 0.0001). Figure 6-3 also illustrates this general positive trend in each wetland area class (non-transformed). However, wetlands did not appear to cluster with other wetlands in the same size class, but rather, formed mosaics with different wetland sizes (Moran's I Index: p-value = 0.088) (Table 6-2).

The spatial distribution of wetlands can be illustrated in various ways. Figure 3-1 indicated where wetlands were identified (and is illustrated again in Figure 6-4a as a reference). Figure 5-6 illustrated the proportion of HGM types within each quaternary catchment. In general, more wetlands are located in the south of the Municipality and along the larger rivers. A spline interpolation (using the nearest neighbour distance as a z-value) illustrates where wetland clustering occurs (in red) (Figure 6-4b). These clusters are more prominent in the south of the Municipality, and along the Swartkops and Coega Rivers than elsewhere (Figure 6-4c).

On a broader scale, key wetland areas can also be illustrated on a quaternary and quinary (sub-quaternary) catchment level. Figure 6-4d and Figure 6-4e illustrates wetland numbers compared to the overall catchment area, for quaternary and quinary catchments in the NMBM respectively. The southern-most quinary catchments support the highest proportion of wetlands. Catchments 9133 and 9183 (coloured in red in Figure 6-4e) had densities of 1.85 and 2.09 wetlands per km^2 respectively. The two other quinary catchments in the south also both had densities of 1.23 to 1.53 wetlands per km^2. The remainder of the study area had average densities of less than one wetland per square kilometre, with densities of less than 0.1 wetlands per km^2 in some of the northern-most catchments.

However, there is a shift in this spatial trend when the total surface area of wetlands is compared to the catchment area (Figure 6-4f). A higher proportion of the quinary catchment surface area is covered by wetlands in the catchments immediately south of the Swartkops River (in the headland areas of the Chatty and Brak Rivers), compared to the catchments along the southern coastline of the study area (Figure 6-4f). These three quinary catchments had wetland coverages ranging from 13% to 20%. The catchments at the south of the study area had coverages from 9% to 10%. In contrast, quinary catchments in the north and west of the study area with wetlands covering less than 1% of the catchment.

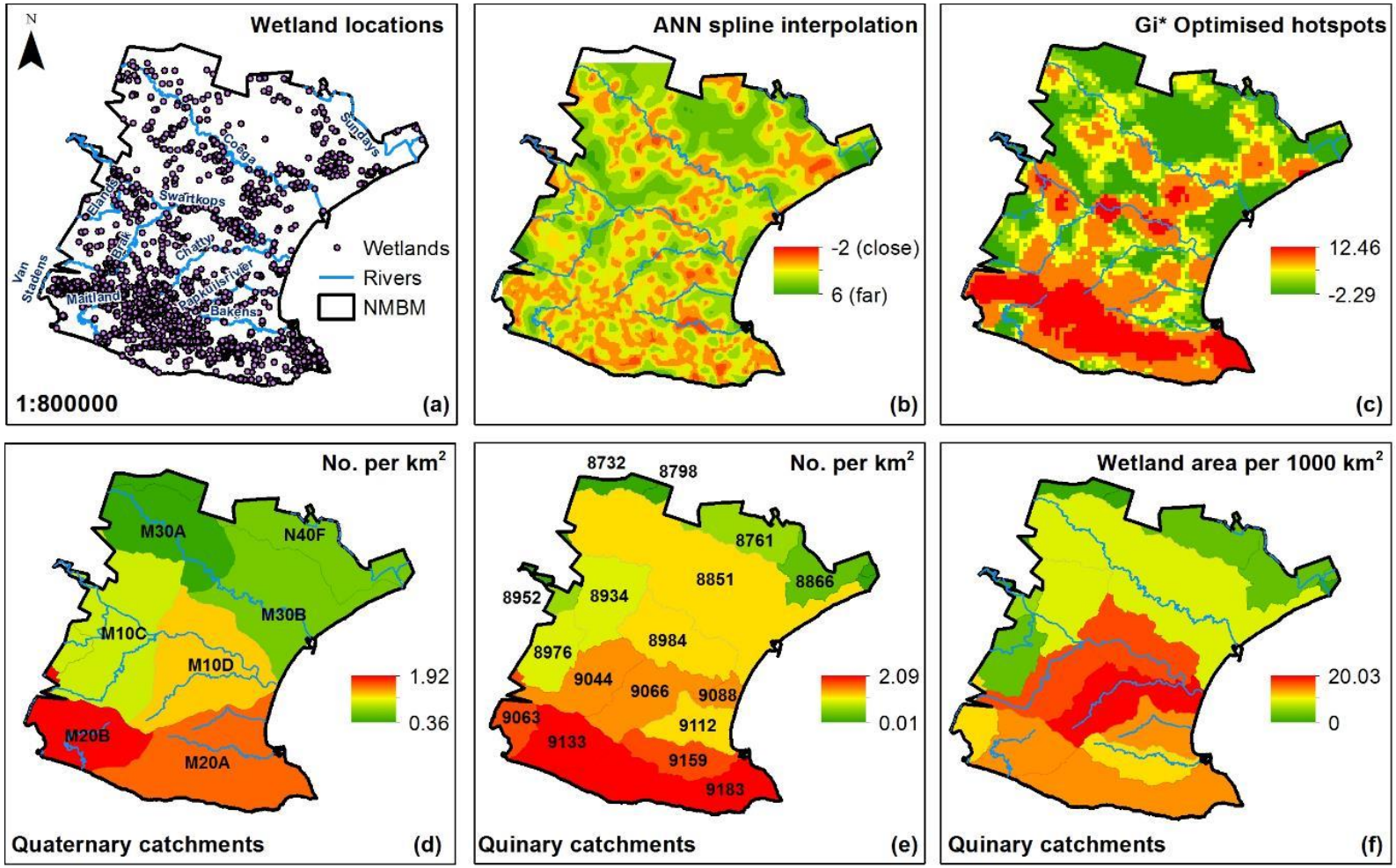

Figure 6-4 **Key wetland areas illustrated by: (a) wetland locations, (b) ANN spline interpolation of wetland density (white indicates no data), (c) Gi* optimised hotspots, (d) wetland density per quaternary catchment taken from Chapter 5, (e) wetland density per quinary catchment where numbers depict the catchment code, and (f) total wetland coverage per quinary catchment area. In general, red areas for maps b-f indicate higher wetland densities. Note: density scales are different. Rivers and catchment numbers are not shown on each map for display purposes.**

Wetlands were found, on average, approximately 326 m from the nearest neighbouring wetland and 1400 m from the nearest river (Figure 6-5). Average distances varied significantly by HGM type, and depressions were significantly more isolated overall (to wetlands and fluvial systems combined) (Figure 6-5) (ANOVA ANN to wetlands: $F_{5, 1701} = 15.047$, $p < 0.0001$) (ANOVA ANN to rivers: $F_{5, 1702} = 35.087$, $p < 0.001$). Seeps and wetland flats were more clustered compared to depressions, with average distances of 280 m and 245 m respectively. However, only seeps were closely associated with drainage lines, being located less than 1000 m away from a fluvial system. Sixty seeps were located less than 100 m from a drainage line, many of which were located at the head of a fluvial network (Figure 6-5). For example, two seeps (connected to other HGM types) were found at the head of a drainage line that links further downstream to the Chatty River (Figure 6-6).

Channelled and unchannelled valley bottom wetlands and floodplain wetlands are, by nature, mostly associated with larger rivers. This was reflected in the lower mean distances to a fluvial system, with floodplain wetlands located less than 100 m away from a river (Figure 6-5). Floodplain wetlands were also highly clustered with other wetlands, with average distances of approximately 226 m (Figure 6-5). In contrast, channelled and unchannelled valley bottom wetlands were significantly more isolated with distances of over 400 m between wetlands (ANOVA ANN to wetlands: $F_{5, 1701} = 15.047$, $p < 0.0001$) (Figure 6-5).

Approximately 42% of the systems in the NMBM were located in complexes (Figure 6-7). Most of these wetland clusters occurred between 50 m to 150 m away from another system. Wetland complexes generally comprised of two to three systems (Figure 6-7), especially when larger systems were present (Pearson's statistic = -0.1981, p-value < 0.0001). There were 25 wetland complexes that contained more than seven wetlands; five of these were complexes of 12 wetlands within 200 m from each other (Figure 6-7).

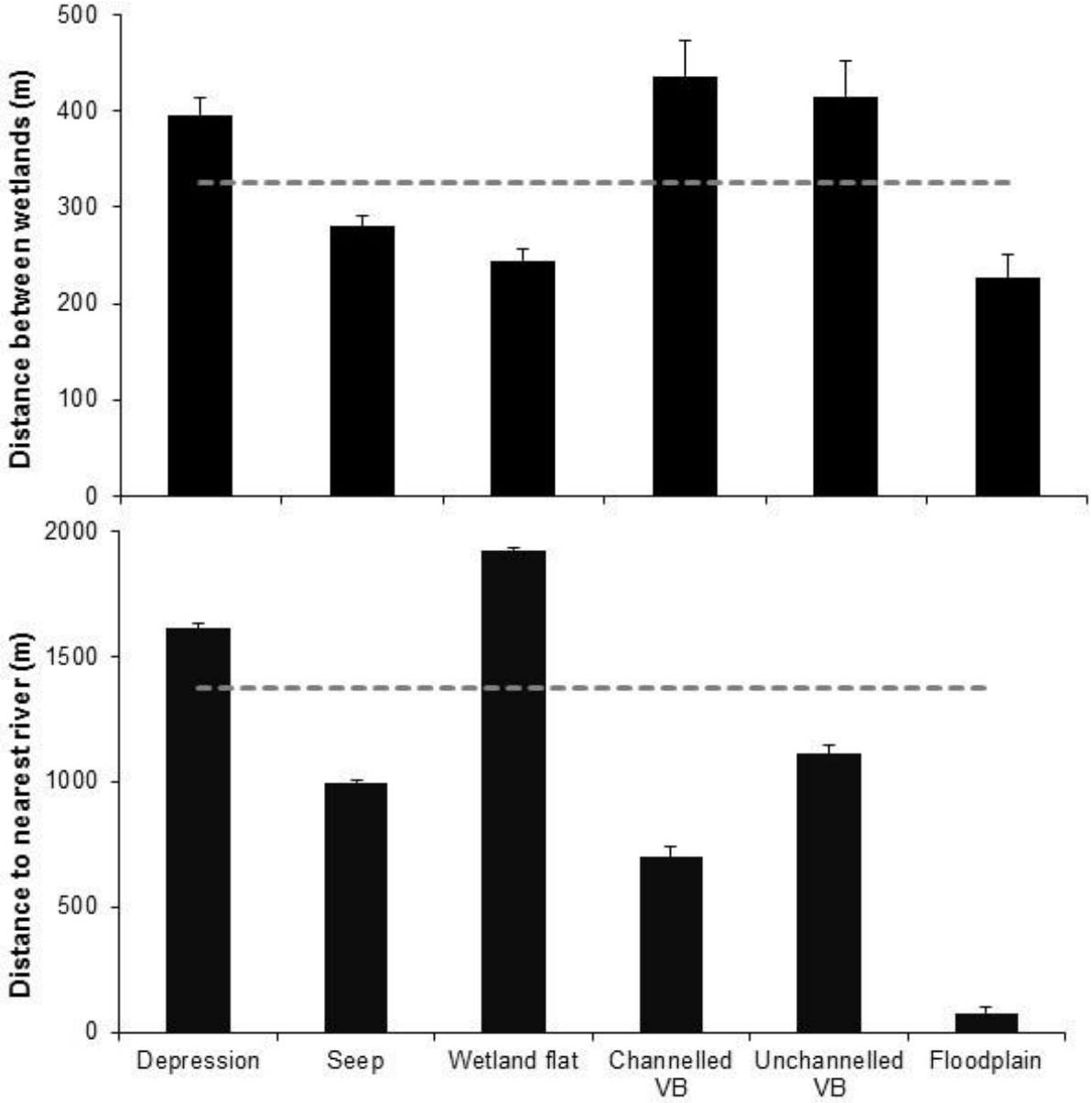

Figure 6-5 **Average distance (+SE) to the nearest wetland (top) and river (bottom) according to HGM type. Dashed line depicts overall average across all HGMs. VB = valley bottom. Note: y-axis scales are different.**

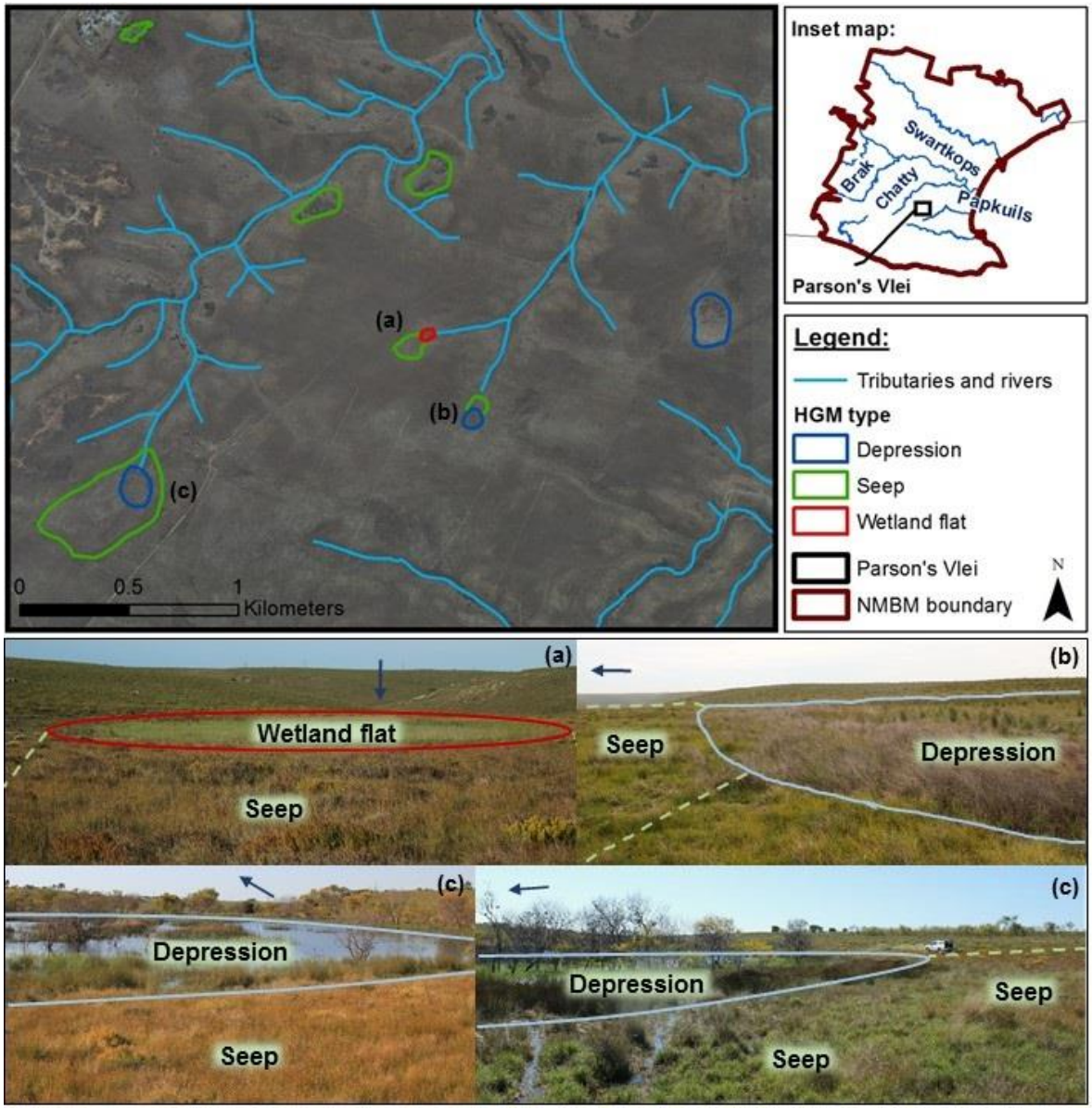

Figure 6-6 **Three wetland sites (a, b and c) found in Parson's Vlei. The sites are illustrated in the top figure, all of which consist of two joined hydrogeomorphic units. Photographs of the same sites are illustrated below (with their associated letter) and with the approximate edges of the HGM type demarcated. The direction of the drainage lines that can be seen in the aerial photograph are also indicated by a blue arrow in each of the pictures. The bottom two pictures (c) are of the same wetland (PV 2) at different angles to illustrate the distinct vegetation zones within and around the wetland.**

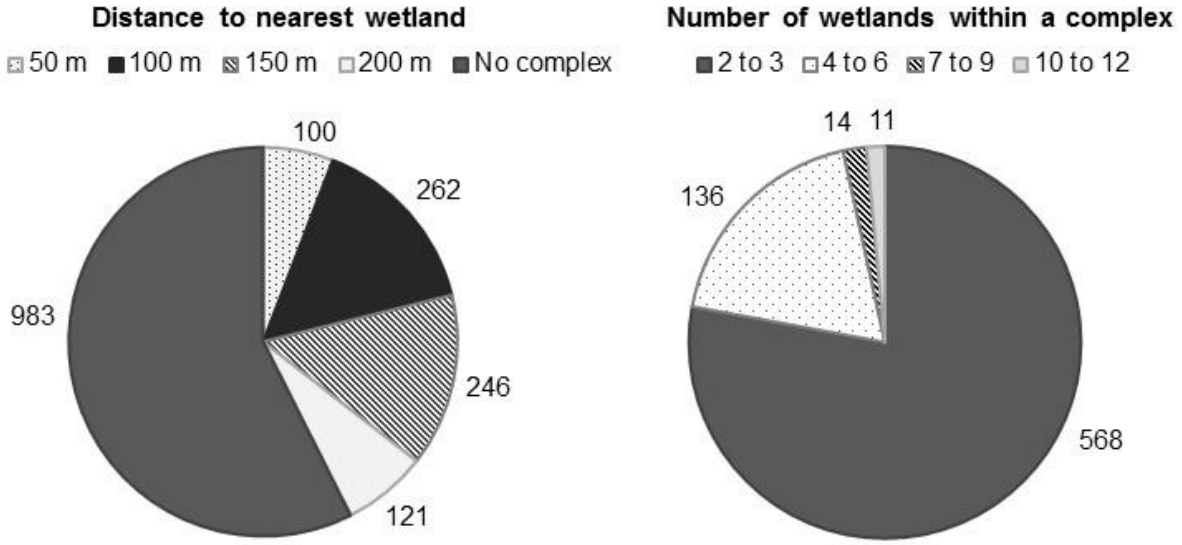

Figure 6-7 Proportion of wetlands that occur within 50 m – 200 m from another wetland (left). Systems not found within 200 m of another wetland were not considered part of a complex. The number of wetland clusters ranging from 2 to 12 wetlands within 200 m of a site (right). Actual numbers within each category are given.

The outcome of the combined cost and landscape suitability maps is illustrated in Figure 6-9. This map indicates areas where environmental features and anthropogenic activities create conditions that are least favourable for wetland formation and resilience. Figure 6-8 and Figure 6-9 both show that the areas where wetland conditions are optimal are in the southern parts of the Municipality. Urban activities on the eastern margins of the study area coincide with some of the potential high wetland occurrence probability areas (Figure 6-8 and Figure 6-9). These activities have affected the vulnerability of these systems. Figure 6-10 shows the proportion of wetlands situated on areas with low to high suitability scores. Overall, 45% of the wetlands in the NMBM are found on the least vulnerable areas (Figure 6-10). The 89 systems that occur in highly vulnerable areas are key conservation priority areas. These systems are further discussed and illustrated in Chapter 8 (Table 8-1).

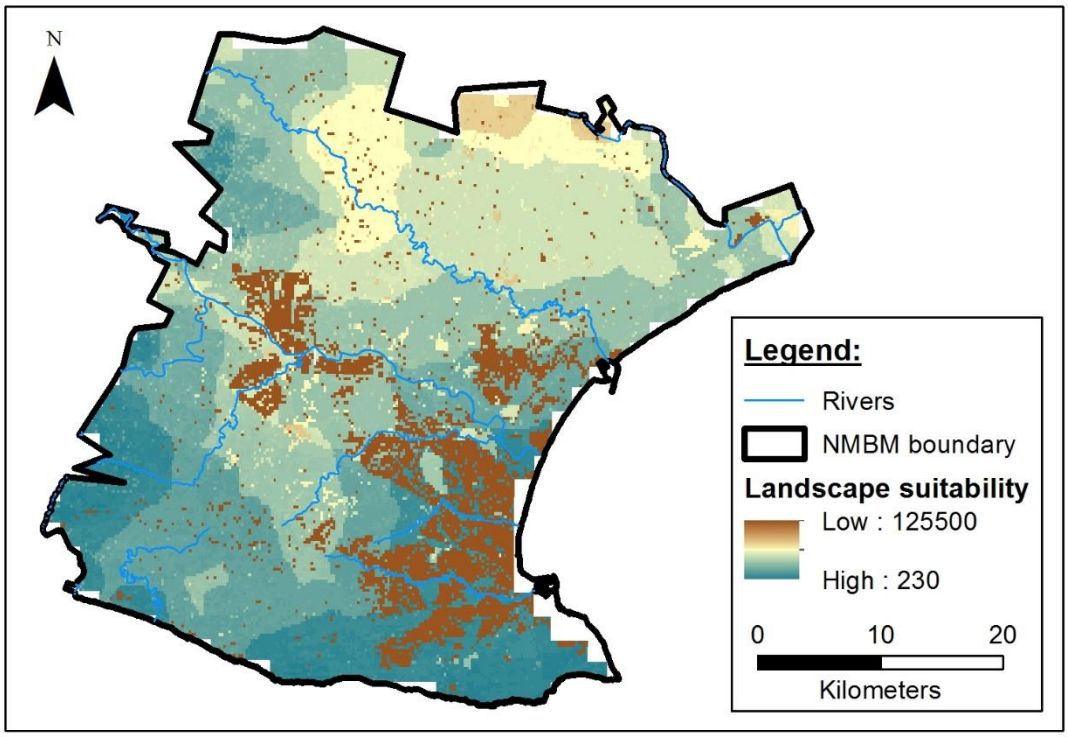

Figure 6-8 **Areas of low to high landscape suitability for wetlands in the NMBM. Data based on land cover, slope, flow accumulation, evaporation, MAP and annual heat units. White areas within the NMBM depict "No Data".**

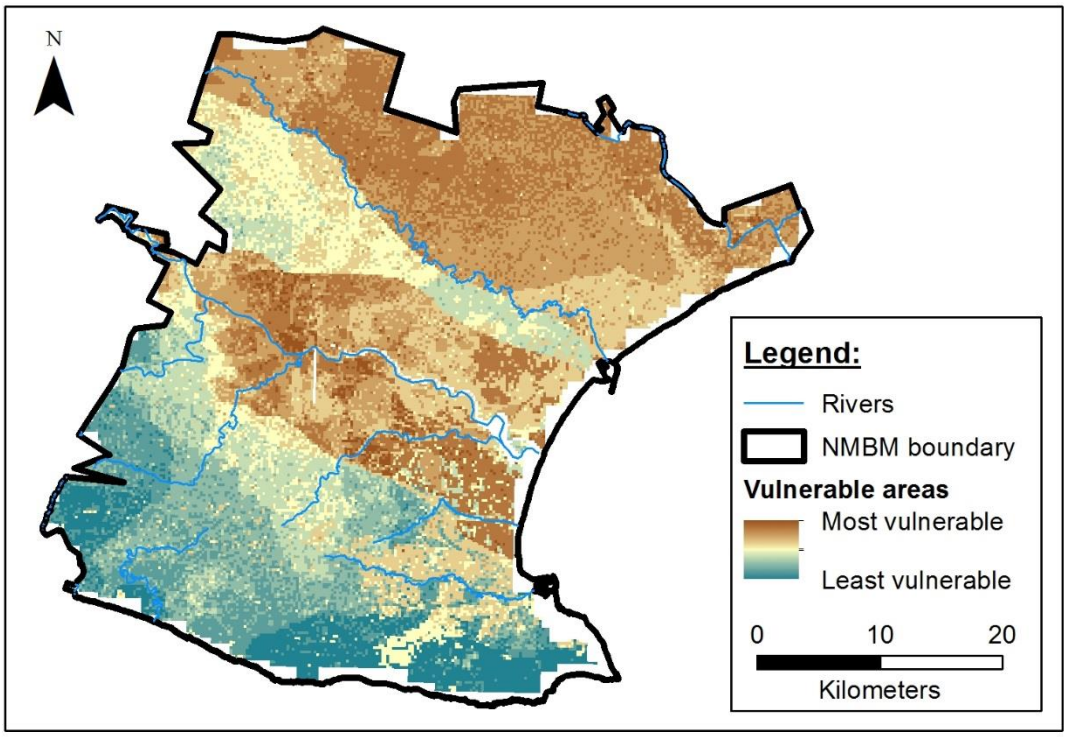

Figure 6-9 **Areas of wetland vulnerability (combination of the LR output and landscape suitability output). Potentially vulnerable wetlands (to anthropogenic or climate changes) would be those situated in the vulnerable areas (in brown) on the map.**

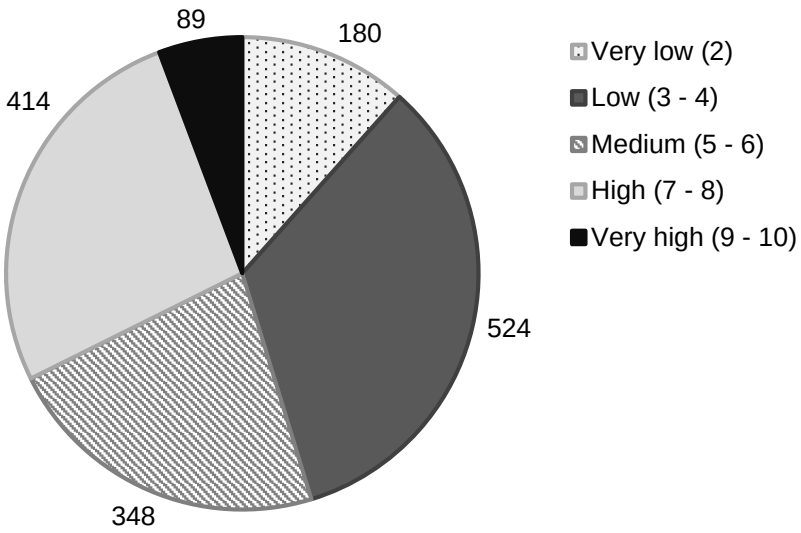

Figure 6-10 Proportion of wetlands situated in very low to very highly vulnerable areas in the NMBM. Numbers in brackets indicate the numerical categories used.

6.4. DISCUSSION

Chapter 5 illustrated the broad scale distribution patterns of wetlands in the NMBM. This chapter has explored these patterns further on a finer scale, illustrating the variation in wetland size, the extent of clustering, and the number of wetland mosaics in the study area. The spatial relationships of these wetlands combined with the influence of anthropogenic activities on wetlands in the NMBM form a crucial backbone for scale-specific management implications. This discussion aims to highlight and explain some of these key findings that are needed to understand wetland ecosystem functioning (Chapter 7), and the overall conservation and management strategies (Chapter 8).

6.4.1. The influence of anthropogenic activities on wetland systems

Cultivation and urban activities currently pose the largest threat to wetland occurrence and possibly wetland function. Depression wetlands were located in all transformation zones, which is in accordance with their wide distribution in the Municipality, and their presence in highly transformed areas as modified or artificial systems (e.g. dams). The low number of channelled and unchannelled valley bottom wetlands and floodplain wetlands in urban areas can mainly be attributed to roads and built up areas near the estuaries. Many larger systems within the urban boundary have been drained or altered to such an extent that the original

HGM type cannot be recognised. Accordingly, anthropogenic activities have influenced the overall wetland occurrence pattern observed in the Municipality, and will continue to affect these systems in the future. It is, therefore, vital that these wetland systems are understood and managed appropriately to avoid further degradation or loss. The effects of anthropogenic activities are complex and is best understood when all available knowledge is taken into consideration. Thus, further details on the anthropogenic threats on wetlands in the NMBM is given in Section 8.3 (page 187), and it is used as a foundation for a description of recommendations for management, conservation and research (Section 8.4).

6.4.2. Landscape structure

A key feature of wetlands in the NMBM is the extent of clustering. The average distance between wetlands of less than 5 ha in size is approximately 0.33 km, which is less than a quarter of that measured between wetlands of the same size class on the south eastern Atlantic coastal plain (USA), with a distance of 1.7 km (Semlitsch and Bodie 1998).

The distance between patches (wetlands) plays a fundamental role in metapopulation dynamics of fauna and flora (Turner *et al.* 2003, Angeler and Alvarez-Cobelas 2005). Although this study did not measure dispersal distances of biota between wetland systems, other studies have suggested that amphibians and wetland-dependent reptiles have ranges of less than 1 km, and often, less than 500 m (Dodd and Cade 1998, Semlitsch and Bodie 2003, Morris 2012). Therefore, the current wetland distribution is probably sufficient to maintain source-sink dynamics (the movement of biota between high and low quality habitats). Even if all the wetlands less than 1.2 ha were removed (89% of the systems), the ANN would still be less than 1 km. If the same proportion of Carolina Bays in the USA were lost, the ANN distance would be greater than 1.5 km between wetlands. As a result, the wetlands in the NMBM are highly clustered and exist at higher densities than those in other areas, even though they are small in size. However, this illustrates the problems with drawing management lines in terms of size or distance. Even if the ANN was still within a normal range for dispersal, removing 89% of the systems in an area would result in a significant loss of habitats for wetland-dependent species, as well as affecting ecosystem services.

In terms of wetland management, wetland complexes are easier to manage compared to managing several individual systems. Managing complexes would also ensure that at least part of the surrounding habitat has to be managed well to maintain the ecological integrity between wetlands (i.e. allow for sufficient dispersal of fauna and flora). Further research should be conducted, however, to ascertain the optimal distance for establishing a wetland complex based on the average wetland size. As a result of the dominance of small systems

in this study area, a smaller radius is possibly more suitable for defining a wetland complex, as these systems are more dynamic with a higher dependency on fauna and flora migrating in and out of the system to maintain the functioning of the ecosystem. An estimated distance of 100 to 150 m is suggested for wetlands smaller than 1 ha in size. However, in areas where larger systems are found, this distance would have to be flexible. In general, distances should possibly be adjusted to include/exclude systems that appear to be within a cluster for management purposes.

In some of the southern quaternary and quinary catchments, wetland densities were relatively high, comparable with well-known wetland areas elsewhere. Tiner *et al.* (2002) looked at almost 70 wetland areas across the USA. Wetland coverage (9% to 20%) in the southern parts of the NMBM were similar to that recorded on the more humid east coast of the USA (Tiner *et al.* 2002) that receive rainfall of over 800 mm per annum (National Weather Service Climate Prediction Center 2004). The south-western parts of the USA, which receive similar rainfall to the wetter parts of the Municipality, had coverages of less than 10% (Tiner *et al.* 2002, National Weather Service Climate Prediction Center 2004). Similarly, wetland coverage in the lower south eastern part of Australia was also approximately 10%, with an average annual rainfall ranging from 580 mm to 780 mm (Taylor 2006). At a coarser scale, wetlands only covered approximately 1% of the NMBM, compared to approximately 3% across Australia and 2.8% in tropical Asia (Junk *et al.* 2013). This further highlights the importance of precipitation on wetland prominence and the presence of numerous small systems.

Using the number of wetlands in a catchment versus the total area of wetlands in a catchment portrays different aspects of wetland coverage. The former will bias towards the presence of many, smaller systems while the latter will highlight the dominance of larger systems. The relatively high wetland coverages associated with the Swartkops River is attributed to the presence of large wetland floodplain systems along the estuary. Catchments also do not account for natural variability in wetland distribution within the area, which could result in disproportionally low density values in some of these catchments and, consequently, exaggerate the density in other catchments (in terms of relative density).

The results illustrate the importance and influence of spatial scale on ascertaining wetland distribution patterns and potential key areas. However, the series of maps in Figure 6-4 illustrate the effect of looking at different aspects of wetland density at various scales. Figure 6-5 indicates that this complexity goes beyond spatial scale and wetland size, but also includes the proximity of wetland types to other wetlands and to fluvial systems. Different spatial (and temporal) scales portray different aspects of wetlands, and this has been

commented on by several authors (e.g. Angeler and Alvarez-Cobelas 2005, Bosiacka and Pieńkowski 2012).

Valley bottom wetlands would not be classified as geographically isolated systems due to their close proximity to stream and river networks. Valley bottom wetlands, in the NMBM, were primarily associated with the Coega and Swartkops Rivers, as well as some of their larger tributaries while floodplain wetlands were found almost exclusively on the Swartkops River. Consequently, their distribution is confined to certain parts the greater study area. Relatively few valley bottom wetlands were found in smaller river catchments with narrow channels and valley floors. Thus, these systems would be likely to show less clustering in areas outside these sub-catchments if they received more rainfall.

Depressions in the NMBM could be defined as the most geographically isolated wetland type due to the larger distances between wetlands and from drainage lines. Many isolated wetland systems around the world are driven by distinct seasonal patterns of inundation and often display temporal connectivity to other systems (see Section 2.9). This relative isolation associated with depressions might also result in different biological responses in these systems compared to the two other HGM types, a topic explored further in the following chapter.

Wetland flats could be termed isolated in terms of their link to riverine systems. However, these systems were found in larger mosaics and could therefore provide important habitat patches (stepping stones) for fauna and flora that disperse (Wagner and Fortin 2005, Bosiacka and Pieńkowski 2012). This, in turn, would have a positive effect on biodiversity in these systems. This is also further addressed in Chapter 7.

Seeps were the most hydrologically connected to both other wetlands and to rivers. Many of these systems were located high in their respective catchments with drainage lines extending towards minor tributaries. An example of some pristine wetlands that were linked to drainage lines, but did not have an outflow are indicated in Figure 6-6. These types of systems are known as headwater systems and are important for the maintenance of instream flow requirements (Puth and Wilson 2001). Thus, these systems could potentially play a large role in both hydrological and biological processes occurring further down the catchment (Whigham and Jordan 2003). Although many of these systems appear to be at the head of drainage lines, the sites observed did not show signs of a nearby spring (Leibowitz and Nadeau 2003, Whigham and Jordan 2003). Thus, the majority of these systems could in fact be isolated (in terms of temporary surface water connections), as only 11% of the seeps were within 40 m

to 50 m of a drainage network. These buffer distances have been used by Tiner (2003a) and Sharitz (2003) to distinguish between isolated and surface water connected systems.

Apart from valley bottom and floodplain systems, many studies have reported surface water connections that occur between systems during periods of high rainfall (Leibowitz and Vining 2003, Cook and Hauer 2007). However, this was not observed at a desktop level (by looking at a series of images over time) or during site visits. The exceptions were wetlands with hydrologically connected HGMs (discussed in the following chapter). Various factors aid surface water connectivity in other regions. This includes sub-surface water connections which can be connected to regional groundwater flows, the surrounding elevations, the geological age of the systems (the formation of a channel through erosion over time) and the intensity and duration of rainfall (Leibowitz and Nadeau 2003, Winter and LaBaugh 2003). The aseasonal rainfall patterns and the relatively young surface geology associated with many of the wetland systems in the NMBM could be inhibiting these processes.

6.4.3. Landscape suitability

The costs assigned to different variables for the landscape suitability scoring system provided some indication of which areas are currently suitable for wetlands to occur. The combination of the LR grid and suitability grid could not be used to improve the accuracy of the LR model, but it did provide insight into which areas are threatened due to anthropogenic activities and changes in catchment processes. Combined with the wetland density maps, the landscape suitability map highlights the impact of landscape processes, rather than only landscape features. Although there is no set method, many authors have made different grid layers and predetermined categories to attempt to narrow down the extreme variability of a study area into manageable units. For example, Rains *et al.* (2013) used a similar method to determine changes in wetland coverage, wetland condition and wetland connection to prioritise areas for conservation and wetland restoration. Chapter 8 describes conservation and management implications for the NMBM based on the landscape suitability and wetland vulnerability maps that were created in this Chapter.

6.5. CONCLUSIONS

This chapter successfully described wetland distribution patterns using spatial statistics, as per Objective 3. Although many of the wetland systems in the NMBM would commonly be termed “isolated”, they appear to be closely connected at a landscape level with 43% of wetlands located within 200 m of another system. Small wetlands (less than 1 ha) were

significantly more clustered compared to larger systems (ANN, p-value < 0.0001), resulting in areas (catchments and sub-catchments) with relatively high wetland densities (Figure 6-4). This finding is important due to the dominance of these smaller systems in the NMBM – where the modification of a relatively small area of land could result in a substantial loss of wetland habitat, compared to a similar disturbance in a less wetland dense area. In addition, the clustering of wetlands could be differentiated by HGM type, with depressions the most geographically isolated compared to the five other HGM types. The relative isolation of these different HGM types illustrates the need to ensure that wetlands are well represented in management and conservation in terms of their distribution (overall coverage) and HGM type.

The geographical isolation and overall wetland density of wetlands in the NMBM might give the impression that wetlands are small patches within a large matrix. The densities of the systems in the NMBM suggest otherwise, especially in the southern half of the Municipality. The high density was evident in the extent of spatial clustering and the prominence of wetland mosaics in the study area. Understanding these spatial patterns forms an important foundation for relating these patterns to wetland functioning, as well as the need to manage these systems at a broader scale than individual sites. What also needs to be established is whether there are different functional responses that relate to the spatial organisation of these wetlands within a landscape, or whether these functions are more related to HGM patterns. This concept forms the basis for the following chapter which investigates these wetland functions.

Potentially vulnerable areas for wetlands were also identified in this Chapter, in accordance with Objective 4. These areas were identified using the landscape suitability map (the anthropogenic and environmental variables that potentially hinder or promote wetland development or persistence) and the LR model (from Chapter 5). These variables included: land cover, slope, flow accumulation, evaporation, MAP and annual heat units. These areas and systems were also used to form management and conservation recommendations for the Municipality that are discussed in depth in Section 8.4.2.

7. ABIOTIC AND BIOTIC CHARACTERISTICS OF EPHEMERAL WETLANDS

7.1. INTRODUCTION

Wetlands are truly multidisciplinary, multi-scalar and multifaceted systems. It is important, therefore, to have an understanding of the abiotic template (from a broad landscape scale to a site level) that the biotic parameters interact with, to fully understand and characterise these systems. Chapter 5 provided the framework on the prevalence of wetlands and their distribution and structure within the NMBM. The spatial patterns between wetland systems were then discussed in Chapter 6, which also addresses the prevalence of wetlands in certain quaternary and quinary catchments within the NMBM. Chapter 6 also highlights the close proximity of wetlands to other sites, thereby indicating how these systems can be connected at a landscape level, which is important when developing management strategies. These connections also need to be known to understand the local-scale features and complex ecological processes within individual wetlands (this chapter), as was illustrated in the conceptual diagram at the beginning of this thesis (Chapter 1, Figure 1-2, page 8).

The abiotic and biotic characteristics of a subset of ephemeral wetlands are described in this chapter, thereby providing an indication of the ecosystem functioning of these systems (Objective 5). As mentioned previously, it is easier to manage/conserve groups (or classes) of wetlands rather than individual units (Roe and Georges 2007). Therefore, this chapter also establishes whether these community patterns are distinguishable at a HGM level and, consequently, whether a combination of landscape and site level data can be used to group wetlands into their respective HGM unit (Objectives 5 and 6).

The study area also lies within a dryland region, defined by United Nations Environmental Programme (2009) as areas with an aridity index of less than 0.65. In addition, the majority of wetlands within the study area appear to be precipitation driven. Knowledge of local rainfall patterns and the position of a wetland within a landscape are therefore needed to understand the dynamics of these wetland systems and other abiotic drivers.

7.2. METHODS

The methods applied herein have been described in Chapter 4, with the exception of those outlined below. A number of ephemeral wetland sites were selected for analysis, based on

the criteria described in Section 4.3. The CS format was used to collect baseline data to classify the wetland in terms of its structure. Both secondary spatial data and primary data collected in the field during 2012 and 2013 were used to describe the characteristics of the subset of ephemeral wetlands. General site characteristics were recorded, and various abiotic and biotic parameters were collected for further analysis. These parameters included: physical and chemical soil characteristics, water physico-chemical attributes, plant, macroinvertebrate and tadpole data. In addition, broad-scale environmental data were collected from several sources and analysed with the wetland site data in ArcGIS or as part of multivariate analysis in Primer and R.

Raw weather data were collated from the South African Weather Service (SAWS). Monthly averages were calculated for the historical data (1950-2013), and monthly totals for 2012 and 2013. This was used as a basis for determining the hydrological characteristics of the sites.

7.2.1. Inundation and saturation periodicity

Zones within sites were coded from 0 to 6 based on their inundation and saturation periodicity (as defined in Chapter 2) (Table 7-1). A large area of inundation or saturation receives a high score, while zones covering a small proportion of a wetland have a smaller score. The example in Figure 7-1 below illustrates a hypothetical wetland with a small seasonally inundated zone (score of 1) and a larger rarely inundated zone (with a score of 3). Scores were assigned such that each wetland had a sum of 6 across all the zones, equating to 100% of the estimated wetland area when full. The same method was used for saturation zones. These scores were then compared across the HGM types.

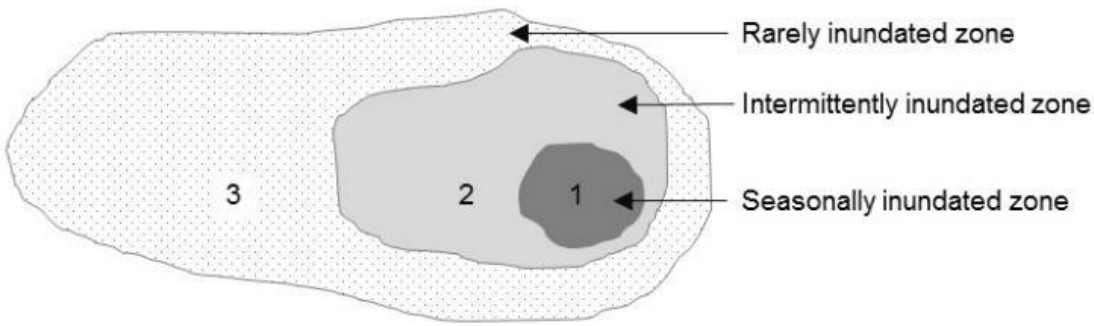

Figure 7-1 Diagram of a hypothetical wetland site with three inundation zones. Numerical scores are given according to the representative portion the zone covers. Scores range from 1 – 6 (see Table 7-1). Note: the total score always equals 6.

Table 7-1 Categories for rating different inundation and saturation zones (displayed in Figure 7-1) within a wetland. Based on the Classification System by Ollis *et al.* (2013).

Inundation/saturation score	Representative proportion of a wetland (%)
0	< 1
1	1 – 5
2	5 – 25
3	25 – 50
4	50 – 75
5	75 – 95
6	95 – 100

7.2.2. Powder X-ray diffraction

Minerals in the soil contribute significantly to the physical and chemical properties of a soil (Whittig and Allardice 1986, da Costa *et al.* 2004). Powder X-ray diffraction (XrD) was used to qualitatively identify minerals in the soil samples using a Bruker D2 Phaser with copper radiation. Details of the method will not be included as a full explanation of the underlying principles of XrD is described in Whittig and Allardice (1986), Warren (1990) and Buurman *et al.* (1996). A scan range of 5-70° was used at a 0.1 second step spin for all XrD analyses. Samples were prepared by grinding with a mortar and pestle and then mounted in standard polycarbonate sample holders. The output files were processed using EVA software to identify the different mineral peaks observed in each sample. The data obtained were used to detect and confirm the presence of various compounds within the sediments.

7.2.3. Plant and macroinvertebrate communities

General methods for biotic data collection are described in Chapter 4. Diversity indices for plants and macroinvertebrates were measured using the DIVERSE function in Primer 6 (PRIMER-E Ltd 2009). The species richness (R), Shannon-Wiener diversity index (H') and Pielou's evenness score (*J'*) were enumerated for plant and invertebrate data using the following equations:

$$R = \frac{S - 1}{Log(N)}$$

$$H' = -\sum_{i=1}^{R} p_i \ln p_i$$

$$J' = \frac{H'}{ln(S)}$$

Where: S is the total number of species, N is the number of individuals, and p_i is the proportion of individuals that are in the ith species.

The vegetation in inundated depressions was subdivided into two categories: wet and dry zones. These two categories were used to distinguish the distinct concentric zonation patterns that are often observed in depressions (associated with changes in slope gradient). Areas with surface water present or 100% soil saturation were classed as wet zones. Dry zones extended from the border of the wet zone outwards, to the terrestrial zone of the wetland.

7.3. RESULTS

7.3.1. The NMBM wetland distribution and environmental characteristics

Wetlands did not appear to be significantly found on particular slope aspects (ANOVA: $F_{2, 1706} = 1.576$, $p = 0.164$). In general, a large portion of the wetlands, from all HGM types, was located on southerly or easterly facing slopes. Wetlands were also found on a range of slope gradients and flat areas, with a significant difference among HGMs (ANOVA: $F_{2, 1706} = 26.56$, $p < 0.0001$). Floodplain wetlands were located on significantly flatter areas than those occupied by other valley bottom wetlands, with an average slope gradient of 0.99°. Channelled and unchannelled valley bottom wetlands had gradients of 2.4° and 2.1° respectively. Seeps were the most distinct HGM type, situated on slopes significantly steeper than the other five HGMs, with an average slope gradient of 3.35°.

Flow accumulation values were significantly higher at wetland sites than at non-wetland sites ($t = 3.468$, $df = 3273$, $p = 0.0005$). These random non-wetland points were the same used in Chapter 5. There were also significant differences in the flow accumulation values in different parts of the landscape (ANOVA: $F_{3, 1485} = 2.724$, $p = 0.043$). Wetlands on slopes ($\bar{x} = 5.09 \pm 0.55$ SE) had higher accumulated flows compared to those on wide valley floors ($\bar{x} = 3.57 \pm 0.32$ SE), benches ($\bar{x} = 3.63 \pm 0.35$ SE) and plains ($\bar{x} = 3.41 \pm 0.83$ SE). Similarly, there was a slight, but significant difference among HGM types (ANOVA: $F_{5, 1483} = 2.141$, $p = 0.058$). Seeps, largely associated with slopes, also had a significantly higher flow accumulation value ($\bar{x} = 5.31 \pm 0.74$ SE) than to other HGMs.

Underlying geology and sediments

A number of the wetlands in the study area were found in areas of more recent geology: on quaternary deposits and on the Algoa and Grahamstown groups (Figure 7-2). Recent deposits as well as formations within the Algoa Group predominantly comprise easily erodible aeolian sand, calcareous sandstone and alluvial gravel (see Appendix C for breakdown of the lithology).

Depressions were located on almost all geological formations with frequencies ranging from two to four wetlands per 10 km^2. A large proportion of the wetlands found on the Algoa Group were associated with alluvial gravels, sand and silt of the Bluewater Bay Formation and calcareous sandstones of the Nanaga Formation.

Low frequencies of seeps were observed on Quaternary recent deposits, the Uitenhage Group and the Bokkeveld Group (Figure 7-2). More than four wetlands per 10 km^2 were observed on the Algoa Group and Table Mountain Group (TMG) (Figure 7-2). A large portion of wetlands situated on the Algoa Group were on calcareous sandstones of the Nanaga formation (over nine wetlands per 10 km^2). Formations within the TMG were primarily comprised of quartzitic sandstones.

Wetland flats were strongly associated with Quaternary recent deposits (over four wetlands per 10 km^2). This unconsolidated material is primarily comprised of aeolian sand, alluvium and fluvial gravel that stretches across the southernmost section of the NMBM.

Channelled valley bottom wetlands were primarily found on shales of the Voorstehoek formation (Figure 7-2). Unchannelled valley bottoms and floodplain wetlands were primarily located on recent/alluvial deposits (Figure 7-2). These formations/deposits are found along the larger rivers in the NMBM.

Wetlands were found on a variety of soil depths, but floodplain wetlands were found almost exclusively on very deep soils (Figure 7-3). Depressions were more prominent on shallower soils compared to the other HGMs (Figure 7-3). Over 90% of seeps and wetland flats were situated on medium to deep soils (greater than 600 mm), with wetland flats predominately found on soils greater than 1200 mm in depth (Figure 7-3). Channelled and unchannelled valley bottom wetlands were also associated with medium to deep soils (Figure 7-3).

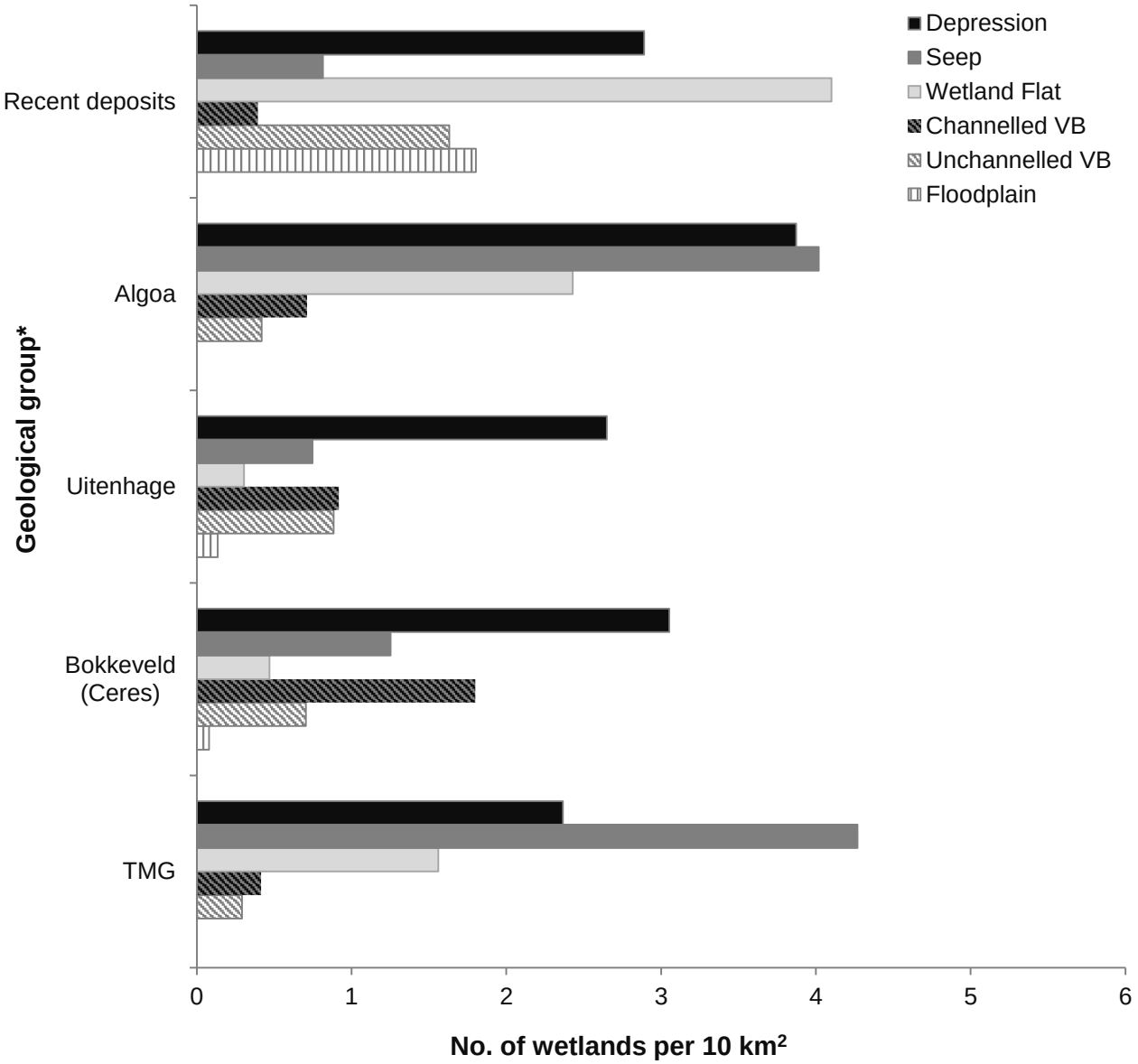

Figure 7-2 Underlying geological groups associated with the HGM types. See Appendix C for full group/subgroup description. * The Grahamstown and the Gamtoos groups are not included due to their small coverage within the NMBM (< 5 km²). Data from Council for Geosciences (N.D.).

The majority of wetlands were situated on soils that have been classified as freely drained structureless soils by the Agricultural Research Institute for Soil Climate and Water (ARC) (2004), or excessively drained sandy soils, supporting the geological data (Figure 7-2 and Figure 7-4). There were also differences among the various HGM types and their associated soils. Depressions were more likely to be found on lithosols compared to the other HGMs, while wetland flats were primarily associated with excessively drained soils (Figure 7-4). In contrast, a large portion of seeps were associated with imperfectly drained soils (Figure 7-4). Therefore, wetlands in the NMBM occur on a variety of soil types, and not just on soils

classified as “wetland soils” by the ARC (2004) spatial dataset. However, these results should be treated with caution as the vector dataset was created at a coarse resolution and results potentially do not illustrate fine-scale variability.

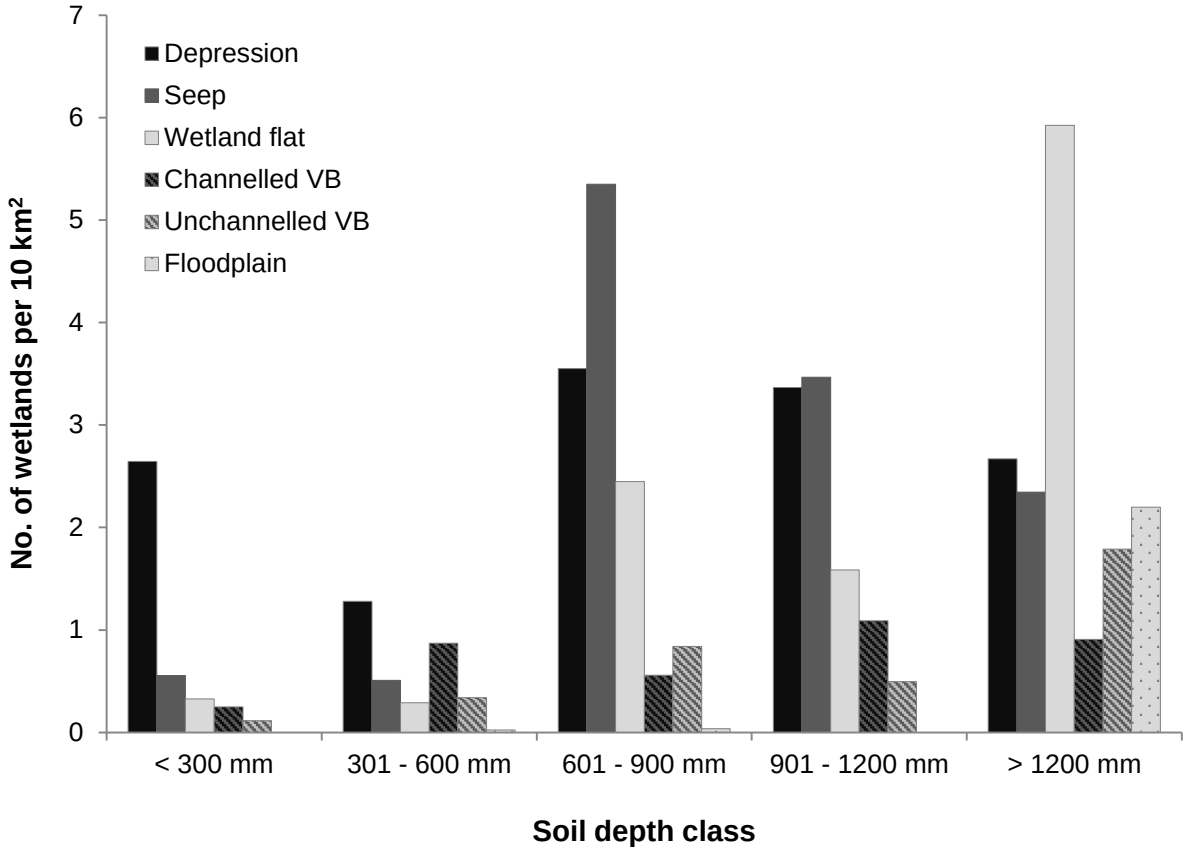

Figure 7-3 Soil depth classes associated with the HGM types. Soil data from ARC (2004).

Approximately 46% of the wetlands in the NMBM were associated with soils with a clay content less than 6%, while only 8% of wetlands were associated with soils of a clay content greater than 25% (Figure 7-5). Approximately 79% and 70% of depressions and seeps were situated on calcareous soils with a higher pH, whereas 55% of wetland flats were found on non-calcareous soils.

As a result of the underlying lithology and soil properties, the majority of seeps and wetland flats had high or very high soil erodibility scores (K Factor > 0.60). Depressions, which were associated with more varied geology and soil types, were mostly associated with moderate soil erodibility scores (K Factor > 0.40).

Wetlands were also associated with fractured rock, with greater densities linked to a higher potential groundwater occurrence (Figure 7-6). Depressions were more evenly spread throughout the different groundwater potential regions (Figure 7-6). Seeps and wetland flats were predominantly located in fractured rocks with a potential discharge of 0.5 – 2.0 $L.s^{-1}$, while the other three HGM units were primarily associated with high yielding fractured rocks and the intergranular rock (Figure 7-6).

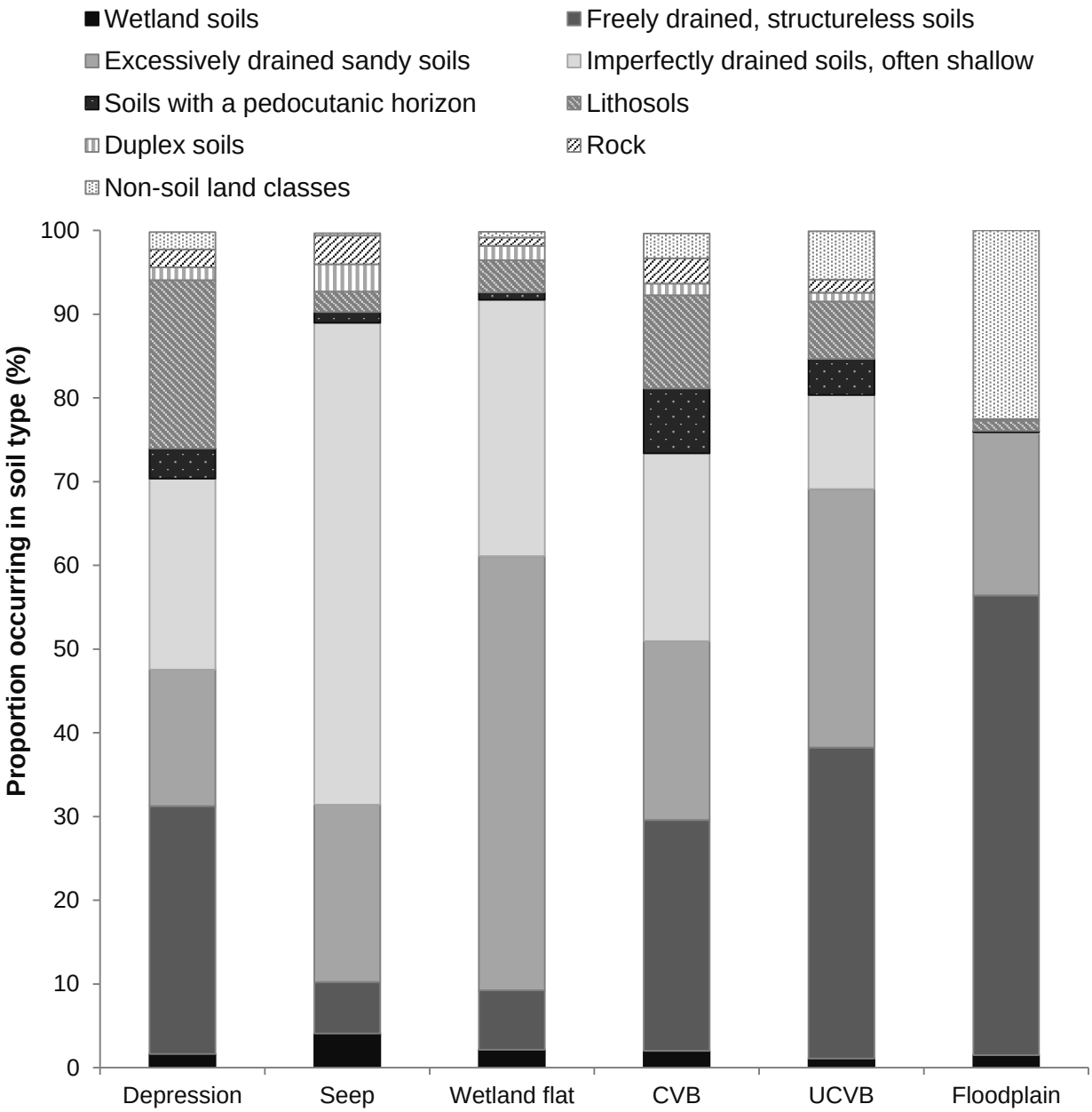

Figure 7-4 Proportion of wetlands found within different soil types per HGM unit. CVB = channelled valley bottom, UCVB = unchannelled valley bottom. Soil data from ARC (2004).

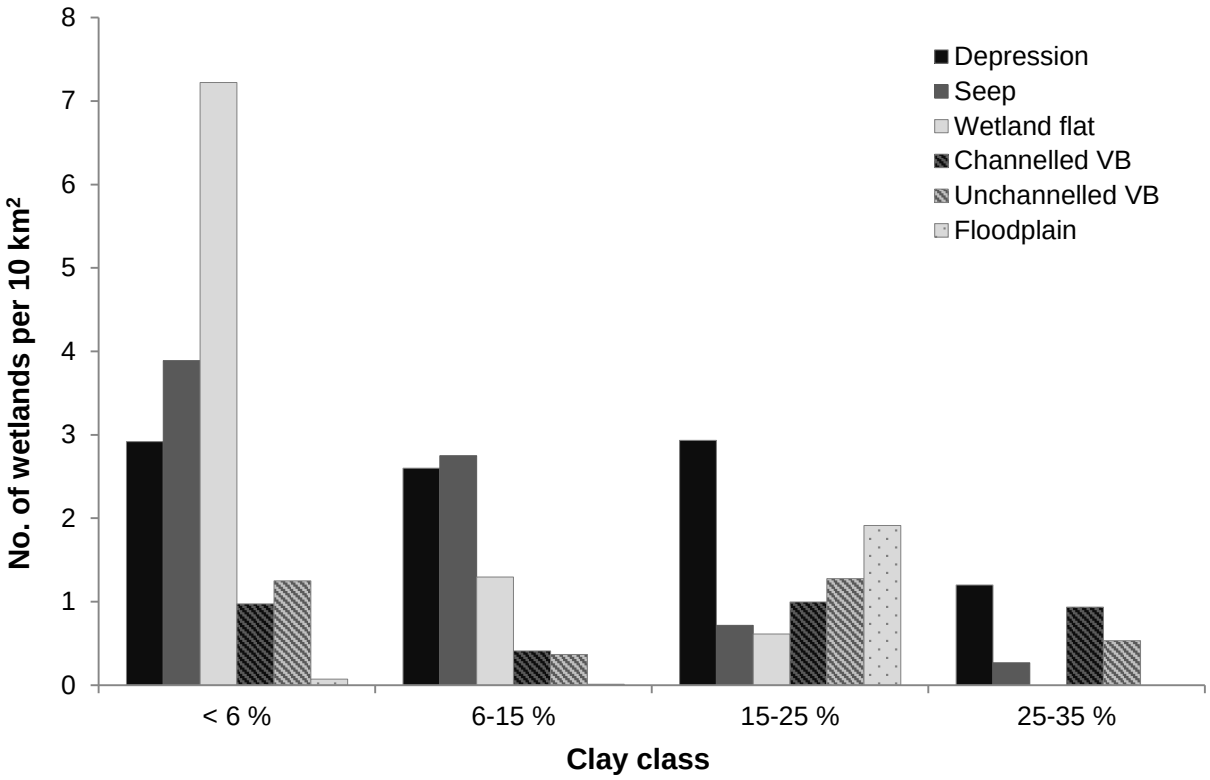

Figure 7-5 Clay classes associated with the HGM types. Soil data from ARC (2004).

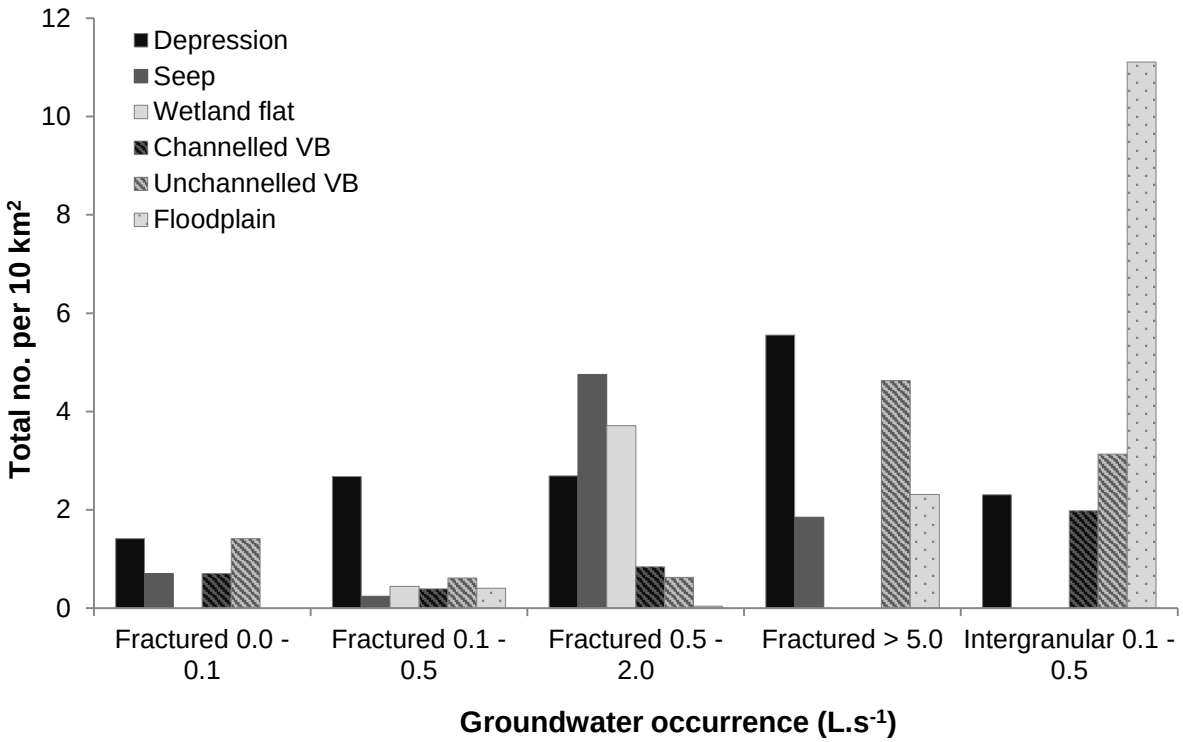

Figure 7-6 Number of wetlands associated with the regional groundwater occurrence (in fractured and intergranular rock). Data from Council for Geosciences (N.D.).

Overview of rainfall patterns experienced during the study

Rainfall in the NMBM is highly variable with no peak rainfall season(s) observed in the long-term and an average rainfall of 618 mm (± 160 mm) per annum (Figure 7-7). Between 2007 and 2010 the NMBM experienced drought conditions, with an average rainfall of approximately 450 mm per year. In 2011, above average rainfall was recorded with a total of 742 mm. In addition, the NMBM experienced flood conditions in 2012 (the first year of the study) where a total of 962 mm of rain fell, 688 mm between June and October (Figure 7-7). In 2013, the NMBM once more experienced below average rainfall, with a total of 575 mm (Figure 7-7). This large rainfall variability has played an important role in the inundation levels and periodicity of the wetlands (Table 7-2), which was accounted for as far as possible in data analyses.

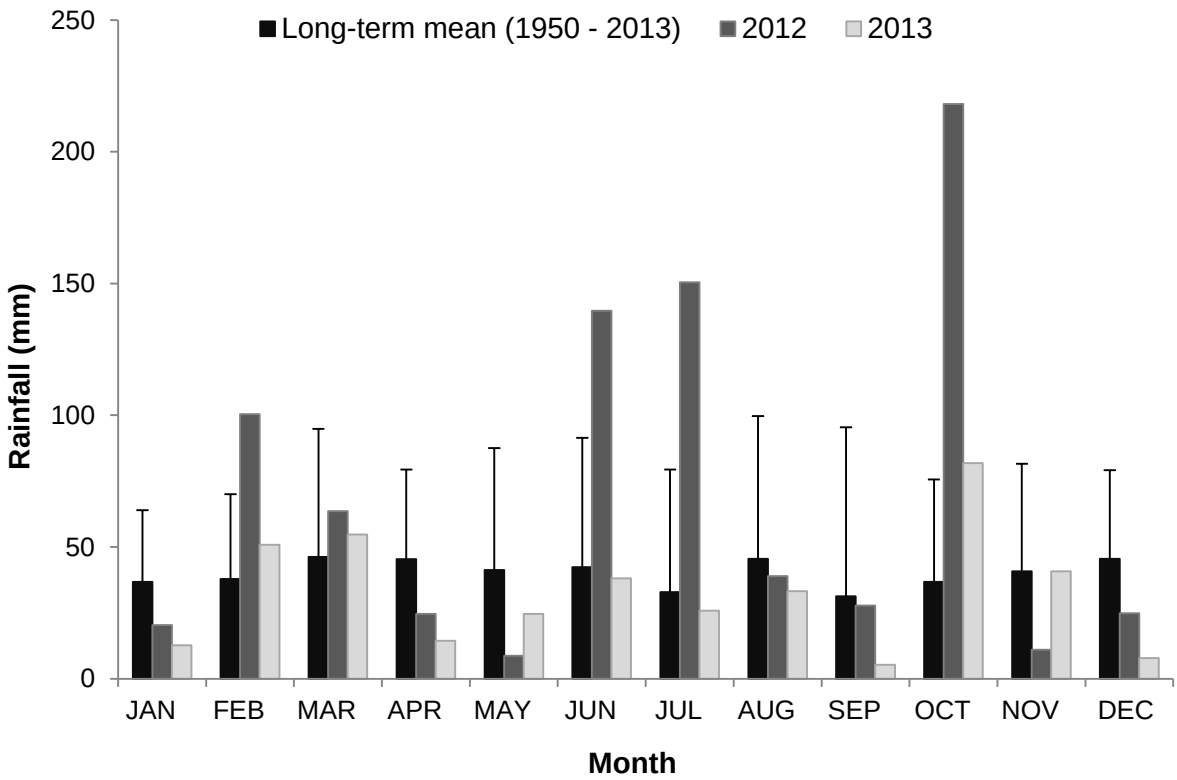

Figure 7-7 Monthly rainfall (mm) measured in the NMBM during the fieldwork season (2012 – 2013) compared to the long-term mean (with standard deviation displayed). Raw data obtained from SAWS and represents three stations: Port Elizabeth (1950-2013), Coega Port (2003-2013), and Uitenhage (1993-2013). The average from all three stations is given.

Table 7-2 Environmental conditions during 2012 and 2013 field work periods.

	2012	2013
Rainfall in preceding months	High with several flood events	Low
General climate condition	Flood	Dry
Inundation levels observed	¾ full to flood (over-full)	Dry – ½ full
Types of wetlands inundated	All (intermittent to semi-permanent)	Only semi-permanent & seasonal

Summary of the environmental characteristics of the NMBM wetlands

Broad-scale environmental patterns were identified between the three HGM types. A summary of these findings of particular interest to this research are highlighted in Table 7-3. These results are discussed further in Section 7.4.

7.3.2. Overview of field sites: Levels 4 – 6 of the CS

Wetlands were sampled on all four landscape units (Level 3 of the CS) (Table 7-4). Once-off sampling was completed at 46 sites at 41 different locations within the Municipality (Figure 7-8) (further details of sites in Appendix F). Site selection was based on a representation of the different HGM types in the study area. A total of 15 inundated sites were sampled in 2012, in 5 of the sample zones. A further 31 sites were sampled in 2013, 17 of which were inundated, and the remainder dry, at the time of sampling. Sites were sampled in all 8 zones in 2013. All 46 wetlands were ephemeral and were delineated to Level 6 of the CS, and the number of sites associated with each of the categories at Levels 4 to 6 of the CS are given in Appendix G: Table G-1 to Table G-6.

At Level 4B-C of the CS some sites were endorheic and exorheic depressions without channelled inflows and seeps with channelled and unchannelled outflows. Wetlands that were in the same location (mentioned above) comprised different HGMs that were connected through surface water. These sites included a seep to a depression, a seep to a wetland flat, and a depression to a seep (Plate 7-1). Another site consisted of three connected seeps on different slope gradients, and with different vegetation characteristics. These sites are discussed in Section 7.4.5.

Table 7-3 Summary of environmental characteristics of the three main HGM wetland types. Slope aspect gives the dominant cardinal points of a compass.Where means are given, the standard errors (SE) and the p-values are also reported (significant at p < 0.05).

Factor	Depression	Seep	Wetland flat	P-value
No. of sites	22	10	14	
Rainfall	All regions	More wetlands found in areas with higher MAP	More wetlands found in areas with higher MAP	-
Slope aspect	NE/E/SE	S/NE/E	S/E/N	
Slope gradient	1.60° (± 0.08 SE)	3.35° (± 0.19 SE)	1.67° (± 0.09 SE)	p < 0.001
Flow accumulation	4.20 (± 0.31 SE)	5.39 (± 0.57 SE)	4.83 (± 0.52 SE)	p = 0.058
Average depth of water (cm)	49 (± 9.6 SE)	12 (± 5.0 SE)	21 (± 4.8 SE)	P = 0.009
Geology type	Bluewater Bay Formation (alluvial gravel, sand & silt) & Nanaga Formation (calcareous sandstone)	Calcareous sandstone of Algoa Group & quartzitic sandstones of TMG	Recent quaternary deposits: aeolian sand, alluvium and fluvial gravel	-
Soil depth	Shallow to deep	Medium to deep (> 600 mm)	Mainly deep (> 1200 mm) but also medium depth	-
Soil types	Lithosols	Imperfectly drained soils, often shallow	Excessively drained sandy soils	-
Calcareous soils	79%	70%	45%	-
Clay class	Sandy loam (51%)	Loamy sand (64%)	Sandy (54%)	-
Potential groundwater occurrence	Fractured & intergranular rock of all potentials	Fractured 0.5 – 2.0 $L.s^{-1}$	Fractured 0.5 – 2.0 $L.s^{-1}$	-

Table 7-4 Distribution of HGM types by landscape unit.

	HGM			
Landscape Unit	**Depression**	**Wetland Flat**	**Seep**	**Total**
Bench hilltop	6	1	1	**8**
Bench shelf			2	**2**
Plain	6	1	3	**10**
Slope	5	8	4	**17**
Valley floor	5		4	**9**
Total	**22**	**10**	**14**	**46**

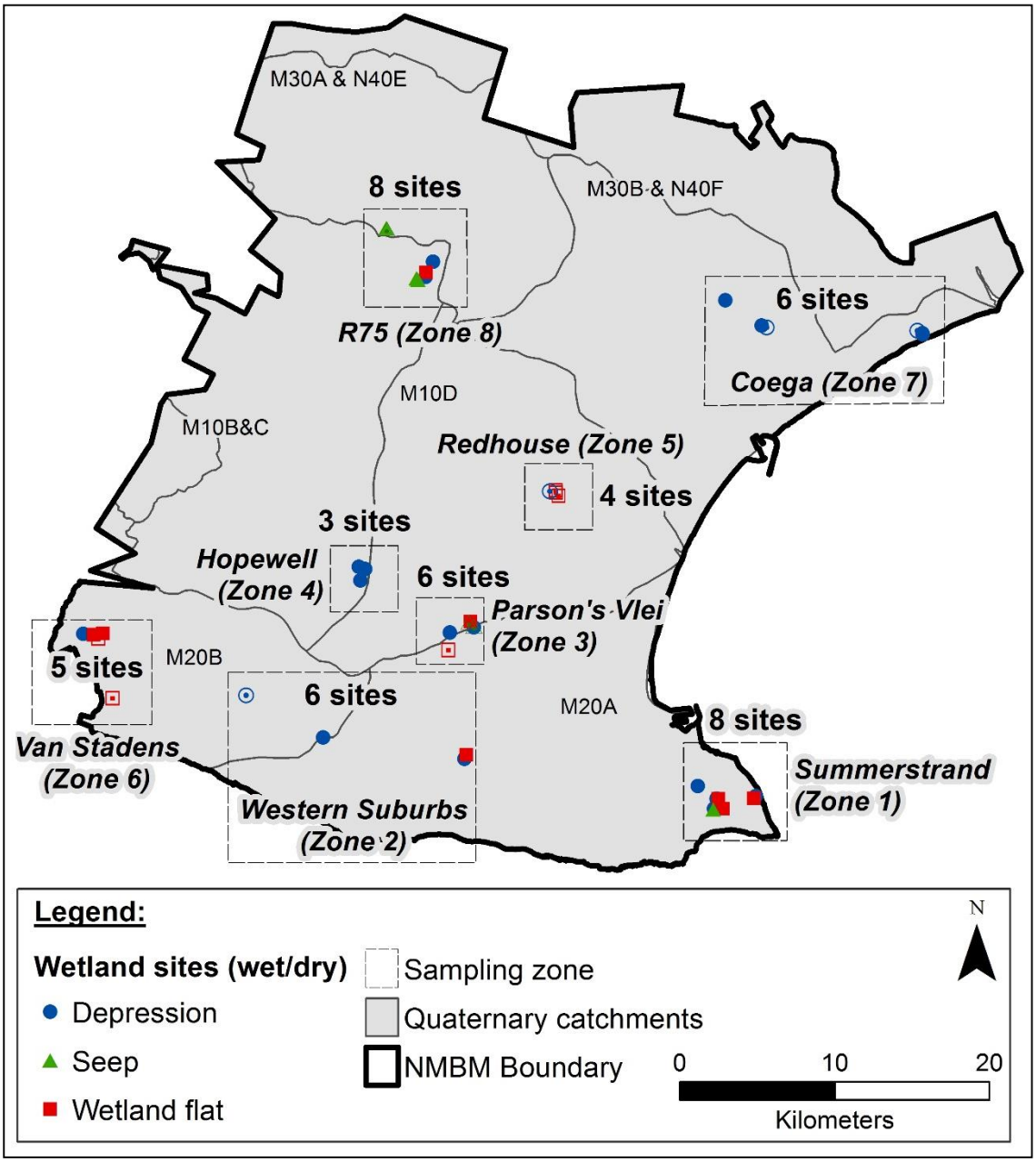

Figure 7-8 **Map of the distribution of the 46 wetland sites in the 8 sampling zones, with the number of wetland sites sampled within each zone. General names of the surrounding area of the sampling zone are also given. Open symbols indicate dry sites while solid/filled symbols indicate inundated sites, at the time of sampling.**

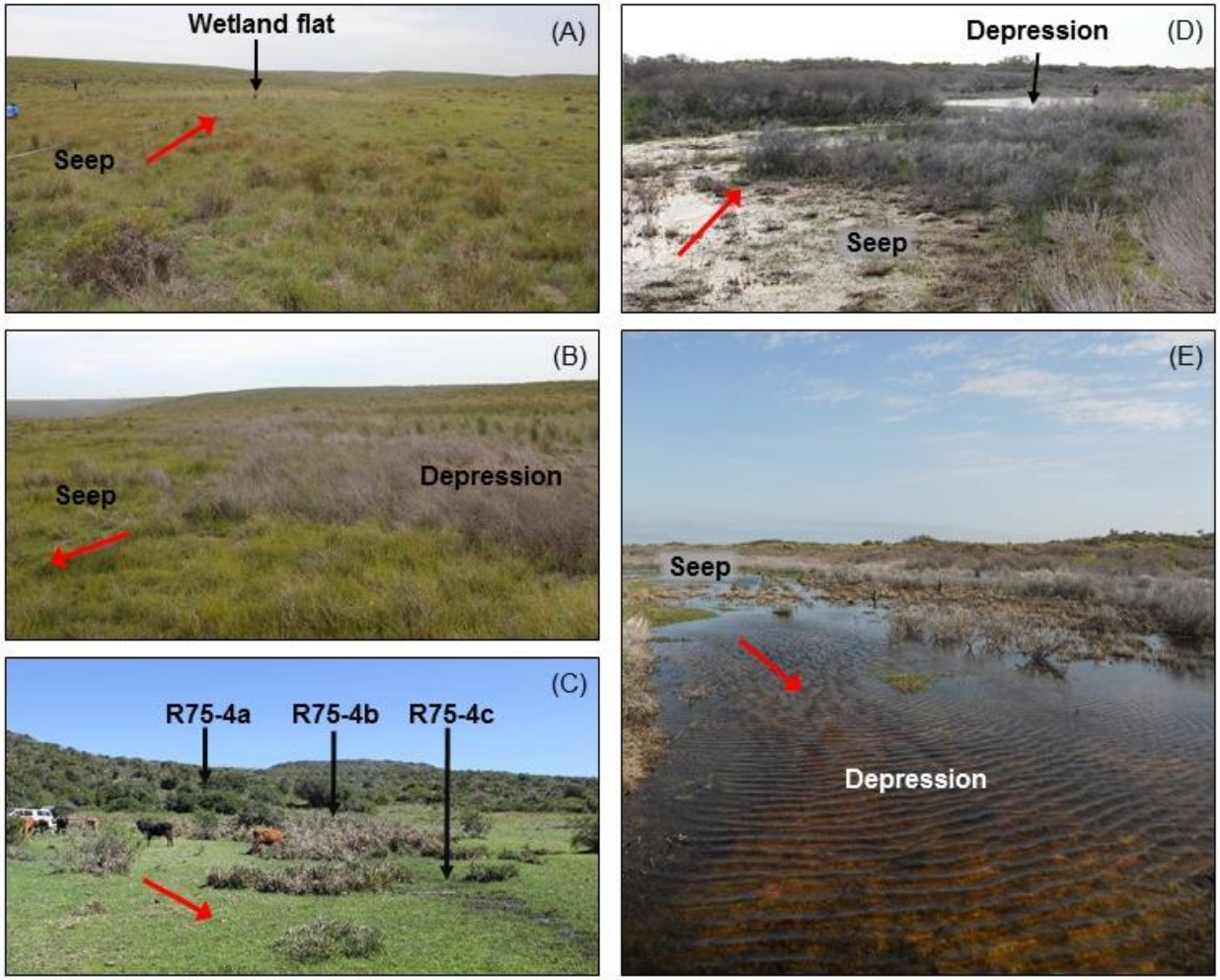

Plate 7-1 **Wetlands sampled within the same location with different HGM units. (A) Seep and a wetland flat at Parson's Vlei (picture taken 06 November 2013), (B) Depression and a seep at Parson's Vlei (picture taken 06 November 2013), (C) Three connected seeps (R75-4a-c) north of Uitenhage (picture taken 05 November 2013), (D) Seep and depression on the NMMU South Campus Reserve. (E) Same wetland as D but looking upslope with depression in foreground. (D) and (E) were taken on two different dates (23 May 2013 and 15 May 2013). Red arrow denotes direction of slope. See Figure 4-1 for site locations.**

Level 5 of the CS focuses on the hydrological regime, defined by inundation and saturation levels. None of the wetlands sampled were permanently inundated. A large proportion of depressions had an area that was classed as permanently saturated, as well as seasonally saturated (Figure 7-9). Seeps showed a similar trend to depressions, but with a larger intermittently inundated/saturation zone, and a smaller permanently saturated zone (Figure 7-9). Water in wetland flats appeared to be more ephemeral in nature than in depressions and seeps, most sites being intermittently to rarely inundated and saturated. In general, it was more difficult to determine the wetland boundary for seeps and wetland flats than in depressions. Average scores for the different zones are given in Appendix G: Table G-2.

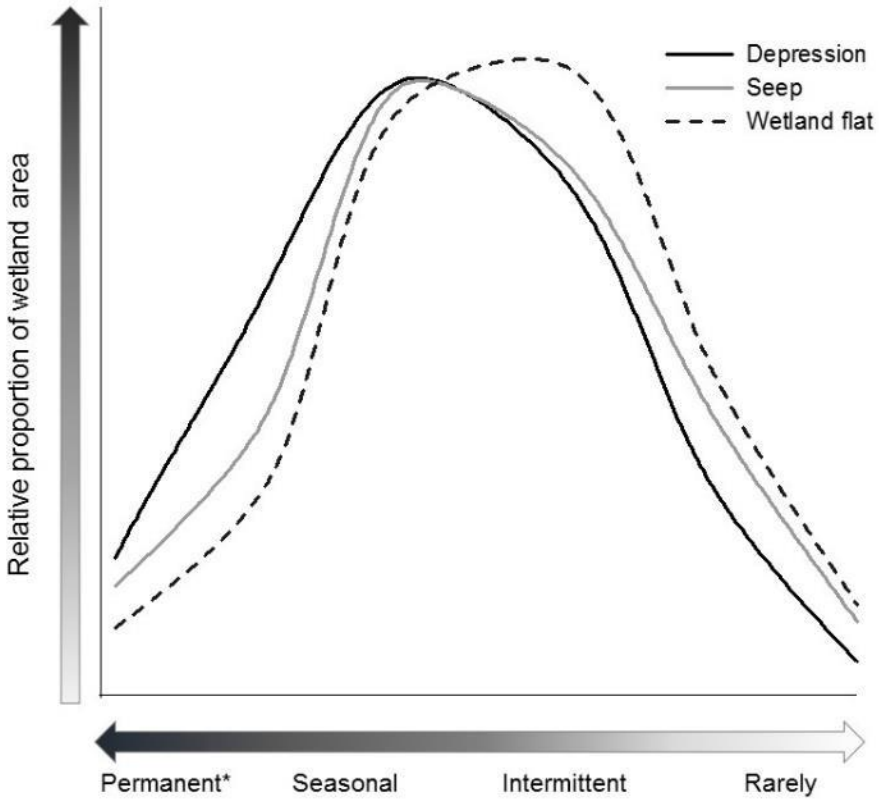

Figure 7-9 Representation of the combined inundation and saturation scores for the three HGM types (See Section 7.2.1). *No permanently inundated sites were sampled; this category pertains only to soil saturation.

Level 6 of the CS descriptively characterises the site. Only relatively undisturbed wetland sites were chosen for data collection. Although some of these sites illustrated a degree of disturbance, usually from surrounding agricultural activities and grazing. Environmental characteristics were also described at this level. For each of the wetlands the following were defined: underlying lithology (using geological maps), substratum types (based on observation), general vegetation, and several water quality attributes. The data obtained at this level were used to explain variability observed in subsequent data analyses.

Not all the wetlands were inundated at the time of sampling. Sample sizes for surface and sub-surface water data and invertebrate data are defined in Appendix G: Table G-5. The majority of the inundated sites were circum-neutral, with six sites being slightly alkaline and two sites slightly acidic. Most of the sites were fresh, with one brackish, one saline, and three hypersaline sites. These parameters are described in detail in Section 0.

The final Level 6 descriptor defines the general vegetation characteristics. Three dune depressions were unvegetated and one seep was dominated by shrubs and thicket. Aquatic and herbaceous vegetation dominated at other sites, which ranged from restios, sedges and grasses to herbs, forbs and algae. Sedges and grasses were the dominant vegetation taxa at most sites. Aquatic vegetation was predominantly associated with depressions, with the exception of one wetland flat. More detailed vegetation data were collected and are described in Section 7.3.4.

7.3.3. Abiotic characteristics

Abiotic data were variable across individual sites and HGM types. Figures and Tables in this section (0) highlight the dominant patterns. The means and ranges for all physico-chemical parameters in soils, surface water and sub-surface water, as well as the nutrients are provided in Appendix H: Table H-1. Detailed soil parameters are also provided in Appendix H: Figure H-1 to Figure H-4.

Soils

Even though only a small portion of the wetlands in the NMBM were located on soils classified as wetland soils (Figure 7-4), various soil wetland indicators were found in the sediment samples analysed at the field sites. The most prominent indicator was high organic matter in the surface layer (assessed visually) of the sediment at 78% of the sites (Figure 7-10). Mottles and concretions were found in cores at 61% of the sites while 57% of the sites had soils with a low chroma (Figure 7-10). Sulfidic odours and organic soils that are more prevalent in permanent wetland systems, were not found at most of the sites (Figure 7-10). Wetlands situated on aeolian sand generally did not have soil indicators of wetland conditions present. The three most prevalent indicators (high organic matter on the surface, the presence of mottles/concretions and a gleyed matrix) were the same for all three HGMs (Figure 7-10).

A number of systems were located on aeolian dunes, and had deep sandy soils with no hard sub-surface layer evident (i.e. were not perched) (Table 7-5). One site, in the Van Stadens Flower Reserve (Zone 6), had a layer of coarse gravels and cobbles as a result of being a relic quarry, so the sediment base could not be determined (labelled as unknown). The

majority of wetlands visited in the field illustrated characteristics of a hard base layer, i.e. a perched system (Table 7-5). The most common perched system comprised a dense clay layer, which was recorded at the base of the soil core at 12 sites (Table 7-5). These clay-based systems were found throughout the different regions of the Municipality, regardless of the surrounding geology and sediment. Calcrete was recorded at seven sites (Table 7-5), all within Zone 1 of the NMBM (see Figure 4-1). Shallow bedrock, at a depth of less than 50 cm, was noted at 10 sites that were mostly around Parson's Vlei (Zone 3) (Table 7-5), and are predominantly associated with quartzitic sandstones of the Peninsula Formation. Five other sites were positioned on variable-depth bedrock with a dense clay layer on the bedrock. These results indicate that many of these systems occur as a result of a perched water table.

Of interest, were three depressions that were located in Hopewell (Zone 4), which had a mixture of gravels, sands and silts (Appendix H: Figure H-2). In addition, ferricrete formations were present at the surface of one site, as well as in the soil profile at two other sites. The presence of iron in these sediments was mainly in the form of ferrihydrite: $FeO(OH)$ and montmorillonite: $(Na,Ca)_{0.33}(Al,Mg)_2Si_4O_{10}(OH)_2.n(H_2O)$, which was confirmed using XrD analysis.

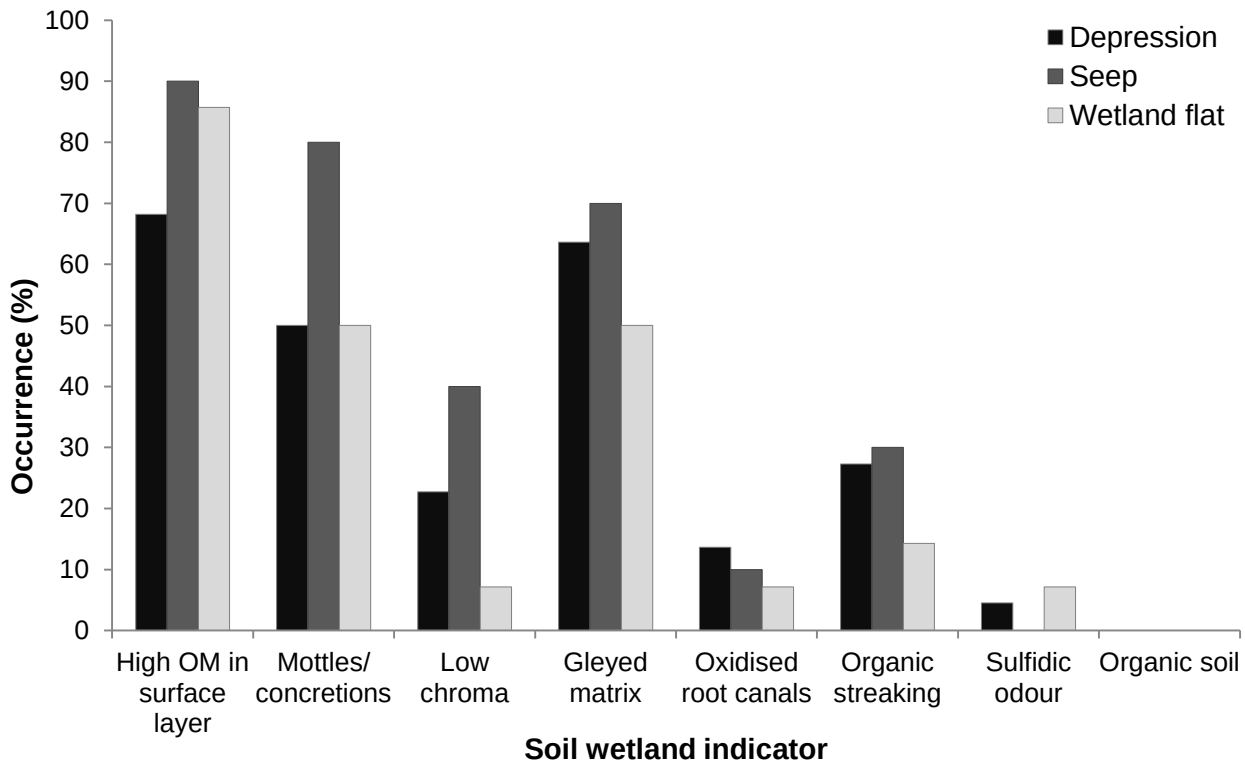

Figure 7-10 Occurrence of wetland soil indicators at each of the field sites, per HGM type. A wetland indicator is taken as present if three or more cores at a site had the indicator.

Table 7-5 Underlying wetland base for all field sites from soil core data and site analysis. See Section 4.4.1 for details on the different categories.

Type of perch	Number of systems
Unknown/ not confirmed	5
Deep (not perched)	7
Perched: bedrock	10
Perched: calcrete	7
Perched: clay	12
Perched: bedrock & clay	5
Total	46

The mean organic matter for wetland sites in the NMBM was 3.36% (Table 7-6). There was variation in the average percentage across geographical areas and HGM units, with slightly higher percentage OM for seeps; although, this was not statistically significant (ANOVA: $F_{2, 43} = 0.091$, $p = 0.914$) (Table 7-6) and much of the variation is thought to be related to the surrounding land use.

There were no apparent patterns in particle sizes per HGM type. One exception was the class size fraction 0.063 mm to 0.125 mm (very fine sand) that comprised a significantly smaller proportion in depressions compared to the other two HGM types (ANOVA: $F_{2,42} = 7.076$, $p = 0.002$). Differences in particle size were mainly attributed to the associated underlying geology or geographical area. Areas that have a sandy underlying lithology (*e.g.* aeolian sand in Zone 1) had a smaller percentage of silt and clay. As expected, dune depressions and coastal seeps, such as sites: DuD 1, SV 1 and 2, and CDD 1 and 3, were dominated by sand-sized particles (See Appendix F for site information).

Sediments in most of the field sites were electrolyte-rich, with an average electrical conductivity (EC) of 1176 µS/cm, indicating slightly brackish conditions (Table 7-6). Sediments from two wetlands in a coastal dunefield were very saline (27 400 µS/cm and 30 400 µS/cm) and were removed from statistical analyses as extreme outliers. Variation in EC can also be attributed to an inland salt pan and a saline coastal seep. With the exception of these saline systems, there was no statistically significant difference in the EC among depressions, seeps and wetland flats (ANOVA: $F_{2, 41} = 0.846$, $p = 0.437$) (Table 7-6).

The pH of the soil samples was generally circum-neutral (pH 6.0-8.0), with the most acidic value of 5.3 and a maximum value of 8.6. Seeps had a slightly lower average pH (7.0) than wetland flats (7.4) and depressions (7.3), although this was not statistically significant

(ANOVA: $F_{2, 43} = 0.899$, $p = 0.415$) (Table 7-6). There was also no geographical trend in the pH of the soils.

Table 7-6 Summary of the mean soil physico-chemical parameters (± SE) for the three HGM types and for all field sites (overall). EC = electrical conductivity.

Variable	Depression	Seep	Wetland flat	Overall
Number of sites	22	10	14	46
Soil organic matter (%)	3.40 (± 0.34)	3.66 (± 0.50)	3.40 (± 0.42)	3.36 (± 0.23)
Soil EC (µS/cm)	1301.30 (± 349.29)	1526.20 (± 493.98)	746.16 (± 417.49)	1175.78 (± 234.65)
Soil pH	7.3 (± 0.17)	7.0 (± 0.25)	7.4 (± 0.21)	7.3 (± 0.12)
Inundation/ Saturation	Seasonal/ Intermittent	Intermittent	Intermittent	Seasonal/ Intermittent

Water chemistry

Physico-chemical properties of water from the field sites are illustrated in Figure 7-11 and Figure 7-12. Data ranges are given in Appendix H: Table H-1. The majority of wetlands in the NMBM had circum-neutral waters. In the surface water, seeps were more acidic ($\bar{x} = 6.47$), than wetland flats and depressions (ANOVA: $F_{2, 29} = 4.221$, $p = 0.0246$). A similar trend was recorded in sub-surface waters, with seeps, again, being more acidic ($\bar{x} = 6.32$); although, these differences were not statistically significant (ANOVA: $F_{2, 26} = 0.4219$, $p = 0.661$).

There was no statistical difference in the EC (ANOVA, $F_{2, 71} = 1.227$, $p = 0.299$) of the sub-surface waters. All three HGM types had fresh to saline EC levels, with overall averages indicating brackish waters. The lowest mean EC of 920.0 µS/cm occurred in wetland flats. Similar patterns were observed in the EC of the soils and in the surface water, the latter of which had a mean of 702.2 µS/cm in wetland flats. The surface waters of depressions ($\bar{x}$ = 803.5 µS/cm) and seeps ($\bar{x}$ = 871.7 µS/cm) were also mainly fresh to brackish with the exception of a few systems that had extremely high EC values. Without these outliers, differences in the surface water EC were not statistically significantly different among the HGM types (ANOVA: $F_{2, 25} = 0.088$, $p = 0.916$). As with the soils, much of the variation in EC could be attributed the associated underlying sediment and geographical position (e.g. coastal systems with a high EC).

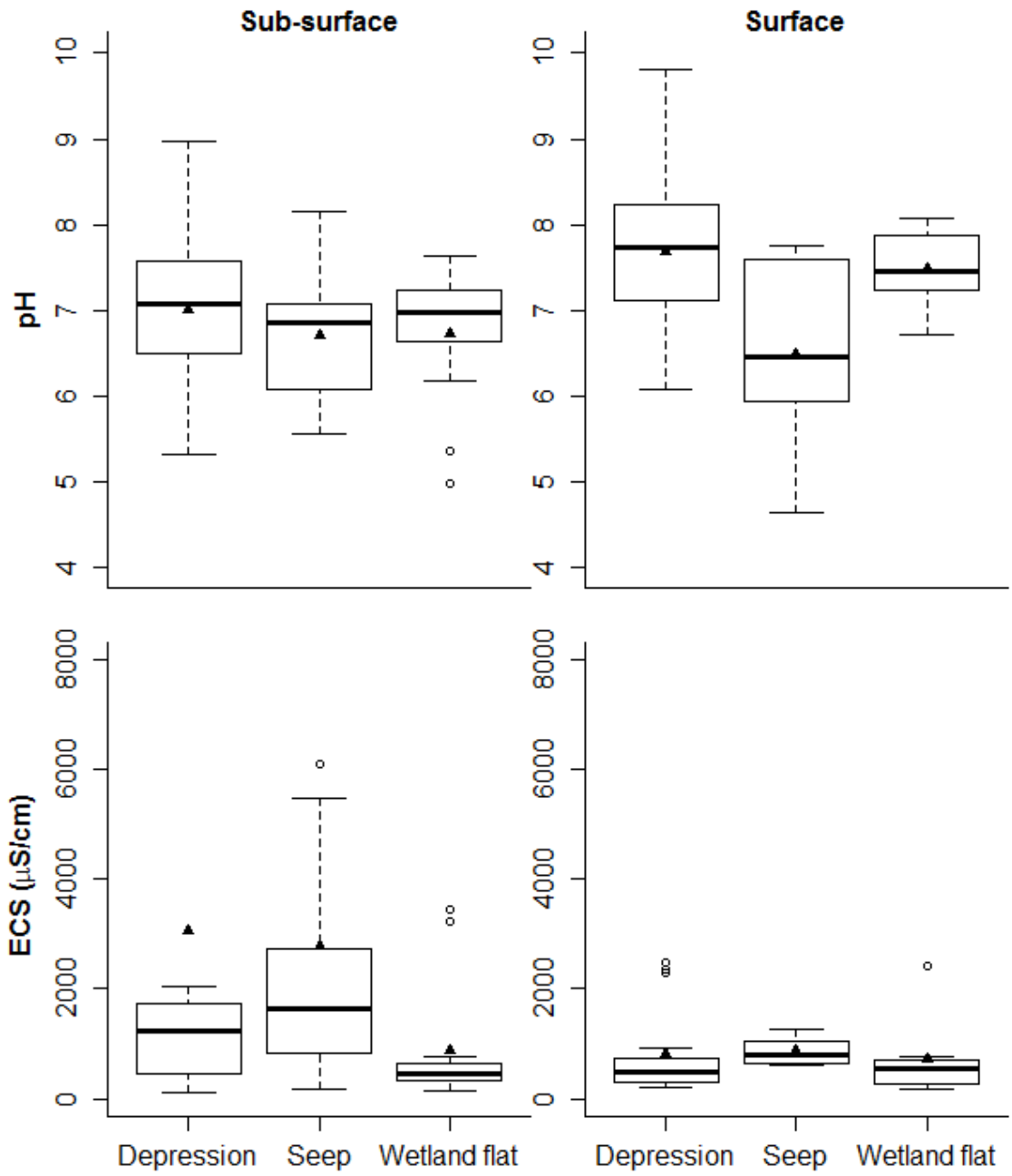

Figure 7-11 Box plots of sub-surface and surface water physico-chemical parameters and their respective standard deviations (SD). Sample sizes for each HGM (sub-surface, surface): depression (17, 18), seep (6, 6) and wetland flat (6, 8). Extreme outliers for electrical conductivity (EC) values were excluded.

Depressions had lower levels of dissolved oxygen in the surface water than the two other HGMs. However, there was no statistically significant difference between the dissolved oxygen levels in the three HGM types (ANOVA: $F_{2, 29} = 0.339$, $p = 0.715$). This corresponds with greater maximum depths measured in depressions ($\bar{x} = 60$; range: 6 cm to 125 cm), with some systems having reached over 1 m in depth. Seeps and wetland flats were significantly

shallower with average depths of 14 cm and 27 cm respectively (ANOVA: $F_{2, 29} = 5.558$, $p = 0.009$).

A positive correlation was found between the percentage organic matter and the soil moisture ($r^2 = 0.55$). However, prevailing weather conditions also played a role regarding the soil moisture content, as a number of samples in 2013 were drier compared to those collected in 2012 (after various flooding events) (Figure 7-7). A weaker correlation existed between organic matter and the soil percentage clay content ($r^2 = 0.34$). The clay content of the soil was also correlated with the sub-surface physico-chemical parameters.

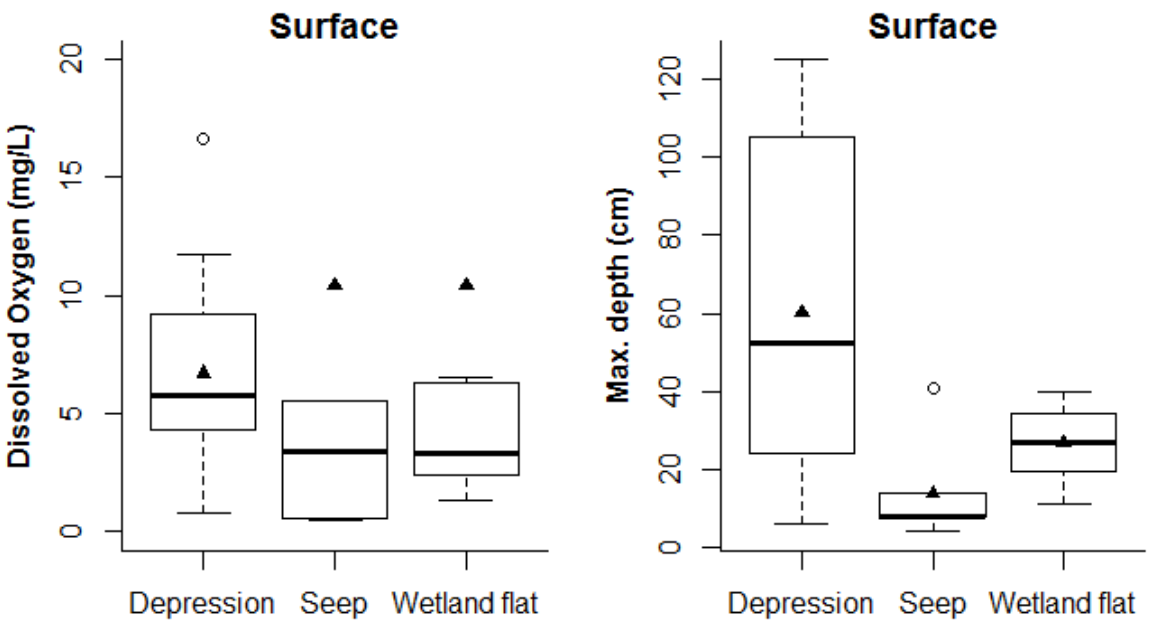

Figure 7-12 Box plots of sub-surface and surface water total dissolved oxygen (mg/L) and maximum depth (cm) and their respective standard deviations (SD). See Figure 7-11 for sample sizes.

Abiotic summary

Key findings of the abiotic characteristics of the wetlands visited are highlighted in Table 7-7. These results provided the basis for explaining some of the variation in community structure decribed in Section (7.3.4).

Table 7-7 Key abiotic characteristics measured or observed at field sites.

Site level characteristics	Summary of findings
Level 5 of CS (Inundation and saturation)	Depressions were more regularly seasonally inundated or saturated than seeps and wetland flats. Wetland flats were primarily intermittently inundated/saturated, with no permanently saturated zone.
Soil wetland indicators	Present at most sites. High organic content at the soil surface, mottles, concretions and low chroma were the most prominent indicators. Soil organic matter was generally high (3.36%).
Physico-chemical properties (surface and sub-surface water)	Overall, systems had good water quality parameters. Salinity, TDS, and EC readings all indicated that the majority of systems were fresh to brackish. Exceptions were coastal dune depressions and inland natural salt pans (saline). Mostly circum-neutral pH readings were measured in both soils and waters (sub-surface and surface). However, some sites were more acidic.

7.3.4. Biotic characteristics

The biotic structure of a wetland provides an indication of function. The biotic data in this section are from once-off sampling sessions at the wetland sites. The data were used to link multi-scalar environmental factors, which have been addressed in this chapter (as well as in Chapters 5 and 6), to wetland distribution, structure and function.

Plant communities

The vegetation characteristics were assessed at each of the field sites and various sources were used to identify plants and their characteristics (as outlined in Chapter 4). As mentioned previously, two dune depressions (CDD1 and CDD2) had no vegetation or macro-algae. These sites were, therefore, excluded from further analysis.

A wide range and diversity of plant taxa were recorded, with 90 plant families identified in the 44 remaining sites. A total of 307 taxa were identified to genus and/or species level. Full species list in Appendix I: Table I-1 and

Table I-2. Sites were generally dominated by grasses, sedges, restios and geophytes, with filamentous algae and macroalgal species, such as *Chara* sp., present in some inundated sites. Herbs and shrubs were also identified, as well as various weed species.

Depressions had the highest mean number of plant species (26.8 species) and the highest species richness among the three HGMs; although, this was not statistically significantly different among the three HGM types (ANOVA *S*: $F_{2, 41} = 0.833$, $p = 0.4429$; ANOVA *R*: $F_{2,}$

$_{41}$ = 1.216, p = 0.307) (Table 7-9). Depressions and seeps had the highest plant diversity of 1.94 (ANOVA *H'*: $F_{2, 41}$ = 0.837, p = 0.440), and seeps the highest evenness score of 0.66 (ANOVA *J'*: $F_{2, 41}$ = 3.100, p = 0.056) (Table 7-9). Wetland flats had the lowest evenness and diversity scores of 0.55 and 1.71 respectively.

Table 7-8 Diversity indices for vegetation by HGM and across 44 field sites for which vegetation data were available.

HGM unit	Mean no. species (*S*)	Species richness (*R*)	Shannon-Wiener (*H'*)	Pielou's evenness (*J'*)
Depression	26.75 (± 11.94)	6.21 (± 2.73)	1.94 (± 0.57)	0.61 (± 0.11)
Seep	22.00 (± 9.44)	5.05 (± 2.28)	1.94 (± 0.55)	0.66 (± 0.08)
Wetland flat	23.57 (± 7.79)	5.12 (± 1.84)	1.71 (± 0.48)	0.55 (± 0.12)
All sites	24.66 (± 10.20)	5.60 (± 2.39)	1.87 (± 0.53)	0.60 (± 0.11)

Over 80% of the plants (84 species) identified were indigenous to SA (Table 7-9). Several terrestrial alien plant species were also recorded, including wattles (Acacia cyclops, A. longifolia and A. saligna) and various grass species (Table 7-9). Only two alien aquatic species were identified, namely, Schoenoplectus triqueter and Elodea nuttallii.

The majority of indigenous plants were of Least Concern according to the Red List of SA plants (Table 7-9) (South African National Biodiversity Institute 2014). One species was classified as Vulnerable on the Red List (Table 7-9 and Plate 7-2), *Crinum campanulatum* (vlei lilly), a freshwater aquatic plant associated with ephemeral wetlands in the Eastern Cape.

Several wetland-adapted and terrestrial plant species were identified at the field sites (Table 7-9 and Figure 7-13). Approximately 55% of the plant species identified are considered to be terrestrial (Table 7-9). Wetland flats showed the most distinct differences between dry and inundated sites with 21% more species of obligate wetland plants in the inundated sites (Figure 7-13). Depressions were similar but the trend was less apparent (Figure 7-13). In contrast, there was only a 1% difference in the proportion of obligate wetland plants in dry and inundated seeps (Figure 7-13).

Table 7-9 Summary of vegetation status of plants occurring across all sampled wetland sites. See Section 4.6.2 for data sources used.

Endemism	No. of plant spp.	Red List status	No. of plant spp	Habitat	No. of plant spp.
Unknown	149	Unknown	161	Unknown	46
Exotic/Alien	48 (19%)	Not Evaluated (exotic)	48 (19%)	Terrestrial	219 (61%)
Indigenous	126 (49%)	Least Concern	197 (80%)	Wetland-associated	29 (8%)
SA Endemic	84 (33%)	Vulnerable	1	Facultative wetland	33 (9%)
				Obligate wetland	80 (22%)

Plate 7-2 Vulnerable Red List plant species, *Crinum campanulatum,* identified in Hopewell Conservation Estate - picture taken in March 2013. This species was recorded several times between 2012 and 2013.

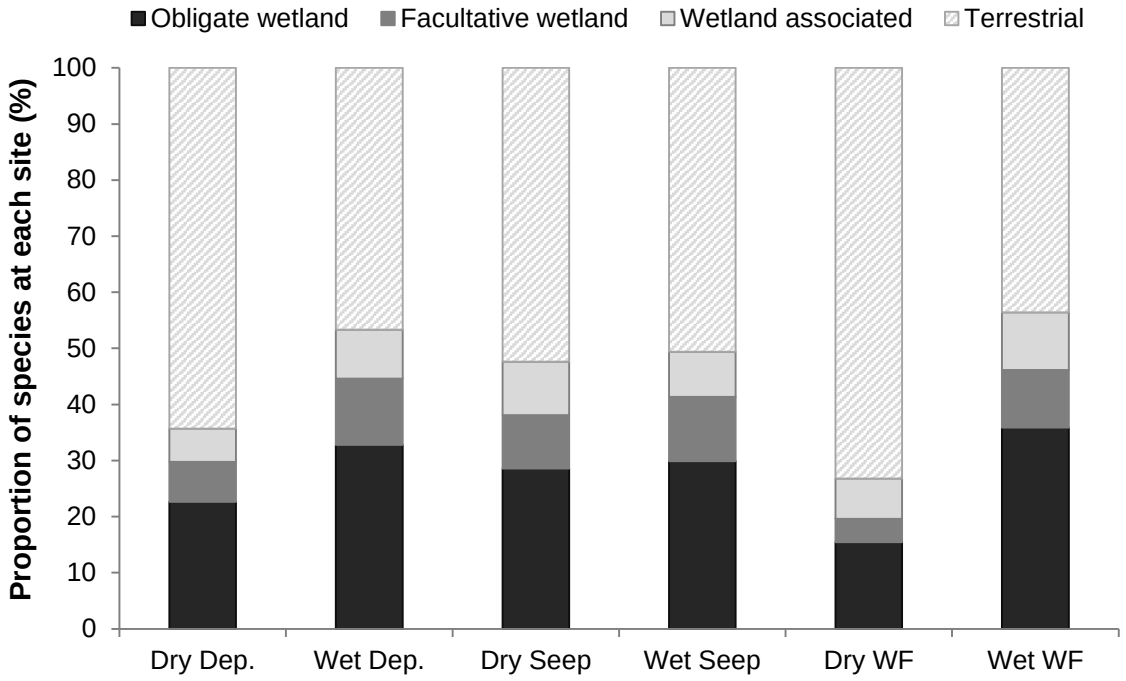

Figure 7-13 Proportion of plant species wetland attributes within each HGM. Sites that were inundated ("wet") and dry at the time of sampling are separated. Dep = depression, WF = wetland flat.

The results of a Bray-Curtis similarity analysis indicated that plant communities were variable across HGM types and locations within the NMBM (Figure 7-14 and Table 7-10). Different grass and sedge species generally defined the various plant communities, which included aquatic, wetland associated and terrestrial species (Table 7-10). Further analyses, described in this section below, were used highlight patterns across the sites.

Wetland plant communities differed within each HGM type, as evidenced by the lack of clear groupings and a high stress level in the MDS plot (Figure 7-15). A constrained ordination: canonical analysis of principal coordinates (CAP) indicated that approximately 61% of the plant species were associated to the HGM type (Table 7-15). Plant community structure was also linked to broader landscape properties such as position in the landscape (Level 3 of the CS) (57%), and the quaternary catchment in which the wetland was found (57%), but to a lesser extent. Slightly more convincing results were observed when wet and dry vegetation zones were analysed separately for each of the depressions, with approximately 68% of the plant community in both wet and dry sites attributed to its HGM as well as the landscape position.

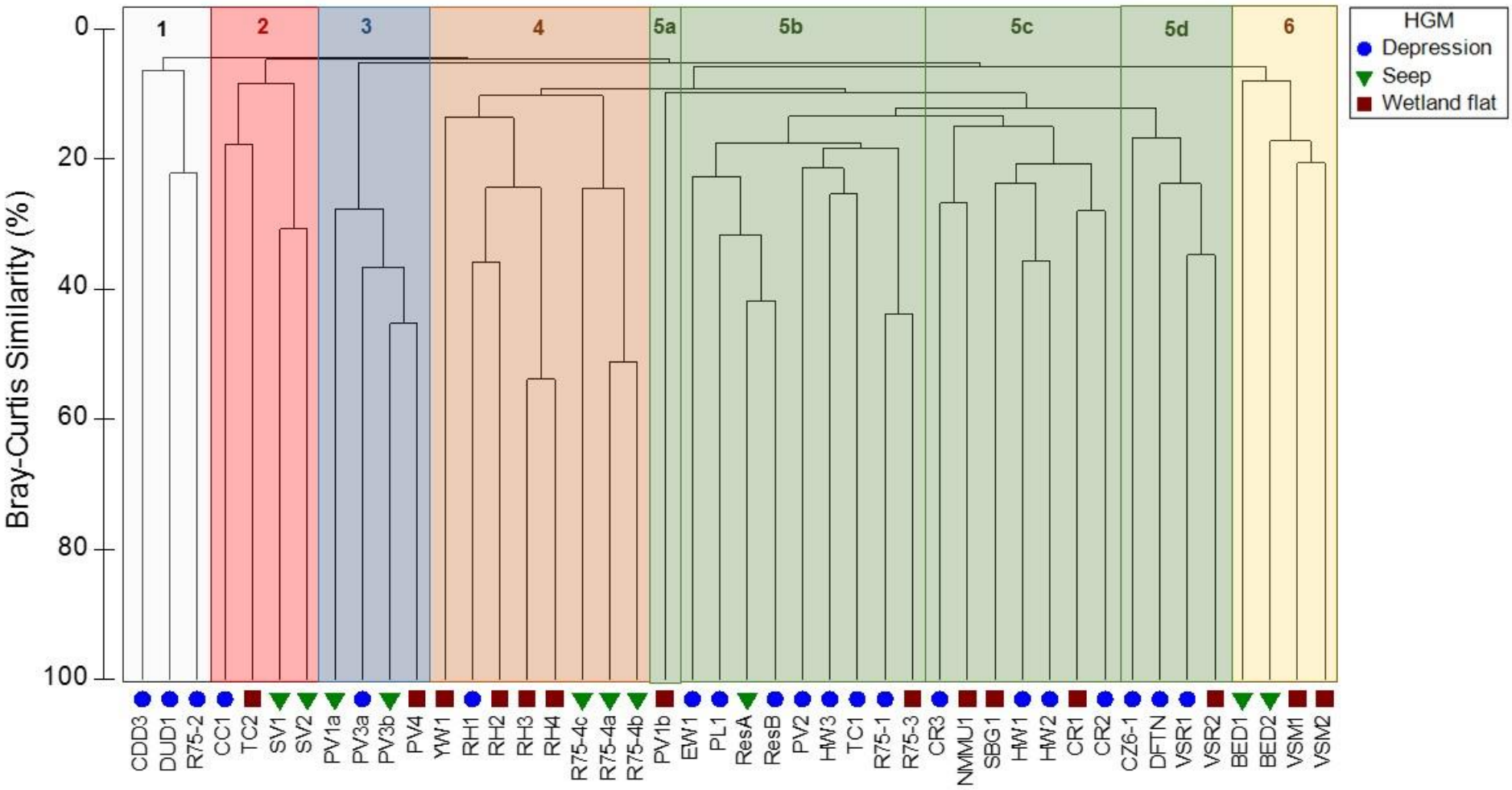

Figure 7-14 **Bray-Curtis similarity index of the plant community structure for all sites in the NMBM. HGM type and site codes are given (see Appendix F for locations). Six communities are highlighted, one of which has been split into several sub-communities. See Table 7-10 for plant community descriptions.**

Table 7-10 The dominant species found in the six plant communities, based on a Bray-Curtis similarity analysis (Figure 7-14). Group 5 was sub-divided into a further four groups which are also indicated below. Where site patterns could be established, these are given. Patterns looked for were: HGM type, landform type (Level 3 of the CS), location, inundated or dry, wetland "age", and wetland size. Note: community 5a is not given as it comprises a single site.

Community No.	Main species	Plant forms & wetland indicator status	General site patterns
1	*Chrysanthemoides monilifera* & chlorophytes	Terrestrial shrub & filamentous algae	Two dune depressions and a natural salt pan, all with limited vegetation cover. Located in different parts of the Municipality
2	*Phragmites australis, Zantedeschia aethiopica, Lemna gibba & Chrysanthemoides monilifera*	Mixture of aquatic & wetland associated grasses, wetland associated geophytes & aquatic ferns	Mixture of HGM types found in the southern part of the NMBM (Zones 1 & 2)
3	*Themeda* sp., *Pennisetum* sp., *Andropogon* sp., *Elegia ebracteata & Epischoenus gracilis*	Terrestrial, wetland associated and aquatic grasses, restios and sedges	Sites all located in Parson's Vlei (Zone 3)
4	*Cynodon dactylon*, *Paspalum* sp., *Cotula zeyheri, Centella asiatica, Schoenoplectus* sp., *Juncus krausii* & *Pennisetum thunbergii*	Aquatic and wetland associated grasses, herbs and aquatic sedges	Mixture of HGM types found throughout the NMBM
5	*Cynodon dactylon*, *Chara* sp., *Schoenoplectus decipiens*, *Imperata cylindrica*, *Isolepis* sp., & chlorophytes	Wetland associated grasses, macroalgae and filamentous algae, and sedges	Predominantly inundated sites of all HGM types and in all parts of the Municipality
b	*Chara* sp., chlorophytes & *Schoenoplectus decipiens*		All sites were inundated at time of sampling
c	*Imperata cylindrica, Eleocharis* sp. & *Schoenoplectus decipiens*		All sites were inundated at time of sampling
d	*Isolepis* sp. & *Cynodon dactylon*		Site data collected in 2013
6	*Pennisetum thunbergii, Cyperus congestus* & *Cynodon dactylon*	Aquatic and wetland associated grasses	None

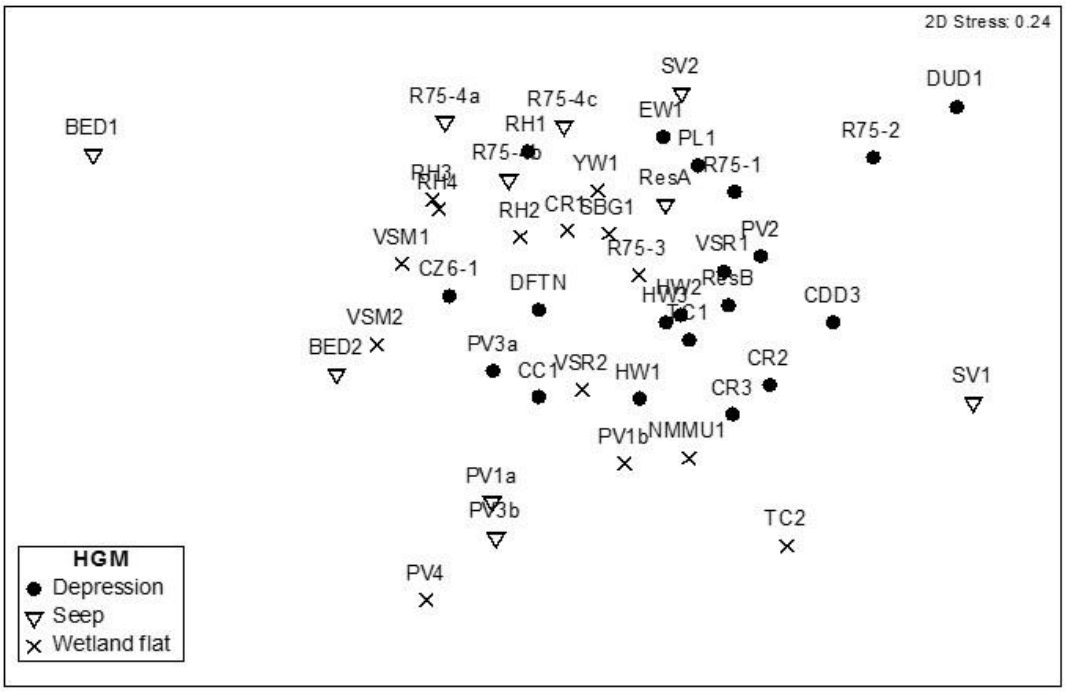

Figure 7-15 MDS plot of the plant communities, at a species level, for the three HGMs. List of site codes and their locations in the NMBM are listed in Appendix F.

A distance-based redundancy analysis was used to ascertain the role of broad-scale and site-level environmental data in defining plant communities. Figure 7-16 illustrates an example where these communities, at both wet and dry sites, are driven by a combination of broad-scale and site level environmental data. A BIOENV in Primer was used to establish which key abiotic variables best explained the dissimilarities among plant communities (Table 7-11). This analysis was repeated for sites that had surface water and/or sub-surface water (as both were not always present). Plant communities were better explained using both environmental and hydrological variables. Both surface and sub-surface water nutrient concentrations (especially, total phosphorus and dissolved inorganic nitrogen) showed correlations to plant community structure. However, both broad and site-scale data were important in all four of the variations of the analyses (Table 7-11).

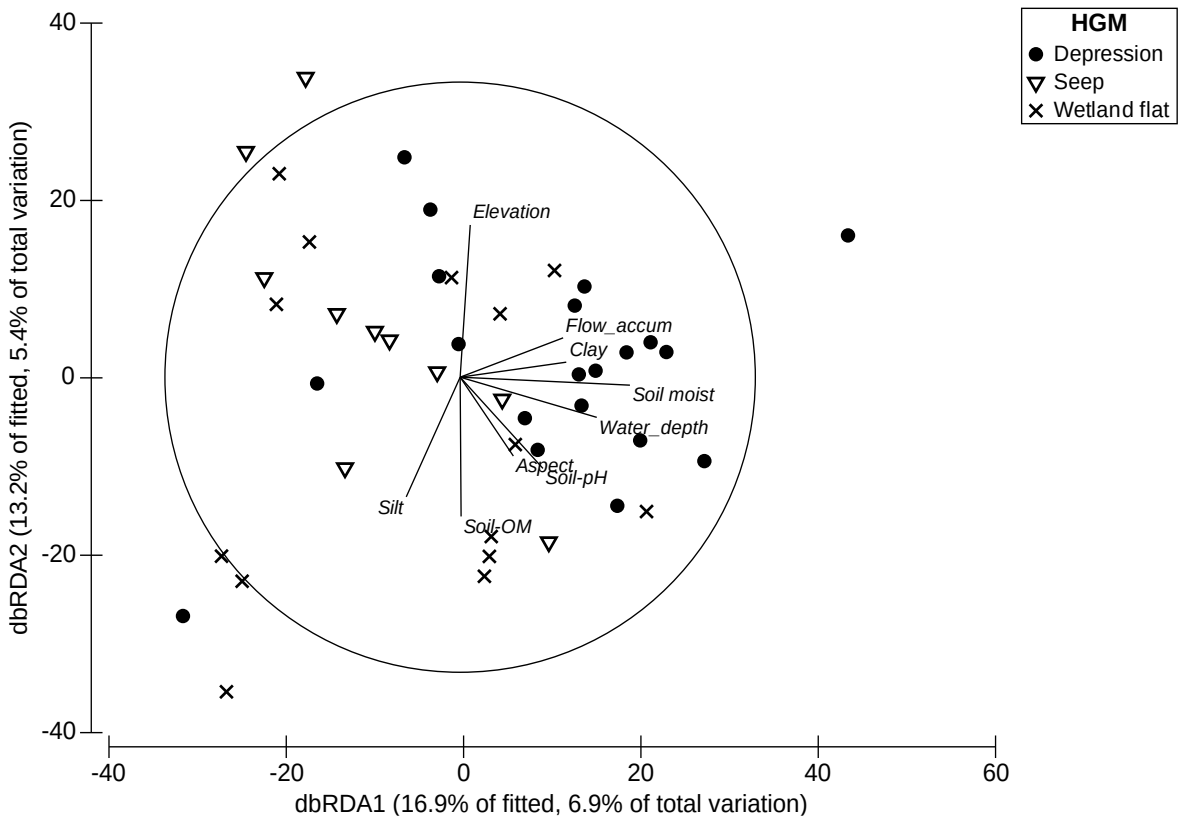

Figure 7-16 Distance-based redundancy analysis (dbRDA) of the environmental variables affecting plant species communities. Only variables with a correlation greater than 0.3 are displayed. See Table 5-2 for abbreviations.

Table 7-11 Key factors influencing plant community structure using four combinations of variables to account for the presence of surface water (SW) and sub-surface water (SSW) at sites. Environmental variables include those listed in Section 4.2.2 (elevation, slope aspect and gradient, solar radiation, evapotranspiration, mean annual precipitation, underlying geology, broad-scale soil characteristics (e.g. depth, clay, calcareous), land use, annual heat units, flow accumulation and direction and groundwater occurrence). * Displayed in Figure 7-16.

Variables	Factors affecting community structure	No. of sites	Spearman Correlation
Environmental variables: data measured at all sites (e.g. soil properties, gradient etc.) *	Elevation, Evapotranspiration (ET), MAP, Soil EC, Water depth	44	0.342
Environmental variables + SW	Annual heat units, Elevation, Soil EC, SW TDS, SW TP	29	0.392
Environmental variables + SSW	Elevation, MAP, Soil EC, SSW pH, SSW TP	26	0.336
Environmental variables + SW + SSW	Elevation, SW TDS, SW EC, SW DIN, SSW pH	23	0.383

Aquatic fauna

A total of 144 macroinvertebrate taxa were identified to lowest practical level at 30 inundated sites. The majority of the taxa were identified to genus or species where possible, with some Orders only identified to family level. Given the sampling apparatus used was at a larger mesh size (1 mm), zooplankton could under-represented in the majority of the samples and the taxa limited to larger invertebrates. However, it was difficult to establish whether their low numbers were due to the mesh size, or was a “true” representation of the macroinvertebrate community that occupied the wetland at the time of sampling. A chick list of species for each of the sites is given in Appendix I: Table I-3 and Table I-4.

Macroinvertebrates were sampled for at 30 sites, and the data collated from the two sweeps (in the marginal vegetation and open water) (see Appendix G: Table G-5 for number of sites per HGM type). *Streptocephalus dendyi* (fairy shrimp), was identified at two sites (PV1b and VSR 2). This species is an obligate wetland species, endemic to SA, and is listed as Endangered on the IUCN Red List (Hamer 1996). *Paradiaptomus natalensis* was found at one site in the Van Stadens area (Zone 6), and is listed as Vulnerable (Hamer 1996). Several other southern Cape and SA endemics were identified, including several aquatic Coleoptera: *Coelhydrus brevicollis, Darwinhydrus solidus, Gyrinus (s.str.) vicinus, Helophorus (Rhopalohelophorus) aethiops,* and *Hydropeplus trimaculatus* (Stals 2007). Several other taxa that were only recorded to genus level are also known to have some species that are endemic to the Eastern Cape and/or SA.

There was a significant difference in the mean number of species, species richness and species evenness among the HGM groups (ANOVA *S*: $F_{2, 26} = 4.801$, $p = 0.017$; ANOVA *R*: $F_{2, 26} = 3.951$, $p = 0.032$; ANOVA *J'*: $F_{2, 26} = 4.979$, $p = 0.015$) (Table 7-12). Most of the significance, across all indices, was attributed to lower scores in seeps (post-hoc Tukey HSDs: $p < 0.05$). Seeps also had a lower Shannon-Wiener diversity score, although this wasn’t significant (ANOVA *H'*: $F_{2, 26} = 2.027$, $p = 0.153$). Depressions and wetland flats were not statistically significantly different from each other in terms of all diversity indices.

Sampling occurred in wetlands that had been inundated for different periods of time, yet there are some patterns in species composition among the HGMs. Depressions and wetland flats were dominated by four families: Baetidae (mayflies: *Cloeon* sp.), Coenagrionidae (damselflies), Corixidae: Micronectinae (aquatic true bugs) and Dytiscidae (beetles). These four families, along with Cyprididae (ostracods) in wetland flats, accounted for approximately 60% of the macroinvertebrate community structure in both HGMs. In comparison, seeps were dominated by “worms” (Oligochaeta) and flies (Diptera). A CAP analysis further indicated the

strong association of macroinvertebrate species with HGM type (70%) (Table 7-15). Level 3 of the CS had the lowest level of accuracy with only 43% of the community structure explained at this level, while 57% of the community structure could be defined at catchment level.

Table 7-12 Diversity indices for macroinvertebrates by HGM in the inundated field sites. Dry sites were excluded and sites CC1 and R75-4c as they only had one taxon.

HGM unit	Mean no. species (*S*)	Species richness (*R*)	Shannon-Wiener (*H'*)	Pielou's evenness (*J'*)
Depression	17.65 (± 13.02)	2.93 (± 1.72)	1.73 (± 0.66)	0.65 (± 0.14)
Seep	4.50 (± 3.21)	1.13 (± 0.90)	1.21 (± 0.56)	0.84 (± 0.10)
Wetland flat	21.63 (± 7.25)	3.29 (± 10.41)	1.71 (± 0.52)	0.58 (± 0.19)
All sites	16.13 (± 11.87)	2.67 (± 1.53)	1.63 (± 0.62)	0.66 (± 0.17)

Ten species of tadpoles were recorded at 15 sites. Two of these species were toads, and the rest were frog species from three families (Table 7-13). All species have been classed as Least Concern by the IUCN and nine of the species are endemic to either SA or southern Africa (Table 7-13).

Most of the frog species utilise wetland habitats only for breeding and early life-stage development. *Xenopus laevis* is the exception as it is aquatic throughout its life cycle. This species was also the most prolific and was identified at 10 sites. No tadpoles were found in seeps but they were found in the marginal vegetation and open water sections of the other two HGMs. Over 71% of the total number tadpoles (n = 1127) were found in depressions.

Macroinvertebrate and tadpole community structure, like plant communities, were influenced by both broad-scale and site level data (Figure 7-17 and Figure 7-18). Macroinvertebrate assemblages were associated with sediment physico-chemical properties (pH and electrical conductivity), precipitation and dissolved oxygen in the water (Table 7-14). Tadpole communities were poorly correlated to the abiotic variables used, including surface water data (Table 7-14). In contrast to plant communities, aquatic fauna were not correlated with nutrients in surface or sub-surface waters (Table 7-14).

Table 7-13 Number of sites where tadpole species were recorded and the total number of individuals identified. "?" indicates that the species identification was made based on timing of breeding and distribution rather than morphological features. * denote South African endemics and ** southern African endemics, listed by the IUCN SSC Amphibian Specialist Group (2013).

Family	Species	No. depressions	No. wetland flats	Total no. individuals
Bufonidae	*Amietophrynus ?rangeri**	1	1	13
	*Amietophrynus pardalis**	1	0	109
Hyperoliidae	*Hyperolius marmoratus***	4	1	49
	*Semnodactylus wealii**	2	0	7
Pipidae	*Xenopus laevis*	8	2	808
Pyxicephalidae	*Cacosternum ?nanum**	5	2	256
	*Cacosternum boettgeri***	6	1	30
	*Strongylopus fasciatus***	1	1	3
	*Strongylopus grayii**	0	2	133
	*Tomopterna delalandii**	4	4	107

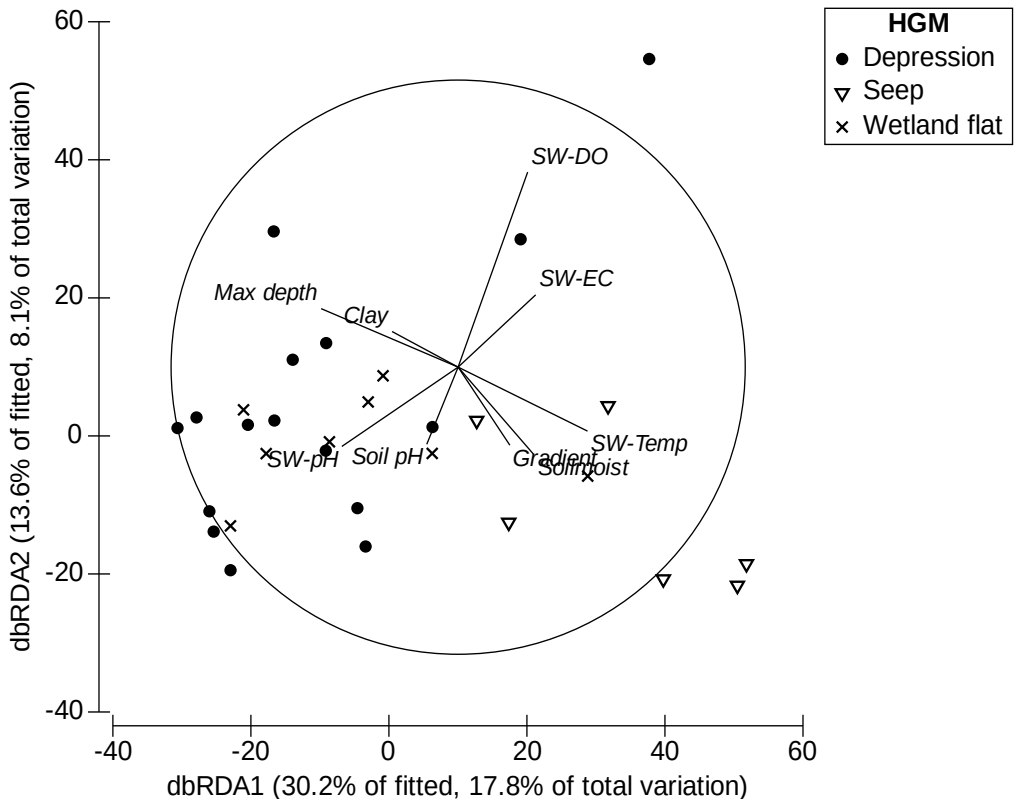

Figure 7-17 dbRDA with environmental variables affecting macroinvertebrate communities. Only variables with a correlation greater than 0.25 are displayed. See Table 5-2 for abbreviations.

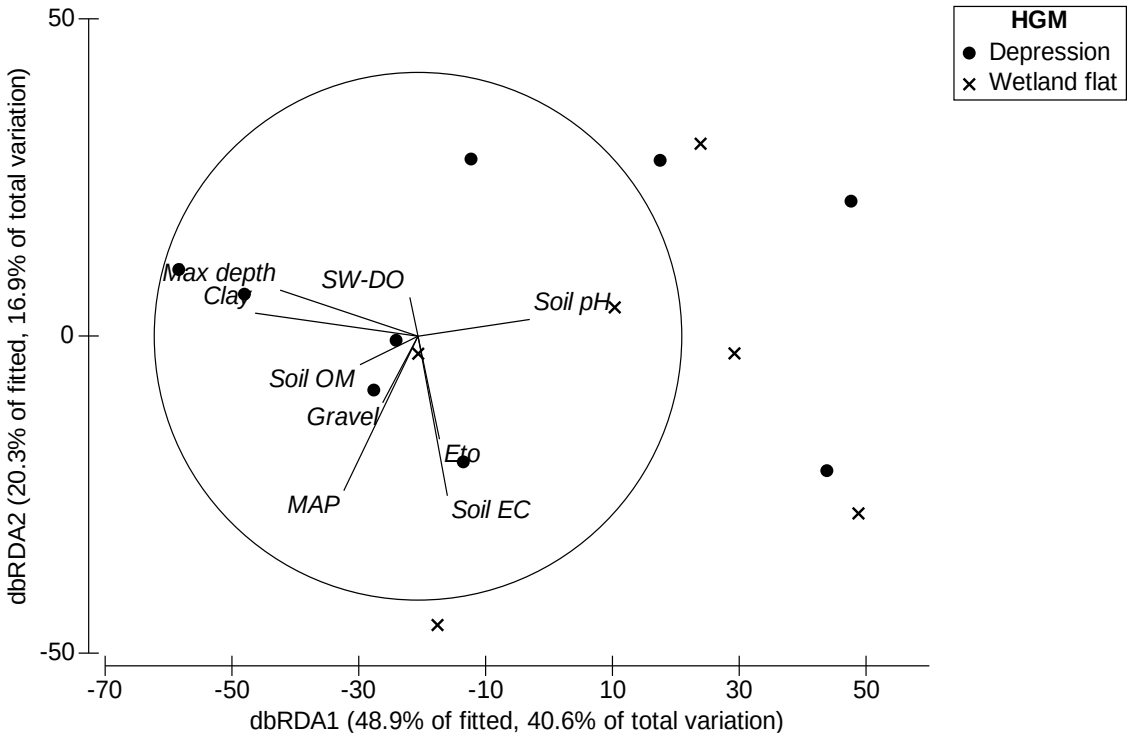

Figure 7-18 dbRDA with environmental variables affecting tadpole communities. Only variables with a correlation greater than 0.25 are displayed. See Table 5-2 for abbreviations.

Table 7-14 Key factors influencing macroinvertebrate and tadpole community structures. DO = dissolved oxygen, EC = electrical conductivity, ET = evapotranspiration, MAP = mean annual precipitation, SW = surface water.

	Variables	Factors correlating with community structure	No. of sites	Pearson's r Correlation
Invertebrates	Environmental variables without SW	MAP, Soil EC, Soil pH, Water depth	30	0.432
	Environmental variables with SW	MAP, Soil pH, Water depth, SW DO	30	0.484
Tadpoles	Environmental variables with and without SW	Annual heat units, Elevation, ET, Water depth	15	0.262

Summary of biotic characteristics

The key biotic findings of this study are highlighted in Table 7-15 below. A diversity of plant, macroinvertebrate and tadpole data were recorded and there were patterns in the community structure that could be evaluated at a HGM level better than at a broader scale.

Table 7-15 Summary of plant, macroinvertebrate and tadpole communities from field sites. CAP = Canonical Analysis of Principal Coordinates. See the Acronym list for environmental abbreviations.

	Plants	Macroinvertebrates	Tadpoles
Total number of taxa	90 families and 307 taxa	82 families and 144 taxa	4 families and 10 taxa. None found in seeps
Species diversity	Depressions had highest species richness and diversity (*H'*). Seeps were also diverse and there were no statistically significant differences between HGM types	Wetland flats scored highest for species richness, with diversity scores similar to depressions. Seeps scored the lowest overall. Significant differences between HGM types	Insufficient data
Red List	*C. campanulatum* (Vulnerable)	*S. dendyi* (Endangered) and *Paradiaptomus natalensis* (Vulnerable)	None
Key factors defining community structure	Broad-scale and site level abiotic factors: elevation, MAP, SW & soil EC, SW TDS, SW & SSW pH. Nutrients important in SW and SSW	Broad-scale and site level abiotic factors: MAP, water depth, soil EC & pH. Not nutrients or water physico-chemical variables	Mainly broad-scale factors: annual heat units, elevation, ET, water depth
CAP result for HGM (%)	61 (HGM best scoring)	70 (HGM best scoring)	Insufficient data

7.3.5. Evidence of ephemeral wetland formation: Grass Ridge, Hopewell and Uitenhage sites

In wetlands, the ecosystem functioning of a system is closely related to the environment in which the wetland developed. Abiotic and biotic characteristics of several ephemeral systems have been outlined. Below are some systems that have been highlighted to illustrate the diversity of wetlands that can be found within a relatively small geographical area, which could result in some of the variation in wetland characteristics observed in the NMBM.

Depressions were located on Grass Ridge Bontveld in Catchment M30B (Zone 7) (Figure 7-19). These depressions are orientated along several paleo-beach ridges associated with the Alexandria Formation. This formation is comprised of calcareous deposits (Appendix C) which could give rise to potential karst topography through the dissolution of carbonates. Evidence of sub-surface slumping can be observed at site PL1 that has a steep downward gradient (6.6°) from above the ridge to the base of the wetland (Figure 7-20).

Moreover, several depressions were also found on a bench hilltop in the Hopewell Conservation Estate (Zone 4) (Figure 7-21). The wetland sites were situated on the same geological and terrestrial vegetation zone and had similar hydrological characteristics. However, sediment particle size distribution varied from a large portion of gravel at one site (HW2), to a clay and silt dominated one at another site (HW1).

Depression site HW2, in the Hopewell area, had large ferricrete (iron) conglomerates along the south eastern edges of the wetland (Figure 7-21). Further indication of high iron levels was observed in the yellow-red tones of the soils and red mottles (Munsell Soil Colour Chart (1994) hues ranging from 10YR to 5R).

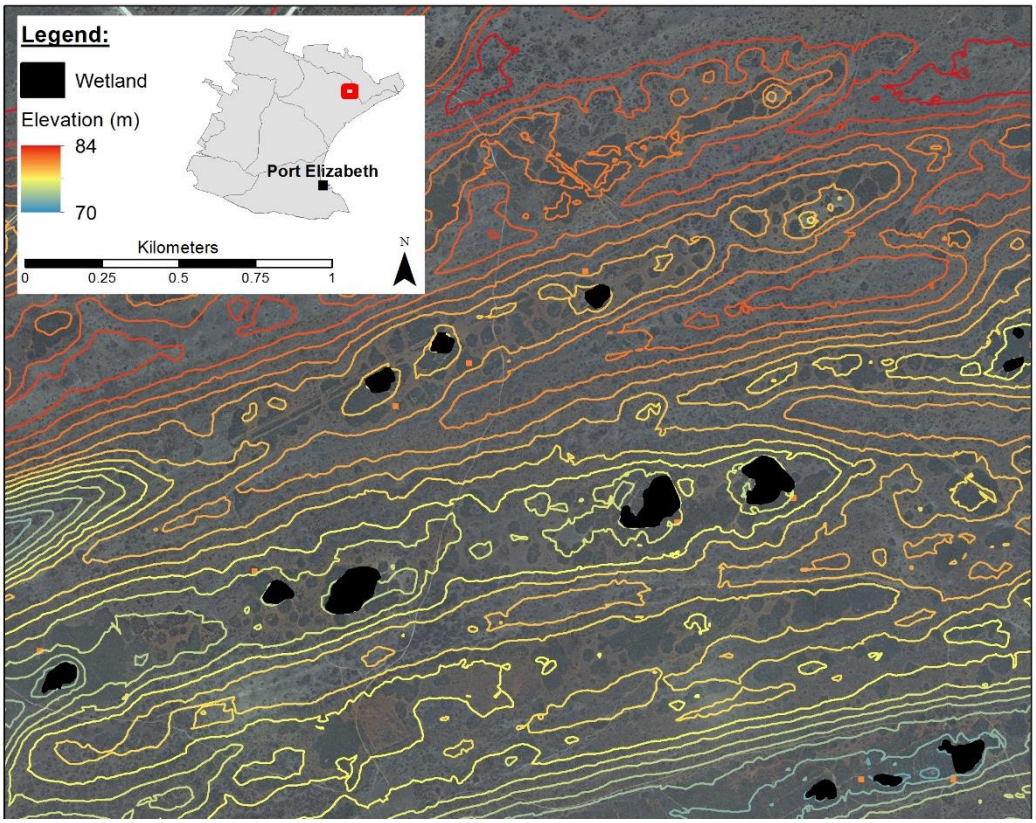

Figure 7-19 Depression lines along the Grass Ridge Bontveld (area highlighted in red on inset map). Contours at 1 m intervals (ranging from 70 m to 84 m as per the legend colours). Note: the depressions (in black) lie in parallel belts to each other corresponding with the palaeo-beach ridges.

The importance of slope for wetland systems can be observed in three hydrologically connected seeps in Zone 8 (see Plate 7-1). A summary of the key characteristics of this connected seep is in Table 7-16. The edge of the wetland is situated on a steep slope that becomes more gradual towards the base of the seep. The source of water is from groundwater that surfaces as a spring with a surface and sub-surface water EC value of more

than double at the base of the system (Table 7-16). There were other physico-chemical changes in the water and soil physico-chemical parameters, but this could be attributed to the impact of grazing which was low on the hillslope and higher at the base of the seep system.

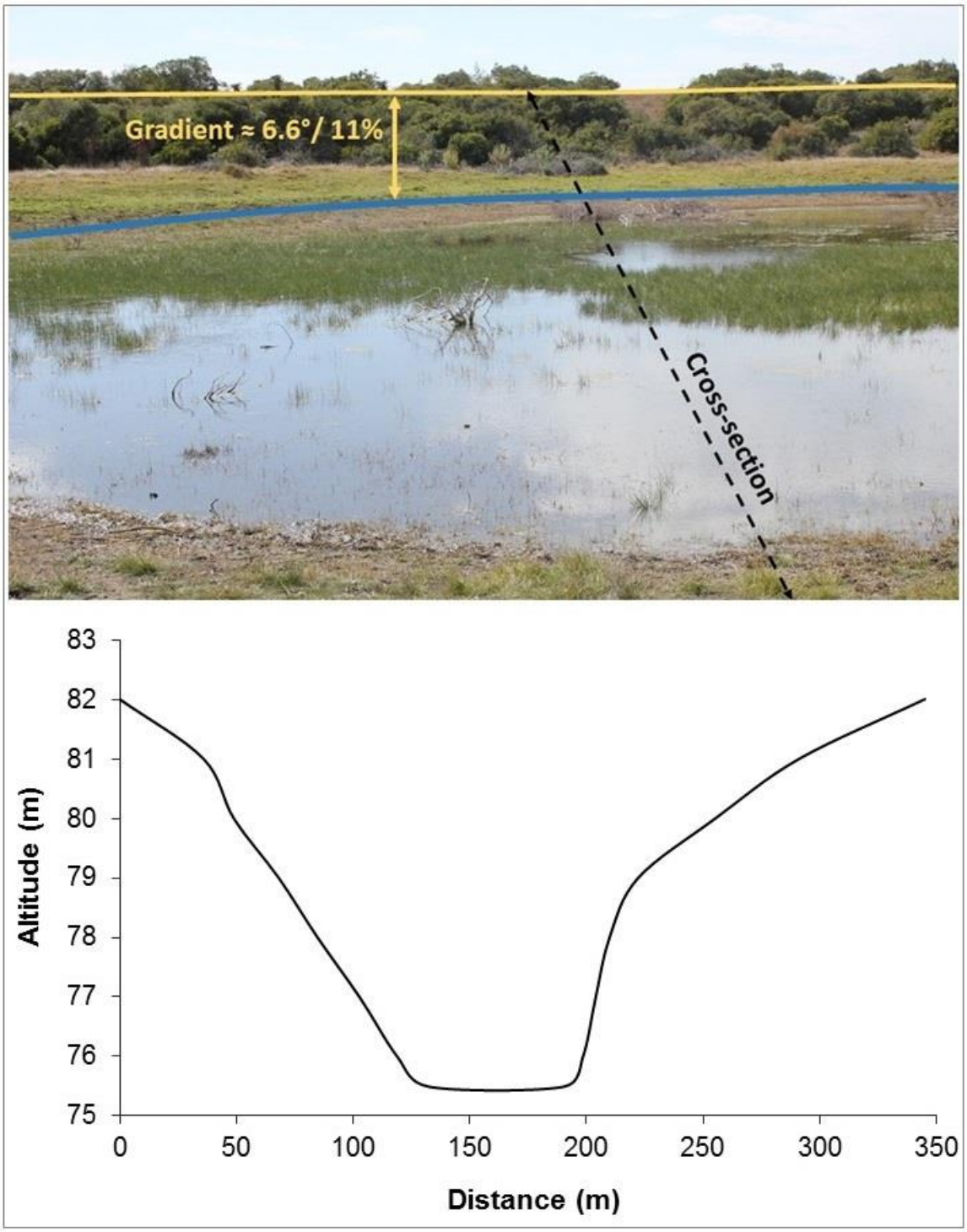

Figure 7-20 A cross section (below) of a wetland depression (above) on the Grass Ridge Bontveld (site PL1), in Zone 7 (Figure 4-1). Blue line indicates the altitude at the base of the wetland at ~ 76 m and the yellow line is the top of the depression at ~ 82 m. Slope gradient is given both as degrees and a percentage. Maximum depth is estimated to be approximately 2 m.

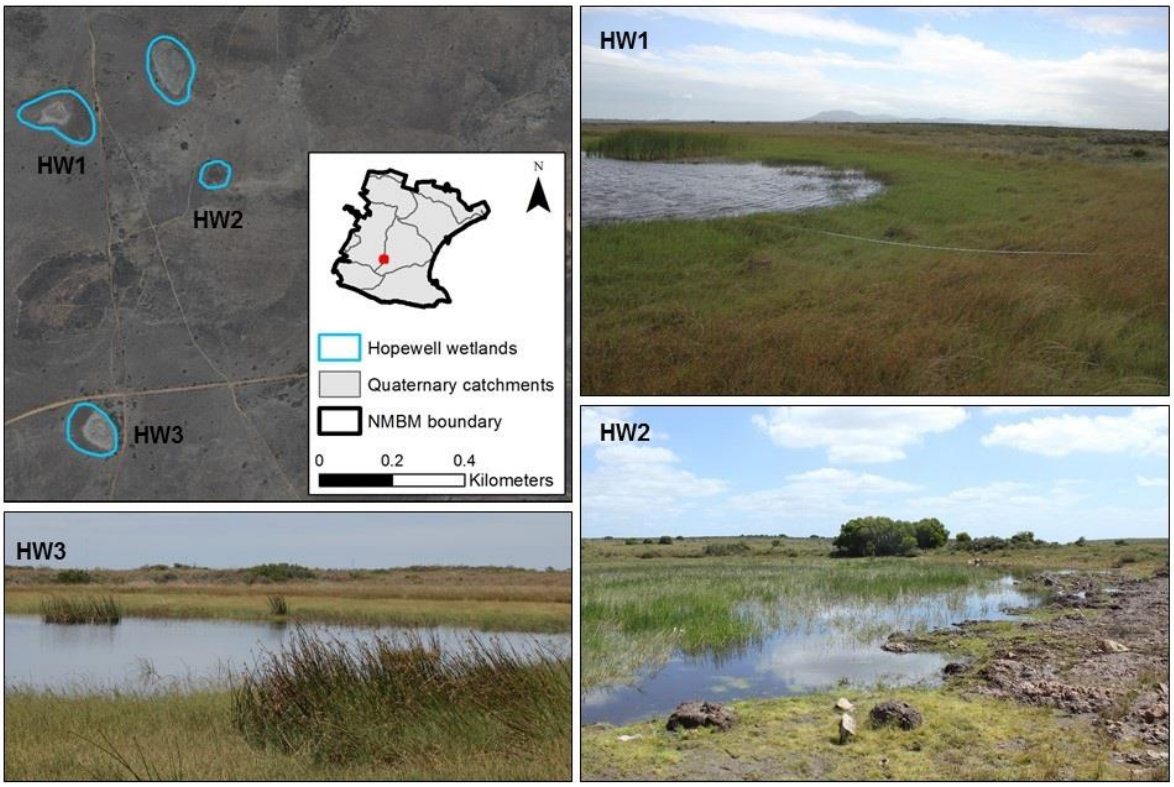

Figure 7-21 Four depressions located at Hopewell (Zone 4, highlighted in red on inset map). A picture of each of the three field sites, when inundated, is also illustrated.

Table 7-16 Summary of the key features for three connected seeps (R75-4A-C) located in Zone 8. SSW = sub-surface water, EC = electrical conductivity, spp. = species, ppt = precipitation.

Feature	R75-4A (top)	R75-4B (middle)	R75-4C (base)
Gradient	Steep (11.3°)	Moderate (8.8°)	Gentle (3.7°)
SW EC value (µS/cm)	1057	627	615
SSW EC value (µS/cm)	1799	707	405
Dominant plant spp.	*Pteridium communalis, Persicaria serrulata*	*Cyperus thunbergii, Pteridium communalis*	*Cynodon dactylon, Schoenoplectus decipiens, Pycreus nitidus*
Water source	Groundwater through fractures	Groundwater (from slope) & possibly precipitation	Seepage from upslope
Perch	Bedrock (TMG)	Clay & bedrock	Clay & bedrock
Type of flow	Interflow	Diffuse unidirectional flow & interflow	Diffuse unidirectional flow and overland inflow
Level of disturbance by humans or animals	Low	Medium	High

Plant communities appear to relate to differences in slope gradient. *Pteridium communalis* and *Persicaria serrulata* were dominant at the top of the seep, and *Cyperus thunbergii* and *P. communalis* at the base of the slope (middle of seep). An increase in plant diversity was observed at the base of the seep, and the plant community was predominantly comprised of grasses (*Cynodon dactylon, Paspalum* sp. and *Eragrostis* sp.) and sedges (*Schoenoplectus decipiens* and *Pycreus nitidus*).

Changes in HGM type along a slope also affected the biological structure in several other systems with two different HGM types. Two examples are highlighted in Table 7-17, and pictures have been illustrated in Plate 7-1. Both of the systems consisted of a depression with a connected seep, either above (Res-A) or below (PV3-B). The depressions were deeper than the seeps in both locations (Table 7-17). The Campus Reserve depression was more diverse across all indices for both plants and macroinvertebrates (Table 7-17). The depression had more aquatic plant species and macro-algae, including filamentous forms, compared to the seep which had more wetland-associated plants (Table 7-17). The seep was also generally comprised of macroinvertebrates in the early stages of their life cycle while the depression had a wider variety of species at different stages of their life cycle (Table 7-17). A similar pattern was observed in Parson's Vlei, with the higher plant diversity being associated with the depression. The plant species in the depression were also generally aquatic, comprised mainly of grasses and sedges. Although the seep below the depression was dry, species associated with freshwater habitats were also identified. These systems are discussed in Section 8.1.3.

Table 7-17 Summary of the key biotic features of two systems, on the NMMU Campus Reserve (Res-A and B) and in Parson's Vlei (PV3A and B), that are comprised of two HGM types that are hydrologically connected to each other. See Plate 7-1 for pictures of the sites. Macroinvertebrates were not compared for PV as no sample was taken at the dry wetland (PV3B). Sp. = species (singular), spp. = species (plural).

Wetland name	Res-A	Res-B	PV3A	PV3B
Relative position	Upslope system	Downslope system	Upslope system	Downslope system
HGM type	Seep	Depression	Depression	Seep
Maximum water depth (cm)	8	14	14	N/A (no saturation or inundation)
Dominant flora	Low lying wetland-associated plants (*Falkia repens* & *Cynodon dactylon*) & algae (*Chara* sp.)	Chlorophytes & *Chara* sp. Freshwater sedges (*Schoenoplectus decipiens, Ficinia capillifolia & Cyperus congestus*) & *Typha capensis*	Mainly aquatic & semi-aquatic grasses (*Pennisetum* spp.) & sedges (*Epischoenus gracilis, Schoenoplectus* spp. & *Isolepis striata*). Some terrestrial grasses (*Themeda sp*.)	Mainly aquatic & semi-aquatic restios (*Elegia ebracteata*) and sedges (*E. gracilis*). Some terrestrial shrubs (*Leucospermum* sp.)
Floral biodiversity				
No. of spp.	27	29	52	30
Spp. richness	6.02	6.47	11.9	6.9
Diversity (*H'*)	1.91	1.74	2.8	2.3
Dominant invertebrates	Mainly Chironomid larvae (*Chironomus* sp. & *Tanytarsus* sp.)	More diverse with Odonates (Coenagrionidae & Libellulidae), Hemiptera (Corixidae) & Coleoptera (Dytiscidae)		
Faunal biodiversity				
No. of spp (*S*)	9	21		
Spp. richness (*R*)	3.1	5		
Diversity (*H'*)	2.1	2.9		

7.4. DISCUSSION

This chapter illustrates the links between abiotic conditions at a catchment scale and fine-scale wetland site data. Despite the large variability in conditions in which data were collected, structural and functional patterns were observed at a HGM level. Only depressions, seeps and wetland flats are described in detail as conclusions could be based on field studies, whereas results on the other three HGMs could only be based on desktop observations.

7.4.1. The success of wetland indicators in identifying ephemeral systems in the NMBM

Individually, several of the indicators could be used to identify a wetland. This illustrates the importance of a hydrogeomorphic approach to wetland characterisation, which has been well covered in wetland classification literature (e.g. Semeniuk and Semeniuk 1995, Smith *et al.* 1995, Noble *et al.* 2002, Job 2009, Day *et al.* 2010, Ollis *et al.* 2015), especially in ephemeral systems where one or more indicators might be absent at a particular point in time.

There was sufficient wetland vegetation at inundated sites for them to be classified as wetlands, where approximately 50% of the 307 plant taxa were obligate or facultative. However, at dry sites (no surface water or soil saturation present) more than 50% of the plants were terrestrial.

Eight of the field sites had no soil wetland indicators. Most of these sites were associated with aeolian deposits in the south-east of the study area where soils are classified as free-draining at a broader scale (although at a local level there was often evidence of perched systems (see Section 7.4.3). Sites that had only two indicators (water and topography) were unvegetated coastal dune depressions, or wetland flats situated on aeolian deposits. Low chroma soils were identified less frequently in this study than what would be expected in wetland soils (Van Huyssteen *et al.* 1997), illustrating the ephemeral nature and the relatively short inundation periods and soil saturation only occurring for a few months during the rainy season (Van Huyssteen *et al.* 1997).

Red, yellow and black mottles indicated the presence of iron and manganese in the soils; consequently, these soils also show reducing conditions indicative of ephemeral systems (Soil Classification Working Group 1991, Kotze *et al.* 1994). This study showed that the mean soil organic matter of 3.36% was recorded in the NMBM wetlands (Figure 5.9) was double the SA average (where 96% of soils have less than 2% organic matter) (Du Preez *et al.* 2011). Although the percentage is lower than many other mineral and organic (wetland) soils which

have more than 12% organic matter (Environmental Laboratory 1987, Brady and Weil 1999, Job 2009), in the context of semi-arid areas in SA, the percentage recorded was significant compared to the SA mean soil organic matter content. The presence of organic matter in the soil has implications for the plant communities in and around the wetland by providing essential nutrients as well as increasing the water-holding capacity of the soils (White 1979). This is also critical in the solubilisation of minerals and biogeochemical cycling post inundation after an extended dry period and increases the ecological resilience of the system as nutrients and water are made available for longer periods of time (Mitsch and Gosselink 2007, Reddy and DeLaune 2008).

7.4.2. General environmental characteristics driving wetland occurrence

The NMBM has highly variable rainfall patterns that vary across different seasons and years. A number of wetlands that were fully inundated in 2012, were dry in 2013. Results indicate that rainfall is important for the occurrence of seeps and wetland flats, and to a lesser extent, depressions (Table 7-3). Consequently, this variability has resulted in distinct distribution and structural patterns in these wetland systems and has contributed to the formation of intermittent ephemeral systems, rather than seasonal ones, which is likely to be evident in other semi-arid areas with non-seasonal rainfall. This increases the difficulty in identifying wetland structure and function at a particular time and the abiotic and biotic characteristics of these systems can provide baseline information that can be used to detect systems in during dry periods/seasons.

Fundamental geomorphic principles can be used to explain wetland occurrence in the NMBM. It was observed that a number of wetlands were generally associated with cooler south-facing slopes; although, this was not statistically significant (p-value = 0.164) (see Section 7.3.1, page120). This would result in lower levels of radiation and, consequently, higher levels of soil moisture (Higgins *et al.* 1997, Petersen *et al.* 2010, Goudie 2013). Some of the variance in the biotical structure is also attributed to landscape components (such as evapotranspiration rates and solar radiation), and is explained further in this section.

Surface water run-off also plays an important role in wetland occurrence (Mitsch and Gosselink 2007). As observed, higher flow accumulation values were associated with wetland versus non-wetland sites ($p < 0.0005$) (see Section 7.3.1, page120). Although this does not take into account catchment-related activities (and the subsequent impact it has on surface water), it does further illustrate the role of surface water, and sub-surface water (as through-flow), on wetland hydrology in this region.

From this study the onset of inundation, in precipitation-fed systems, is facilitated by a series of rainfall events where water becomes increasingly available in the sub-surface soil horizons (Leibowitz and Nadeau 2003, Euliss *et al.* 2004). As the local water table is raised, the rate of infiltration slows down, eventually reversing the direction of flow and allowing the wetland to inundate (Rosenberry and Winter 1997, Zedler 2003, Euliss *et al.* 2004). Precipitation is known to drive many ephemeral systems in semi-arid areas such as vernal pools, Carolina Bays and some prairie potholes in the USA, gilgais in Australia, and endorheic pans in SA (Allan *et al.* 1995, Roshier *et al.* 2001, Leibowitz and Vining 2003, Winter and LaBaugh 2003, Zedler 2003).

The combination of wetland morphology, hydrology, soil physico-chemical properties and the surrounding landscape creates a platform for various plant and macroinvertebrate communities (Cook and Hauer 2007, Ralph *et al.* 2012, Kobayashi *et al.* 2015). The biotic structure of the wetland is, in turn, indicative of its function within the landscape (Higgins *et al.* 1997, Mitsch and Gosselink 2007). Although, variables measured at both a local and catchment scale were important in defining community structure, the canonical analysis of principal coordinates (CAP) scores indicated that both vegetation and macroinvertebrates were better characterised by their HGM unit than by their position in the landscape (Level 3 of the CS) or broad-scale environmental features. This illustrates that a specific set of processes occurring within a wetland is determining the structure of plant and macroinvertebrate communities. Similar findings are found throughout the literature, with many studies emphasising the importance of a combination of drivers that explain the observed community structure (Drinkard *et al.* 2011, Corry 2012, Sim *et al.* 2013, Raney *et al.* 2014). With this variability in mind, an attempt has been made to distinguish the main components that characterise each wetland HGM type. These are described in Sections 7.4.4 to Section 7.4.6.

7.4.3. Perched wetland systems

A number of field sites in the study area were associated with moderately deep to deep, well-drained soils. This could be a result of mis-classification due to the coarse resolution of the national dataset, or could be indicative of other environmental processes occurring. If drainage is facilitated by the sediment, then another ‘barrier’ (impermeable layer) is needed to allow water to collect to promote wetland development. These barriers can be in the form of shallow bedrock, calcrete and other precipitates that harden and are resistant to dissolution, erosion and percolation of water (Shaw 1988, Rains *et al.* 2006, Goudie 2013). As a result, a perched water table is formed above this barrier (Figure 7-22) (Zedler 2003,

Rains *et al.* 2006). Perched wetland systems were recorded across the different geological and vegetation types within the NMBM.

The prevalence of perched systems across HGM types and geographical zones indicates that in an environment such as the NMBM, where evapotranspiration is greater than precipitation, an impermeable sub-surface lenses might be a key foundation to the development of a wetland system, regardless of HGM type. A diagram depicting the conceptual relationship is illustrated in Figure 7-22. These perched systems can also function independently from the regional groundwater table, which is not thought to be a major factor in driving inundation patterns in ephemeral depressions, seeps and wetland flats of the NMBM. The wetland fills as the impermeable layer intercepts the rainfall (and the resultant percolation of water), allowing water to pool above it (Pyke 2004).

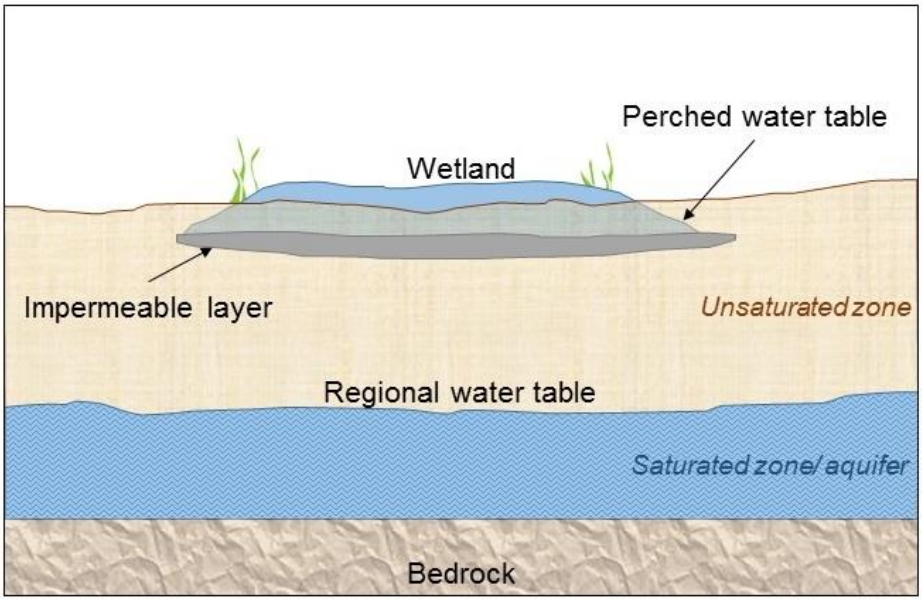

Figure 7-22 Hypothetical diagram of the effects of an impermeable layer of rock below the surface, creating a perched water table on which a wetland can form, which is thought to be a key process for wetland formation in the NMBM.

7.4.4. Depression wetlands

Depressions were the most common HGM type identified in the NMBM, and they were found in a wide range of landscape settings than seeps and wetland flats (see Table 7-3). They were prolific in the drier northern parts of the study area whereas seeps and wetland flats were more common in the southern parts of the Municipality, which receives more rainfall.

Therefore, in the NMBM, the prevalence of depressions might be due to other factors besides rainfall which are outlined below.

The depression systems in the NMBM are isolated from other surface waters, with no apparent link to channelled hydrologic systems. Geographically isolated depressions have different names and various drivers of inundation around the world. Drivers include: snowmelt (prairie potholes and tarns in the Midwest of the USA and New Zealand), rainfall and surface runoff (playas and vernal pools in south-west USA), and groundwater (turloughs in the karst region of Ireland) (Johnson and Rogers 2003, Tiner 2003b, Zedler 2003, Mitsch and Gosselink 2007, Bartuszevige *et al.* 2012). Rainfall did not explain the distribution of depressions within the NMBM. For example, more depressions were found in the north-east of the study area (Catchment M30B) that only receives approximately 430 mm of rainfall, compared to the south-east which receives approximately 660 mm per annum. The lack of available surface water (precipitation) in these much drier areas (MAP of 400 - 500 mm) suggests that there also might be a link to sub-surface water (through-flow) in order to sustain these systems in the area. Systems that are possibly driven by through-flow include those in Catchments 30B and 10C (Figure 4-1). This link to sub-surface water would also aid in lengthening the hydroperiods of these systems (De Steven and Toner 2004).

Section 7.3.5 describes several depression systems that illustrate the range of environmental settings that these systems are associated with. These findings are elaborated on further in this section. Various processes are known to result in depression formation. Besides some of the key processes that are most likely at play in the NMBM, depressions in the study area could have also have developed through stochastic processes such as aeolian deflation, salt weathering and animal trampling (Goudie and Wells 1995, Goudie 2013).

Figure 7-19 illustrates a series of depressions in Zone 7. This area consists of paleo-beach ridges associated with the Alexandria Formation that is superseded by the more recent Bluewater Bay Formation (Illenberger and Burkinshaw 2008). Another series of ridges is found between the Swartkops and Coega rivers (Illenberger and Burkinshaw 2008). However, most of this latter area is now part of the Motherwell development, which has obscured the topography. Thus, it is highly likely that, based on the model and knowledge of the area, that wetlands have been lost in this area due to development.

These relict dunes of the Grass Ridge area have high levels of calcium carbonate (Illenberger and Burkinshaw 2008), which is associated with karst formations. Various other types of karst formations, including depression systems known as dolines, uvalas and poljes have been recorded to the north of the NMBM (Marker 1988, Lubke and De Moor 1998). Dolines are the

smallest of these features and are most likely similar to what has been observed at Grass Ridge. An example of one of the systems is illustrated in Figure 7-20. The steep embankments on either side of the basin indicate that sub-surface slumping has occurred. The calcium carbonate (associated with the Alexandria Formation) dissolves, resulting in the collapse of the superseding geology (Bluewater Bay Formation). The slightly alkaline conditions measured in the soils and water at these sites also indicates the presence of such carbonates. This substrate would also facilitate through-flow, thus maintaining soil moisture for longer periods of time compared to other HGM types.

Turloughs, in Ireland, are distinctly groundwater driven (Sheehy-Skeffington *et al.* 2006, Mitsch and Gosselink 2007). Geological data (Council for Geosciences N.D.) for the NMBM indicates a potential groundwater yield of 0.1 – 0.5 $L.s^{-1}$ that flows through fractured rock, which would limit groundwater input to the system. However, soil characteristics indicate the presence of a perched water table beneath the three field sites in the Grass Ridge area. Soil cores were mainly comprised of fine-grained sediment (fine silt to clay sized particles). Bedrock, or an impenetrable clay layer, was reached within 20 cm to 60 cm of the soil surface. This shallow depth to an impermeable layer would facilitate the development of a perched water table and allow through-flow of sub-surface water. The perched layer and the topography combined would increase the period of saturation and inundation, allowing a wetland to form.

Several coastal interdune depressions were identified and data were collected at three sites, one in Summerstrand (Zone 1) and two in Coega (Zone 7). These systems were shaped by aeolian processes similar to that observed by Tiner (2003b). High electrical conductivity (EC) values in the soils and surface and sub-surface waters indicates that there is seawater intrusion, a phenomenon described by Winter and LaBaugh (2003). Two interdune depressions, in Zone 1, correspond with the relic headland bypass dune system, and thus, were also shaped by aeolian processes. The high EC values have excluded many taxa and as a result, diversity indices for these systems were low. The low plant and invertebrate diversity indices were also recorded for an inland salt pan (Zone 8), with similarly high EC values.

Another depression of interest was in Hopewell (Zone 4 – Figure 4-1) which had large ferricrete formations around the edge of the wetland (Figure 7-21 and Plate 7-3). X-Ray diffraction analysis confirmed the presence of haematites and ferrihydrites. Ferricrete formation is associated with the precipitation and accumulation of iron compounds (Goudie 2013). Thus, the development of this compound requires alternating dry and wet periods (Wirt *et al.* 2007, Goudie 2013). During inundation the iron reduces and dissolves out of the soil.

When it reaches the unsaturated soils (along the outer edges of the wetland) the iron oxidises, and precipitates out, forming an iron cemented conglomerate (Wirt *et al.* 2007). This would result in the morphology of this wetland.

Plate 7-3 Ferricrete outcrops along the edges of a depression (in the foreground) at Hopewell Conservation Estate.

Gilgais are well-known features in semi-arid and temperate areas such as New South Wales (Australia), south-western Poland, India and the Texas Gulf Coast (USA) (Hallsworth *et al.* 1955, Kishné *et al.* 2009, Pal *et al.* 2012, Kabala *et al.* 2015). These systems have been classified as depressions, but could also be a wetland flats, if the wetland is nearly level. These gilgai formations are a result of the wetting and drying of clay which causes cracking and sinking in some areas (the depressions) and mounds in between these areas (Fey 2010, Goudie 2013). As with ferricrete formation, gilgai require alternating wet and dry periods for these depressions to form, as well as the presence of swelling clays, such as montmorillonite or smectite (Kishné *et al.* 2009, Fey 2010, Goudie 2013). Several wetlands in the north western part of the Municipality (Zone 8 – Figure 4-1) meet some of the criteria for the formation of these micro-reliefs, including a gentle slope, a minimum of 30% clay and the presence of montmorillonite (which was confirmed through XrD analysis). However, full soil profiles have not been done and, therefore, it is difficult to determine whether vertisols are present (another criterion). These systems are also more dispersed compared to those observed in the NMBM — approximately seven wetlands within a 4 km radius. Therefore, it is unlikely that these systems are typical gilgai micro-relief structures, although similar processes could be occurring.

Community patterns

Depressions in the NMBM have formed through various processes, are structurally diverse, and have different hydrological drivers. Some of this variability is expounded on later in this chapter. Although some of the depressions could be by their various abiotic processes, the same similarities did not apply to the plant communities. In general, there were more distinct zonation patterns in depressions to wetland flats and seeps. The open water zone was less diverse compared to the outer edges of the wetland in terms of plants and was dominated by obligate wetland plants such as sedges and aquatic grasses. All these species are able to withstand prolonged inundation periods, including anoxic environments.

The wetland boundary or waters edge had a greater number of species than the open water zone, all of which are able to tolerate a variety of soil saturation periods. The significance of water depth and soil moisture in the multivariate analysis (Figure 7-16, page 145) illustrates the importance of micro-topography and the constant environmental fluctuations that affect these saturation periods. These patterns are more pronounced in depressions due to steep soil moisture gradients that give rise to their concentric zonation patterns along the soil moisture gradient (Tiner 1993b, Seabloom *et al.* 2001). This environmental gradient has also provided a wider variety of biotypes which have resulted in the higher diversity indices in depressions than in wetland flats and seeps.

Plant community structures differed in wet and dry sites, which is characteristic of systems that are largely influenced by hydrology (Bledsoe and Shear 2000, Winter 2001, Euliss *et al.* 2004). However, both wet and dry sites had obligate or facultative wetland plants present. It is important to note that all the dry sites sampled were inundated in the previous year of sampling, and were probably dry for approximately six to nine months prior to sampling. Thus, the presence of certain obligate and facultative plants perhaps illustrates the ability of these plants to sustain themselves during dry periods (i.e. a lack of soil saturation). This knowledge should be applied when trying to identify wetlands after extensive dry periods.

The inundation phase at the time of sampling had a relatively small effect on the plant communities in comparison to average inundation duration for the HGM type. The longer inundation periods observed in depressions (compared to the other two HGMs) did, however, affect the species found in the wetland. Todd *et al.* (2010) found that certain plant communities (such as red mangrove scrub and pine savanna), in the Everglades, were more specific in their habitat selection with regard to inundation period and water depth than others (e.g. *Cladium jamaicense* (sawgrass)) which were tolerant of a wider range in environmental conditions. However, species abundance, diversity and distribution patterns are also a result

of numerous feedback systems that occur within transitional plant communities (such as wetlands) that are also dependent on the direction of change (adapting from dry to wet or vice versa) (Seabloom *et al.* 2001, Mitsch and Gosselink 2007). These dynamics are well described in literature pertaining to ecological resilience, stable states and succession theories (Gunderson 2000, Beisner *et al.* 2003, Stringham *et al.* 2003).

The sediment characteristics and presence of water (in the soil or at the surface) are correlated better to the plant community structure compared to nutrients in the surface water. This is likely due to wetland sediments being a nutrient "sink" which results in a re-cycling of these nutrients within the system, while nutrients in the water are taken up by plants first (Euliss *et al.* 2004). Other studies have also indicated a similar poor relationship between plant species and nutrient availability, due to the confounding effect of the hydrologic regime and morphology of the wetland (Pollock *et al.* 1998, Bedford 1999). In addition, various authors have also shown that sediment properties can be used to predict and explain the presence and abundance of various plant species within a wetland (Lougheed *et al.* 2001, Pulido *et al.* 2012, Angiolini *et al.* 2013). The lack of statistical significance of these variables could indicate that nutrient analysis also needs to be conducted on the soil, the latter of which has the ability to store significantly more nutrients and indicate more long-term nutrient patterns, which still play an role in the plant and macroinvertebrate community structure (Whigham and Jordan 2003, Mitsch and Gosselink 2007).

The broad scale (climate variables) and the local site (soils, inundation phase, wetland size etc.) characteristics still do not adequately define plant communities (variables only account for 23% of the variation). Difficulty in defining clear patterns have also been observed in other wetland studies (Kirkman *et al.* 2000, Bullock and Acreman 2003, De Steven and Toner 2004). This further illustrates the diversity and complexity of these systems that interact at a range of spatial and temporal scales (De Steven and Toner 2004, Euliss *et al.* 2004, Angeler and Alvarez-Cobelas 2005). Thus, the wetland continuum concept by Euliss *et al.* (2004) is a useful tool for explaining why this variability was observed. The continuum concept is further discussed in Chapter 8.

Macroinvertebrates strongly correlated with soil characteristics, water depth and the amount of oxygen in the water. The high diversity and numbers of macroinvertebrates in depressions can be linked to habitat diversity (distinct marginal and open water zones) (Batzer and Wissinger 1996). However, the slightly lower diversity compared to wetland flats could be due to the exposed open water zone which provides less cover for macroinvertebrate species (Batzer and Wissinger 1996, Hornung and Foote 2006). Consequently, more species were identified in the marginal vegetated zone. The greater number of invertebrate predators found

in the depressions would also increase in predation and competition among species thereby reducing diversity scores (Semlitsch and Bodie 1998). The various physico-chemical properties of the soil and water as well as the diversity and distribution of the vegetation provide unique habitats for macroinvertebrate and tadpole communities at both spatial and temporal scales (Batzer and Wissinger 1996, Ferreira *et al.* 2012).

7.4.5. Seeps

The majority of seeps were formed on areas with more resistant underlying geology, such as quartzitic sandstone. Fractures in the rock would be key in allowing groundwater to enter the wetland as a spring or as interflow (Tiner 2003b, Lin *et al.* 2014). The seeps in the NMBM were associated with a relatively high groundwater potential (which would allow water to seep through fractures in the underlying rock) and along with shallow soils, may facilitate a shallow water table or an area for soil saturation to occur (De Steven and Toner 2004). Sub-surface water sources may also be perched aquifers. As a result, these seeps can be characteristically defined by the sub-surface water inputs and throughputs as indicated in Ollis *et al.* (2013). Although seeps were the shallowest in terms of water depth, their longer inundation times, compared to wetland flats, is most probably due to this groundwater or sub-surface water input. These hydrological patterns were observed in three connected seeps (discussed below). The prevalence of seeps in the wetter portions of the study area and their occurrence on south and easterly facing slopes does, however, indicate the importance of the indirect surface water inputs (through overland flow or interflow) to these HGM types.

There were several hydrological drivers that influenced plant and macroinvertebrate community structure on seeps. Wetland plant categories were more similar in both wet and dry seeps compared to wet and dry systems in the other two HGM types. These seeps had a relatively high proportion of obligate wetland plant species present at both inundated and dry sites. This was related to sustained periods of soil saturation from sub-surface water input. Like wetland flats, seeps were shallow and had no open water zone. This would have a large impact on the communities, reducing the proportion of aquatic species for both plants and macroinvertebrates. In depressions vegetation zones were concentric, primarily associated with a soil moisture gradient, with an open water zone towards the centre (as observed by Tiner 1993b, Seabloom *et al.* 2001, De Steven and Toner 2004). In seeps, these plant community shifts are primarily associated with changes in gradient down the slope. Thus, gradient, soil moisture and water depth drive plant community patterns in seeps. However, the shallow water and short inundation lengths have limited the development of aquatic macroinvertebrate and tadpole species, possibly resulting in the low species richness and total macroinvertebrate numbers recorded, which has been observed by Batzer and

Wissinger (1996) and Tarr *et al.* (2005). The absence of tadpoles is also due to the shallow water depth as most frogs lay their eggs in the water or on leaves in direct contact with water (Du Preez *et al.* 2009). *Strongylopus* spp. is the only genus of tadpole observed in the NMBM that lays eggs in moist soil conditions (Du Preez *et al.* 2009). Although these were not recorded at any of the sites, it is possible that species in this genus, and other similar species, could be recorded in seep systems.

An example of how slope, hydrological factors and disturbance can influence plant communities can be observed in a series of three seeps in Zone 8 (Plate 7-1, 130). The boundaries of each of the plant communities were observed with differences in slope gradient. However, these plant communities are also driven by hydrological factors. The high EC values and low pH values of the water samples measured in this area would indicate that this water is associated with (uncharacteristic) water quality of the TMG aquifer in the region, which surfaces as springs in the area (Lomberg *et al.* 1996, Maclear 2001). The water then flows above and below the soil surface as interflow before it reaches a clay layer at the base of the slope (as observed in soil cores). This would slow down the rate of infiltration and percolation of the water and would result in water pooling at the base of the slope. The perched water could also be fed by rainfall (when it occurs). Cattle grazing and trampling also had a large observable impact on the vegetation cover from the middle to the base of the seep. The base of the seep was the most disturbed and Gunderson (2000) and Corry (2012) suggest that this may significantly affect the species diversity and lower plant heights.

7.4.6. Wetland flats

Recent alluvial and fluvial deposits, as well as the sandstone formations, were associated with a large number of wetland flats. Although sandstone can be resistant to erosion, cracks or weak points in the geology would create a suitable area for water to collect, and the chemical and physical erosion to occur, eventually forming a shallow pool (Shaw 1988, Tooth and McCarthy 2007). In addition to the substrate, the horizontal stratigraphy of the quaternary deposits, and the prominence of wetland flats on shallow slope gradients, also facilitates the pooling of surface water (as opposed to surface run-off or overland flow). These ‘pools’ allow the water to remain at the surface for longer periods, creating an environment for wetland-associated plant, macroinvertebrate and tadpole communities to form (as observed by: Euliss *et al.* 2004, Cook and Hauer 2007).

The wetland flats in the south-eastern corner of the study area (Zone 1) are orientated along a south-west to north-east axis. This corresponds to the prevailing wind direction and the direction and topography of the relic bypass dunefield systems (which has now been

stabilised) (Illenberger 1986, Goschen and Schumann 2011). Therefore, wind has influenced both the landscape and wetland morphology in this region.

Many of the sampled wetlands were located on sandy soils (classified from field analysis) and classified moderately deep to deep soils (Agricultural Research Institute for Soil Climate and Water 2004). However, soil cores dug at each of the sites indicated that many of these field sites were located on a shallow impermeable layer. Hard rock was reached within 1 m of the surface at six sites. In Zone 1 (Figure 4-1) the bedrock was calcrete. This part of the study area is known to have calcrete lenses (Roux 2000) and it was also found at depression sites in this region. The calcretes are formed from the dissolving of calcium carbonate present in the sediment (mainly from shell fragments) which then precipitate out as calcrete (Goudie 2013). The presence of calcrete has also resulted in moderately alkaline soils and water compared to systems in other areas of the NMBM.

Observations in the field indicated that wetland flats in the study area were mostly precipitation driven, as per the CS by Ollis *et al.* (2013). As a result of limited groundwater input and a large surface area to volume ratio, these systems would have rapid inundation cycles (due to higher evapotranspiration rates). This was observed in the sampled sites. These abiotic conditions and hydrological drivers have played an important role in the current structure of wetland flats. This, in turn, has impacted the plant and macroinvertebrate community structure.

The inundated phase at the time of sampling had a relatively small effect on the plant community structure in comparison to general inundation periods associated with wetland flats. There was a stronger link between vegetation and the HGM type than vegetation and the landscape unit (Level 3 of the CS). Thus, along with inundation, the physical shape or structure of a wetland also influences the vegetation (such as slope gradient and abiotic conditions) (Tiner 1993b). In wetland flats, the less distinct ecological gradient within the wetland would, for example, result in a less defined soil moisture gradient (Tiner 1993b, Mitsch and Gosselink 2007). Wetland flats would have a less defined mosaic-like plant community structure than depressions which have more defined (concentric) vegetation zones along the slope gradient (Tiner 1993b, Seabloom *et al.* 2001). The lack of environmental gradient would result in more uniform conditions, possibly reducing the number of plant species.

In addition to wetland morphology, plant communities were also related to soil physico-chemical characteristics (EC, pH and OM). These conditions are what distinguished wetland

flats in the Municipality from other flat systems found elsewhere. As with depressions, morphology and abiotic characteristics have resulted in distinct plant communities.

Wetland flats scored high in the macroinvertebrate diversity indices. This reflected an emerging population as longer inundation periods are linked to an increase in predators which might decrease the abundance and diversity of organisms lower on the food chain (Semlitsch and Bodie 1998, O'Neill and Thorp 2014). The mosaic structure of the vegetation both within and on the periphery of the wetland also provides refuge for macroinvertebrates, which would result in an increase in abundance and diversity (Batzer and Wissinger 1996, Hornung and Foote 2006). Tadpoles were found in wetland flats, however, these numbers were limited. These lower numbers were due to the shallow water depth and subsequent short inundation periods associated with wetland flats (and seeps) which favour species with short developmental stages and metamorphosis times, as noted by Euliss *et al.* (2004).

The literature on the abiotic and biotic structures of isolated wetland flats around the world is limited (Whigham and Jordan 2003). Pocosins, and other organic and mineral soil flats, are wetland flats found on the south eastern coastline of USA (Mitsch and Gosselink 2007). Pocosins are nutrient poor with acidic soil that is usually peaty or sandy with shrubs and trees dominating (Rheinhardt *et al.* 2002, Mitsch and Gosselink 2007). Wetland flats found in the Municipality were structurally different. Both the soils and water were circum-neutral with similar, naturally low, nutrient values compared to the other wetland types in the region, with much lower levels of organic matter, and dominated by grasses and sedges. Both pocosins and wetland flats in the study area are precipitation driven, drying up annually through evapotranspiration, with little connectivity to regional or sub-surface flows (Rheinhardt *et al.* 2002, Whigham and Jordan 2003). However, pocosins are found in regions with a nett water surplus (Rheinhardt *et al.* 2002). These factors emphasise the structure of wetland flats found in the NMBM and the different components that facilitate wetland development.

7.4.7. Characteristics of a mosaic of wetlands: morphological and biological variation

The variability in abiotic characteristics at both site and catchment level (as well as the magnitude of their influence) explains why different plant, macroinvertebrate and tadpole communities can be observed in wetlands in close proximity to each other. For example, in Theescombe, a *Phragmites australis*, *Lemna gibba* and *Juncus rigidus* dominated wetland flat is approximately 200 m away from a bowl depression dominated by *Chara* sp. in the open water and *Schoenoplectus decipiens, Sporobolus africanum, Paspalum distichum* and *Carpobrotus mellei* along the wetland edge (Figure 7-23). Both sites were dominated by

invertebrate filter-feeders. However, the diversity and abundance of invertebrates in the depression were higher than in the phragmites-dominated wetland flat. Although data were not collected on the other surrounding HGM units (Figure 7-23), the close proximity of these morphologically diverse systems is noteworthy.

These systems in the Theescombe complex are unique in the study area as they appear to have a greater input from groundwater or sub-surface through-flow that maintains saturation in these systems for longer periods of time during dry periods compared to other systems that appear to be primarily driven by surface water. The seasonality of these systems (rather than more intermittent inundation periods) was also indicated by a gleyed matrix (Soil Classification Working Group 1991, Department of Water Affairs and Forestry 2005) towards the base of the soil cores at both sites.

This series of wetland systems illustrates the diversity of wetland types and plant, macroinvertebrate and tadpole communities that can exist in a small area, with similar hydrological inputs. Similar observations by De Steven and Toner (2004) have been made elsewhere, which emphasises the importance of a holistic approach to determine wetland structure and function, as well as the importance of studying systems within a landscape context to understand the connectivity among these systems. The importance of these types of systems in the study area is expounded on in the following chapter.

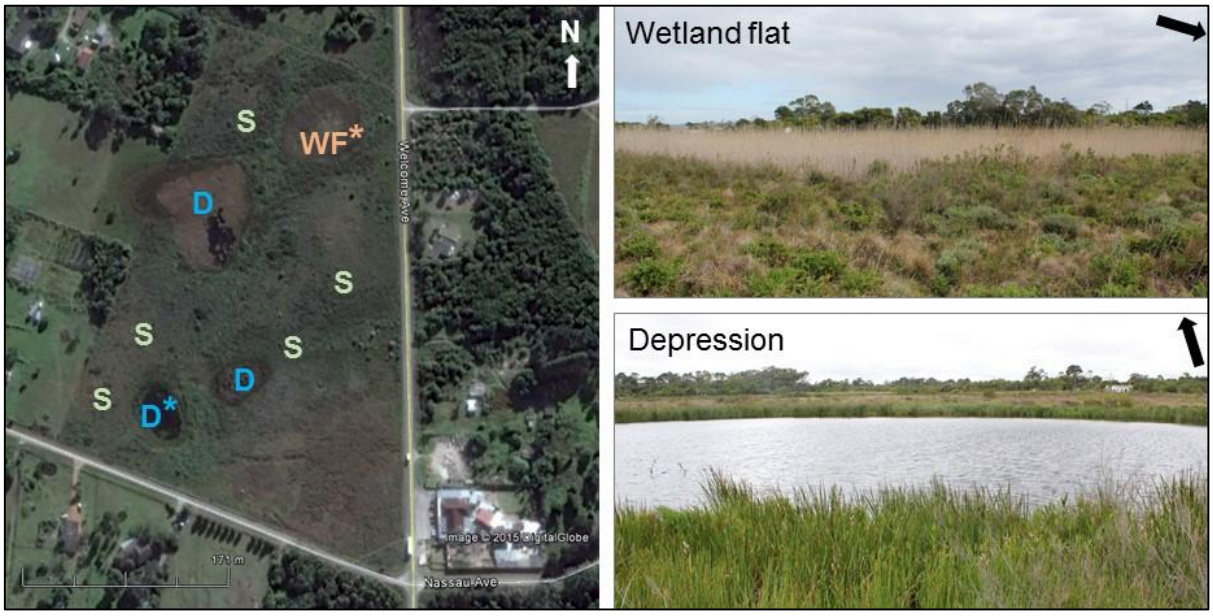

Figure 7-23 Wetland systems found in the Theescombe Wetland Conservation Area (Zone 2). D = depression, S = seep, WF = wetland flat. Black arrows indicate direction of north and * denotes field sites that are shown in the two pictures opposite. Slope drains towards the west (blue arrows).

7.5. CONCLUSIONS

This chapter has examined the abiotic characteristics and community patterns for depressions, seeps and wetland flats in the NMBM. The functioning of these systems that is described in this Chapter, was further highlighted using examples of sites visited during this study, illustrating some of the different processes that have resulted in the current variation in wetlands (both in terms of structure and ecosystem functioning).

Field data collection was completed at 46 sites between 2012 and 2013 to Level 6 of the CS. Abiotic and biotic characteristics of the ephemeral wetlands were described and used to infer wetland function (Objective 5). Patterns were observed among HGM types despite the high variability in underlying geology, soils, vegetation biome, rainfall, inundation phase and other environmental features, which further addresses Objective 5. This has important implications for management, which is discussed further in Chapter 8 (Section 8.4.1, page 195).

A total of 307 plant species collected at the wetland sites were identified to genus or species level. Over 30% of these species were endemic to SA, with one species classified as Vulnerable on the Red List, *Crinum campanulatum*, a freshwater aquatic plant found in ephemeral wetlands in the Eastern Cape. Aquatic invertebrates were collected at inundated sites, with a total of 144 taxa identified to family level or beyond. *Streptocephalus dendyi* (fairy shrimp) was found at two sites. This is an obligate wetland species that is endemic to SA and is listed as Endangered on the IUCN Red List. Another Vulnerable species on the IUCN Red List was the *Paradiaptomus natalensis*, a SA endemic species which was found at one site in the south-west of the Municipality. Several other SA and southern Africa endemics were identified.

Ten tadpole species were recorded at 15 inundated sites. There were two toad species and eight species of frogs, only one of which, the *Xenopus laevis*, was exclusively aquatic. This frog species relies on a network of aquatic systems, such as ephemeral wetlands, within their habitat range, which has important management and conservation implications (see next Chapter (Section 8.1.3, page 179).

The majority of small, inland wetland systems in the study area are ephemeral in nature. These wetlands appear to be precipitation driven, as observed by the increase in wetland density in the wetter portions of the Municipality, as well as in field observations/data. A number of broad-scale and site-level abiotic properties characterised the three HGMs sampled including, elevation, precipitation, and soil and water physico-chemical variables. These properties explained some of the mechanisms driving plant, macroinvertebrate and

tadpole community structures. Thus, community structure was best defined at a HGM level, and not at broader scales, with different mechanisms that influenced these communities in each of the HGMs. Key broad-scale data in plant and macroinvertebrate communities also corresponded to variables that were significant in the LR model (Chapter 5), illustrating the multi-scalar interactions occurring in wetlands.

One of the key findings of this study was the different environments in which depressions are found. Depressions were found equally within different rainfall areas and could be attributed to a number of geomorphological processes which includes (non-exclusively): groundwater interactions in coastal dune depressions, possible karst features, ferricrete formation and gilgai development (clay shrinking/swelling). These systems were also functionally diverse, providing different habitats such as open water and marginal vegetation, as a result of steep ecological gradients that have influenced soil properties. Accordingly, depressions were generally the most diverse and had the highest species richness for plants, macroinvertebrates and tadpoles, compared to seeps and wetland flats.

Seeps and wetland flats were both found primarily in the wetter portions of the Municipality and both had less distinct vegetation zonation patterns compared to depressions. Seeps generally scored lower across the diversity indices for plants and macroinvertebrates, and no tadpoles identified. Wetland flats had more similar diversity indice scores to depressions, with lower scores in plant diversity, and higher scores in macroinvertebrate diversity.

The importance of a perched water table in wetland formation and structure is also indicated in this Chapter. The latter was especially prevalent in wetland flats which were often found on calcrete or clay (lenses). There was also large degree of variability observed among wetlands within close proximity to each other, such as the three connected seeps in Zone 8 and the wetland complex in Theescombe. Various hydrological and geomorphological drivers, at multiple scales, have consequently shaped the structure of these wetland systems.

The findings for the three HGM types illustrate the complex interaction and relationship between both landscape and site-level data (Objective 6). Data need to be collected at multiple scales in order to sufficiently explain wetland occurrence and why certain wetland characteristics are evident in some systems but not in others. A similar multi-scalar approach is needed to establish the links between wetland structure and the resultant functioning. The key environmental variables indicated in this chapter are an important component of understanding this link. A general discussion is given in the following chapter to address this multi-scalar concept in more detail, by incorporating information obtained through the different aspects of this research (carried out in Chapters 5, 6 and 7).

8. GENERAL DISCUSSION, RECOMMENDATIONS AND CONCLUSIONS

8.1. KEY FINDINGS AND GENERAL DISCUSSION

Key findings of the research that were presented in Chapters 5, 6 and 7 are highlighted in Section 8.1 of this chapter. Each chapter (5-7) addressed certain objectives within the relevant chapter, at a particular spatial scale and/or by using different methods. Therefore, this Chapter integrates those findings to draw out some overarching patterns that were observed for wetland distribution and structure and, to a lesser degree, ecosystem functioning on some ephemeral systems, in the NMBM.

Threats facing wetlands in the NMBM and the various management and conservation strategies that can be used to mitigate against these threats are addressed in this Chapter. Section 8.2 addresses some of the limitations of this study. Based on this research, conservation and research priority areas have been defined for wetlands in the NMBM (Section 8.4.2). Future research strategies for wetlands in semi-arid areas are also described. The conclusion of this Chapter provides an overview of how this study has addressed each of the research objectives and the overall project aim.

8.1.1. An overview of wetland formation, occurrence and structure

The research carried out in the NMBM, since 2012, has illustrated the importance of studying wetland systems across all climate zones within a country, and that wetland research should not be limited to “wetter” or more seasonally predictable areas. This study has also used a variety of existing datasets that describe the spatial arrangement of the surrounding environmental variables. These existing environmental datasets have also been used, along with fine-scale data collection (Chapter 7), to illustrate multi-scalar patterns within the landscape.

A comprehensive wetland dataset now exists for the NMBM. The outcomes of Chapters 5 and 6 highlighted some of the broad-scale wetland distribution patterns (at a quinary and quaternary catchment scale) and have provided valuable information on wetland structure at multiple spatial scales, from an individual site, wetland complex to wetland density within a catchment. A total of 1712 wetlands were identified in the NMBM on all four landscape units (valley floors, coastal plains, slopes and benches) (Chapter 5). This number was almost three times more than the original estimate based on the National Wetland Map IV (Nel *et al.* 2011).

The six HGM types, namely, depressions, seeps, wetland flats, channelled and unchannelled valley bottom wetlands and floodplain wetlands (as described by Ollis *et al.* (2013)) were identified in the study area (rivers were excluded). The wetlands covered an area of approximately 1789 ha, one quarter of the total area of surface water in the Municipality, and approximately 1% of the total size of the study area. Depressions, seeps and wetland flats were the most common wetland types, comprising 80% of the number of wetlands in the dataset, although their contribution to total surface area was less, at approximately 50% (Section 5.3.1) (Table 8-1). Unchannelled and channelled valley bottom wetlands are, on average, larger in terms of surface area compared to seeps, wetland flats and depressions. Few studies have indicated a similar diversity of HGM types within sub-catchment areas and attempt to relate them to the surrounding environment.

The size of a wetland was highly variable within the NMBM, across landscape units and the different HGM types, with 86% of the wetlands being less than 1 ha in size (Chapter 5). Although smaller wetland systems are abundant in other semi-arid and Mediterranean regions (Semlitsch 2000, Bowen *et al.* 2010, Mutaner *et al.* 2013), the dominance and distribution patterns of these systems was far more distinct in the NMBM (Chapters 5 and 6), which highlights the contribution of these wetlands to a network of water resources across the landscape (as seen by other authors such as Semlitsch and Bodie (1998) and Palik *et al.* (2003)).

The majority of these smaller wetlands were naturally occurring, undisturbed systems, that were not previously identified and were, consequently, at an increased risk of being degraded or destroyed (Semlitsch 2000, Bowen *et al.* 2010). The largest natural wetland in the NMBM was a floodplain wetland of 57.06 ha. Most of the larger wetlands, however, were classed as modified or artificial, and many of them were primarily associated with the Swartkops Estuary floodplain (which is highly impacted by anthropogenic activities). Some wetlands associated with this Estuary are discussed in Section 8.3.

As discussed further below, the patterns of wetland occurrence in the NMBM are a result of various environmental processes that occur at different scales. Overall, rainfall patterns have a strong influence on wetland distribution and wetland ecosystem functioning in the NMBM (Chapters 5, 6 and 7), the latter of which was recorded in the multivariate analyses of the community structures (Table 8-1). Many of the wetlands in the NMBM appear to receive their main hydrological input through precipitation (Table 8-1), and the onset of inundation appears to be facilitated by a series of rainfall events, which has also been observed in other regions (Roshier *et al.* 2001, Leibowitz and Nadeau 2003). The importance of rainfall for wetland inundation in the NMBM indicates that several geomorphological processes need to occur to

facilitate water pooling in an otherwise semi-arid landscape. Changes in rainfall, therefore, will have a large impact on the occurrence of wetlands in the region (see Section 8.3 for further information).

Some geomorphological processes driving wetland presence and inundation can be observed remotely. However, field studies provided key understanding on the underlying geomorphological processes that have resulted in some of the wetland distribution patterns and wetland structures in the NMBM. For example, calcrete lenses were associated with the presence of wetland flats and depressions (Section 7.4.3, page 158) in the southern part of the Municipality (Table 8-1). Clay lenses were recorded in different regions (e.g. Zones 2, 4 and 8) (Figure 7-8, page 129) and shallow bedrock has facilitated wetland formation in Parson's Vlei. Likewise, ferricrete fomations are also present, especially in the Hopewell area (Zone 4), which has also contributed to current wetland structure. Wetlands were also associated with interdune depressions, which are located along the northern part of the NMBM coastline and along the headland bypass system (Zones 1 and 7). These dune wetland systems are often difficult to identify on remote imagery due to the constant changes in the dune formations and short inundation lengths. Relict dune features, and the presence of calcium carbonate, have contributed to bands of depressions that have formed, some of which appear to be typical of karst topography, such as the wetland PL1 in the Coega area (Zone 7) (Figure 7-8). The identification of these features provides an important basis for future research (see Section 8.4).

One of the key features influencing the presence of wetlands in the study area is the occurrence of local "perches" of calcrete or clay lenses, which facilitate the formation of wetlands in this semi-arid landscape with limited to no groundwater input. Most likely, these perches also lead to the higher wetland densities (Figure 6-4, page 105) and a high occurrence of wetland clustering, by allowing rain water to accumulate in several areas where perches have a suitable substrate to form. The importance of perched layers for precipitation-fed, ephemeral wetland occurrence has been acknowledged in literature such as vernal pools in the USA (Zedler 2003, Rains *et al.* 2006), as well as systems associated with clay, calcrete or silcrete lenses that are found in various semi-arid and temperate regions (Shaw 1988, Goudie 2013, Dippenaar 2014, Duguid 2015). Zedler (2003) also addresses the importance of these perches for the development of wetlands in the surrounding areas. This is achieved by water collecting in the subsurface layers (from precipitation) where it is transported above the perch without percolating further downwards into the regional water table. This sub-surface water can then feed into other springs and seeps that occur downslope. This is likely the case in Zone 3 around Parson's Vlei, and would explain the prevalence of hillslope seeps in an area that receives less rainfall than the perched wetland flats in Zone 1. The shallow

bedrock in Parson's Vlei most likely forms a more uniform perch and, along with the topography, allows the (rain) water to collect and travel further distances across the landscape, resulting in a relatively high density of wetlands in the area.

The presence of wetland flats on younger deposits, compared to depressions, suggest that wetland flats are "younger" features in the landscape that could potentially become depressions over time, if the right conditions occur. Some of these conditions that would facilitate a depression forming in precipitation dominated areas include aeolian deflation, chemical and physical weathering and animal trampling (Goudie and Wells 1995, Goudie 2013). Depressions have formed in areas where these underlying geomorphological processes are recorded, such as in the Grassridge area (Zone 7).

Seeps, on the other hand, are predominantly driven by slope (Table 7-3), in accordance with their HGM type (see Ollis *et al.* (2013) for the classification of HGM types), and possibly do not require the same mechanisms needed for depression formation. In addition, many seeps were associated with parts of the landscape with higher flow accumulation scores (Table 7-3). Flow accumulation is indicative with increased runoff and combined with the presence of shallow bedrock intercepting the land surface (creating perches) would that facilitate the development of these systems, even if there is limited groundwater input and these systems are reliant of sub-surface interflows. Although Ollis *et al.* (2013) indicate that groundwater is not needed to facilitate saturation/inundation in a SA context, the extent to which this is the case is not known. Most other regions recognise groundwater as an important water source needed for seep development (also known as hillslope seeps, slope wetlands, headwater slope wetlands etc.) (Smith *et al.* 1995, Noble *et al.* 2002, Brooks *et al.* 2011, Duguid 2015), indicating that the prevalence of these precipitation driven (including water input via interflow) seep systems in the NMBM is relatively unique.

As many of these geomorphological features occur at fine scales, it is difficult to always predict where these wetlands would occur over the entire landscape. Hence, the need for site studies, which can be used to infer the underlying causes of the distribution in the surrounding areas. Although not the focus of this study, channelled and unchannelled valley bottom wetlands and floodplain wetlands in the study area could also be linked to similar geomorphological processes. Unlike depressions, wetland flats and seeps, however, fluvial processes such as sediment deposition and flooding from the nearby river, would play a key role in the physical structure, inundation patterns and, ultimately, the community structures of these relatively large-sized systems in the NMBM (as observed by: Gurnell *et al.* 2012, Moggridge and Higgitt 2014).

Table 8-1 Summary of findings by HGM type. ANN = average nearest neighbour, env = environmental, LR = logistic regression, spp. = species, SE = standard error.

Attribute	Depression	Seep	Wetland flat
Location	Variable	Slopes	Coastal plains
Total number	518	471	388
Modified or artificial (%)	26 (agriculture)	43 (agriculture)	34 (agriculture)
Average size (ha) (±SE)	1.10 (± 3.82)	0.44 (± 1.37)	0.34 (± 0.61)
High density areas	Throughout the NMBM	Southern portion	Southern portion
ANN to wetland (m)	396 (above average)	280 (below average)	245 (below average)
ANN to river (m)	1616 (above average)	998 (below average)	1923 (above average)
% in mosaics	48	57	68
Average LR probability score	0.46 (poor)	0.73 (good)	0.68 (good)
Key env. variables for the LR model	*Elevation, flow accumulation & direction, mean annual precipitation (MAP), temperature, groundwater occurrence*		
Relative inundation periodicity	Long (seasonal)	Medium (seasonal to intermittent)	Short (intermittent)
Water sources	Variable	Interflow and precipitation	Precipitation
Abiotic characteristics	Perched	Perched	Perched
Plant diversity	High diversity & spp. richness	High diversity & low spp. richness	Low diversity
Key env. variables for plant communities	*Elevation, MAP, soil electrical conductivity, various sub-surface & surface water (physico-chemical parameters & nutrients)*		
Key factors/processes associated with plant diversity	1) different environmental processes associated with formation & occurrence 2) longer inundation periods due to wetland structure (i.e. maximum depth)	1) sustained periods of soil saturation 2) species changes associated with changes in slope gradient 3) less isolated than depressions 4) rainfall	1) Less habitat diversity/zonation - no open water zone like depressions 2) short inundation periods 3) rainfall

Attribute	Depression	Seep	Wetland flat
	3) habitat variety due to concentric zonation patterns		* should have higher diversity due to close proximity to other wetlands
Macroinvertebrates	High diversity	Low diversity & spp. richness	High diversity & spp. richness
Key env. variables for macroinvertebrate communities	*MAP, soil pH, water depth, dissolved oxygen*		
Key factors/processes associated with macroinvertebrate diversity	1) Habitat diversity – open water and marginal vegetation zones 2) Species predation and competition associated with longer inundation periods	1) lack of sufficient surface water depth & the resultant short inundation period 2) rainfall	1) Vegetation cover provides refuge 2) Shorter inundation period therefore fewer predators 3) rainfall * should have lower diversity if shallow pools & short inundation lengths limit species diversity
Tadpoles	9 species	None	8 species

8.1.2. The role of the logistic regression model in understanding broad scale environmental factors

Some collinearity and higher variance decomposition proportion (VDP) values did not seem to affect the model outcomes with all four model iterations with approximately 66% accuracy. Therefore, emphasis should not need to be placed on the order of variable deletion in similar models when this technique is applied elsewhere. The probability map output also relates to the known wetland density maps, with a generally higher probability of wetland occurrence in the southern part of the Municipality corresponding to areas of higher densities and higher wetland clustering (Figure 6-4, page 105). The northern part of the study area was considered less suitable for wetland development, as well as having lower probability scores (from the LR model) and lower density values, predominantly due to lower rainfall and higher evapotranspiration rates, compared to the southern areas of the NMBM (Figure 6-8, page 110). This model can be applied to other data scarce regions where only basic wetland inventories are available, to indicate areas where there are higher probabilities of wetland occurrence. This would help focus efforts and reduce the resources needed to build more comprehensive datasets.

Section 5.4.2 (page 89) outlined some of the factors that could affect and be used to improve model performance (data availability, climate patterns, wetland size and variability in neighbouring pixel values). In addition to these, two further factors that would negatively affect model performance can be ascertained from the research carried out in Chapters 6 and 7. Firstly, the degree of wetland isolation corresponds with the ability of the LR model to detect a wetland. Seeps were the most closely structurally connected HGM types (Figure 6-5, page 107) and also had the highest average probability score of 0.73 (Table 5-9, page 85). In comparison, depressions, which were the most geographically isolated, had the lowest probability scores (Table 8-1).

Secondly, if some of the wetlands are driven by karst topography (Section 7.4.4, page 159), this would facilitate wetland development even when environmental factors used in the model would not predict them. Consequently, a portion of the relative inaccuracy of the model can also be explain by variations in the wetland formation process and the resultant structure of the wetlands. These models are, therefore, likely to be more successful in areas with more uniform underlying geology. Attempts should be made to use similar methods to improve regional datasets where data is available.

The results of the LR model indicated that several environmental variables were important in predicting the occurrence of a wetland in the NMBM. These variables consisted mostly of

hydrological aspects of the landscape such as rainfall, potential groundwater occurrence and flow characteristics, as well as elevation and temperature (Chapter 5) (Table 8-1). The LR model outputs provided insight on key broad-scale environmental variables that proved to be important in understanding ecological processes occurring at local scales (such as areas of high wetland densities in Chapter 6). Plant and macroinvertebrate communities were also related to these broad-scale environmental variables as they are affected by the timing, frequency and length of inundation of the system (Table 8-1). This insight would be invaluable in regions where field work has been limited and can be used to help identify what environmental data should be collected at finer scales when baseline research is conducted.

8.1.3. Hydrogeomorphic types and plant and macroinvertebrate diversity

The field sites described in-depth in Chapter 7 illustrate the variability and complexity of wetlands in the NMBM. Level 4 (the HGM unit) of the CS explained more of the variability in the site community structure than the broader landscape (Level 3 of the CS) (as per the results of various CAP analyses in Section 7.3.4). The value of underlying geomorphological processes has been discussed by several authors (Leibowitz and Nadeau 2003, Euliss *et al.* 2004, Rossi *et al.* 2014). In this study, this value is highlighted in the diversity of plant and macroinvertebrate communities in the three HGM types. Firstly, this demonstrates that classification techniques, utilising both hydrological and geomorphic principles, provide useful indications of the biological functioning of a system. Secondly, the need for data collected at different scales also suggests that using remote sensing techniques, that primarily interpret landforms, might be limited in terms of their accuracy, as they do not consider more fine-scale environmental conditions or factors. Thirdly, and possibly the most fundamentally important concept, is that the different HGMs have different properties that are influenced by their geographic position, which influences their community structures. The first two aspects have already been covered in previous sections in this Chapter, while the third aspect is explained further in this section.

This study has illustrated the diversity of wetland formation processes, the resultant wetland structure and, to an extent, ecosystem functioning (Chapters 5, 6 and 7). Within an area of less than 2000 km^2 there are systems that have formed on both older and the more recent, quaternary deposits. As a result, both isolated and connected HGMs have formed and many of these are associated with a perched water table (as discussed in Section 8.1.1). The underlying geology (and associated physico-chemical properties of the sediments), rainfall and position in the landscape have, as a result, played a key role in influencing the community composition and structure in the NMBM wetlands (Table 8-1).

The diversity of depression formation processes (Section 8.1.1), combined with the different rainfall zones present in the study area, and are reflected in the diversity of the plant and macroinvertebrate communities. The relative geographical isolation of depressions could have also resulted in the higher plant diversity that was recorded (as observed by Semlitsch and Bodie (1998) and Leibowitz (2003)), compared to seeps and wetland flats. This isolation also indicates the importance of these systems as stepping stones for biotic connectivity between wetlands (Blackwell and Pilgrim 2011, Bosiacka and Pieńkowski 2012), which is thought to be the case in the NMBM. However, the higher diversity is more likely to be facilitated by slightly longer inundation times and deeper waters (providing hydrological stability) in depressions which have a variety of microhabitats for plants and macroinvertebrates, which several authors have also indicated (see: Bledsoe and Shear 2000, Seabloom *et al.* 2001, Brendonck *et al.* 2015). Accordingly, the relatively high diversity in depressions in the NMBM is probably a result of a combination of the underlying geology, water depth, proximity to other systems, and possibly the length of inundation.

If species diversity is negatively influenced by increased isolation of a wetland from other wetlands, then wetland flats should have higher diversity scores than depressions as they were more clustered (Table 8-1). This trend was recorded in macroinvertebrate data but not in the vegetation data. Therefore, proximity to other systems also does not appear to positively or negatively affect plant species diversity for wetland flats in the NMBM (as is the case in depressions). This is likely due to the overall proximity of all HGM types being sufficient to maintain biodiversity (i.e. adequate dispersal of fauna and flora) and/or the physical structure of wetland flats does not facilitate distinct vegetation zones (as is the case in depressions), which would reduce the diversity of habitats within the system (Bledsoe and Shear 2000, Seabloom *et al.* 2001).

The higher than expected plant diversity in seeps could be a result of extended soil saturation (from interflow) and the lack of an open water zone (as with depressions), which results in a mosaic of plant species (Tiner 1993b, Seabloom *et al.* 2001, Euliss *et al.* 2004). However, in general, the shallow water and shorter inundation periods associated with seeps resulted in lower numbers of aquatic species recorded than numbers in depressions (Table 8-1). Similar observations have been made by Murkin and Ross (2000), Brendonck and De Meester (2003) and Euliss *et al*. (2004). This diversity pattern was also observed at two sites, in the NMMU Campus Reserve and Parson's Vlei, where a depression was connected to a seep (Section 7.3.5: Table 7-17). At both sites the depressions had higher plant and macroinvertebrate diversities than the seep, regardless of whether the depressions were located up or down slope of the seep. This pattern illustrates that HGM type (and the resultant morphology of the habitat) has a stronger influence on the wetland community than position or angle of slope in

depressions and seeps. However, slope position and gradient is still a contributing factor, as was observed in a series of three connected seeps in Zone 8 (Section 7.3.2, Plate 7-1). In contrast, the link between shorter inundation periods, shallower water depths and a lower species diversity (as mentioned above) did not appear to be as apparent in wetland flats as a high diversity and species richness scores was recorded for macroinvertebrates (Table 8-1). For each of these HGM types, plant and macroinvertebrate community structure and diversity trends are apparent but cannot be over-simplified (or always accurately predicted) due to the many complex interactions that occur within these systems.

Euliss *et al.* (2004) described two other factors which play an important role in understanding the ecosystem functioning of an ephemeral wetland during the inundation phase, namely, the relationship between groundwater and atmospheric (precipitation/surface) water (known as the "Continuum Approach"). The majority of the wetlands observed in the NMBM are likely to be recharge systems, due to the minimal connectivity to the groundwater table in many of the systems. Euliss *et al.* (2004) note that recharge systems provide an important water source in the landscape and are therefore important refuges for aquatic and terrestrial fauna.

The ephemeral nature of the wetlands and the climate present in the study area means that the full spectrum of the atmospheric water scale (drought to deluge) exists. Although there were similarities in the community composition in the NMBM which paralleled what was described in Euliss *et al.* (2004), where certain plant species corresponded with the inundation phase of the wetland, there were also overarching patterns in these communities that were apparent despite the inundation phase of the wetland relative to other systems. This study has shown that plant and macroinvertebrate community structures can be described in highly variable systems with once-off data collection. The value of the Continuum Approach by Euliss *et al.* (2004) should still be acknowledged, however, even in systems such as the ones identified in the NMBM. Researching wetlands with the Continuum Approach would provide an idea of the more complex environmental interactions that occur within a wetland system, and could provide the information needed to identify at what stage of the inundation cycle a particular wetland is in. Consequently, it would better predict how the structure and functioning of a system might change over time. This more in-depth understanding of a wetland would also provide critical information needed for sustainable conservation and management of these dynamic, ephemeral systems.

8.1.4. Influence of scale on determining wetland distribution and density

The importance of conducting intensive research across all geographical areas was highlighted through this research. The Eastern Cape has a relatively low number of naturally

occurring wetlands recorded compared to other provinces, but this is not reflected by what has been recorded in the NMBM (Chapter 5). Therefore, the NFEPA dataset (National Wetland Map IV) is a good base, but it is not suitable for managing ecosystems or municipal planning at a local level as the level of inaccuracy is too large. This emphasises the need for more intensive research around growing urban areas to ensure that wetland systems can be incorporated into conservation strategies and urban planning.

There was more than a five-fold increase in wetland density and coverage from the north to the south of the Municipality, with wetland densities in the south being comparable to areas with wetter climates (over 800 mm per annum) elsewhere, such as in south western USA (Tiner *et al.* 2002) and south eastern Australia (Taylor 2006) (as described in Chapters 5 and 6). This variability in wetland density means that patterns that are apparent at one scale get lost at another level/scale (Table 8-2). Determining key wetland areas by numbers and by size also reveals different results. Wetland coverage (percentage cover) was more suited to areas with larger systems, while wetland density (number per km^2) was more suited to areas with more numerous, smaller systems. The variability in looking at different measures of wetland density at quaternary and quinary catchment levels highlights the need to define an appropriate scale in order to prioritise certain systems over others.

Interpolation and optimised hotspot techniques provided a more detailed picture of key wetland areas (Chapter 6). However, both these interpolation techniques require a variety of data that were not always easily obtained, or have to be inferred, which reduces the accuracy of the analysis. At a quaternary catchment scale, there can be large differences in the distribution of wetlands, compounded by natural variability in the landscape (morphology). Consequently, wetland distribution should probably be described at a quinary catchment level as it is likely to be the most accurate and most appropriate scale for management, as these catchments can display spatial patterns that are reflected at finer scales, resulting in a better representation of the distribution patterns. Both individual wetland systems and complexes can be assessed at a quinary level (both Chapters 6 and 7 provide such examples). Spatial scale is also important when assessing directional connectivity between wetlands within a catchment (e.g. facilitating the movements of amphibian species) (Dodd and Cade 1998, Morris 2012). The dominant land uses that occur within a quinary catchment compared to the number of wetlands can also be used to highlight priority areas to focus conservation activities at this spatial scale. For example, highly developed or degraded areas that also appear to have relatively high densities of wetlands should be prioritised for research and possible conservation of a representative sample that would maintain the overall network of wetlands within the area.

Wetland density goes beyond spatial scale and wetland size, and also includes the proximity of a wetland to other wetland systems and fluvial systems. Many authors have illustrated how different spatial (and temporal) scales portray different distributional, structural and, at finer scales, functional aspects of wetlands (Amezaga *et al.* 2002, Turner *et al.* 2003, Amat *et al.* 2005). Consequently, the spatial organisation of a wetland provides insight into the scale at which these systems should be managed and contribute towards understanding broader-scaled landscape functions, as has been highlighted by Leibowitz *et al.* (2000) and Leibowitz and Nadeau (2003).

8.1.5. General principles of complexity and connectivity in the NMBM wetlands

The complexity of the wetland systems in the NMBM, as well as the biological diversity across HGM types and geographical regions, illustrates the need to understand the underlying geomorphological and climatological processes, a fundamental concept in the field of landscape ecology. The interactions of these processes can be described in terms of a puzzle analogy. The frame is the geomorphic template on which wetlands occur and the inner puzzle pieces are the various abiotic characteristics and the biotic responses of a wetland. In this study, the LR model used a variety of landscape variables to predict and, therefore, explain wetland occurrence. Although it was not a perfect fit, it formed the frame for the template for wetland occurrence. The links between the frame and the inside puzzle pieces lie in the structural and functional connectivity between wetland systems (the latter of which has yet to be addressed in this region), that occurs at multiple spatial and temporal scales. The inside puzzle pieces are the relationships between the abiotic conditions at a site (e.g. the sub-surface and surface water hydrology) and at a landscape level, including the biological communities (i.e. vegetation, macroinvertebrates and amphibians), which were explored with various multivariate analyses.

Many authors have argued the importance of small and geographically isolated wetland systems (Semlitsch and Bodie 1998, Semlitsch 2000, Leibowitz and Nadeau 2003, Zedler 2003), and the same holds true for the NMBM. Approximately 86% of wetlands were “small” in the NMBM, i.e. less than 1 ha, and the loss of one of the small size classes would result in a significant loss in wetland numbers.

The concept of isolation and connectivity can be addressed in three ways. Firstly, connectivity can be measured by establishing whether there are temporary surface water or groundwater connections. This is not applicable to inter-wetland relationships in the context of this research.

Secondly, connectivity can be established at a functional level. This functional approach requires intensive research on specific species, which falls beyond the scope of many wetland studies. Anecdotal evidence can be useful, however. For example, *Xenopus laevis* was the most common frog species identified in this study, collected as tadpoles in half the inundated wetlands, and were generally dominant in the systems they were found in. This species is aquatic throughout its life cycle, except when migrating to new habitats overland. *X. laevis*, therefore, requires a network of aquatic habitats, such as ephemeral wetlands with a range of inundation periodicities, to maintain their distribution ranges and gene flow (Lobos and Garin 2002, Tinsley *et al.* 2009). The prevalence of *X. laevis* illustrates the need for a network of wetlands to provide "stepping stone" for biotic connections in the landscape.

Thirdly, connectivity can be described structurally. This study has illustrated the merit in determining structural connectivity using spatial statistical methods and proximity to other hydrological features (Chapter 6), the latter of which only a few authors have applied with regard to ephemeral wetlands (see: Waterkeyn *et al.* 2008, Kahara *et al.* 2009).

8.2. RESEARCH LIMITATIONS

The digital mapping of wetlands using aerial photographs in a GIS was successful. However, the dataset could be further improved by using a combination of methods and photographs from different years and seasons (Murphy *et al.* 2007, Martin *et al.* 2012). The lack of clear inter- and intra-annual rainfall patterns make it difficult to identify some of the smaller, more ephemeral systems as the timing of inundation is aseasonal (i.e. not all wetlands will be inundated at the same time). The aerial photographs used in this study are also a snapshot picture in time, and were also taken during a dry period, which means that it was possibly harder to accurately identify more cryptic systems (as the photographs are not captured at the "best" time) (see Section 5.4.1 on page 85 for further information). However, sites with a low certainty level (Section 4.2.1, page 51) were verified using Google Earth Imagery, which has a variety of imagery dates available, at high resolutions, as well as field visits.

Both the strength and weakness of the research was in the relatively large size of the study area. In multi-disciplinary and multi-scalar studies there is a trade-off between the breadth of knowledge and data that is considered (across different scientific disciplines), and the depth of understanding that can be ascertained with the (sometimes less-detailed) data collected. Broad-scale landscape patterns could be scaled down and used to infer wetland distribution and structure at multiple scales. However, the large area also meant that not all sites could be studied in detail. The diversity of the landscape also introduced variability into the data.

This meant that care had to be taken to distinguish between natural variability over the landscape and statistical variability between the sample groups (e.g. HGM types). However, the overall patterns observed in this study would not have been picked up if more intensive sampling had been carried out on a small subset of systems, or one system, over a longer period of time.

Wetlands in the northern parts of the Municipality were more difficult to study for two main reasons. Firstly, many of the wetland sites around Uitenhage were located on private farm lands, which were gated and only farm workers present with no contact details of the land owners. Secondly, the vegetation in the northern areas was thicket (albeit degraded in some areas), which made it difficult to find gaps to get to a site (even when using aerial photographs to find animal tracks). This meant that several wetlands could not be confirmed, and potentially more “ideal” sampling sites could not be used.

The extent of agriculture in the southern parts of the Municipality meant that there were not sufficient natural wetlands that could be sampled, hence, modified wetlands were sampled. Care was taken, however, to note the extent of modification and possible influence on the results.

Ideally, there should be as much uniformity in the timing of sampling as possible. However, the nature of the field data collection and laboratory processing meant that there was a limit to the amount of fieldwork conducted at a particular time. This also meant that fieldwork occurred over two years (2012 and 2013). The large difference in rainfall between the two years meant that many samples were collected from wetlands at different stages of inundation. Water samples were collected at all 2012 sites; however, only half of the 2013 sites had water present at the surface or sub-surface. This limited the data analyses that could be done and, consequently, made data patterns more difficult to clarify. It also would have been helpful to sample equal amounts of wet and dry sites, for all three HGMs, to have a more robust comparison of results, as well as the same systems in a wet and dry state to compare the changes that occur; however, this was not possible in the context of the funded work. Therefore, other site and broad-scale environmental data had to be used in the analyses. The results of this study indicate that soil physico-chemical properties and landscape factors (such as evapotranspiration, rainfall and elevation) could also be used to infer wetland function when surface or sub-surface water was not present. This meant that both landscape and site level data are needed to explain the community structure of wetlands (Objective 6), and that even samples collected in the dry season provide useful information on the wetland community structure.

A further problem is also introduced when sampling at different stages of the wetlands inundation cycle. Invertebrates hatch from the wetland sediment egg bank under specific species related conditions, such as temperature, inundation length and the number of inundation occurrences (Brendonck and De Meester 2003). Insect species also colonise a wetland at different rates depending on their dispersal mechanisms (Euliss *et al.* 2004, Morris 2012) (see Section 2.10 for more detail). Timing of sampling would then affect the data in terms of what species were recorded and the life stages present at that time. However, the results showed observable patterns across HGM types despite the timing of sampling. This illustrated that the underlying hydrogeomorphological processes driving each wetland type played a strong role in influencing community structures that mitigated the variability introduced by the timing of sampling. Nonetheless, further samples should be collected at the same sites to establish whether these trends are still apparent when running multivariate analyses on the additional data.

The complexity and dynamics of a wetland system, especially ephemeral systems, can only be understood when frequently analysing a particular system over a period of time (i.e. throughout an inundation cycle), as described by Euliss *et al.* (2004). This concept was briefly decribed in the previous section (Section 8.1.3). However, as mentioned above, once-off sampling of the wetlands in this study was needed to capture the diversity of systems and, consequently, limited the depth of information that was collected. This limitation was possibly mitigated by the stage of inundation in which sampling took place. Samples collected in 2012 had communities that represented early to mid-stages of inundation community structures, while sites sampled in 2013 represented those that were in the late stages of inundation or almost dry after the extensive rainfall in the previous year or were newly inundated due to recent rainfall events in 2013 (see Table 7-2 on page 127). Consequently, any trends observed within HGM types incorporated this variability to a certain degree. The timing of sampling, therefore, provided both benefits and limitations to the type of conclusions that could be drawn. There was also monitoring data collected on six sites during the same time period of this study (see Schael *et al.* (2015)) and more in-depth analysis of these sites should clarify the patterns observed.

Lastly, the abiotic and biotic characteristics of wetlands only provide some understanding of the underlying ecosystem functions. Establishing what ecosystem services were provided by each of the field sites would have improved this baseline data to provide a more accurate indication of how these systems function within the landscape.

8.3. ANTHROPOGENIC AND ECOLOGICAL THREATS TO WETLANDS IN THE NMBM

The first section of this chapter discussed the key findings of this study. One of the most important factors influencing wetland occurrence, structure, and ecosystem functioning in the NMBM, are anthropogenic activities. In addition, there are also ecological and ecosystem threats to these systems. The threats facing wetlands world-wide was outlined in the Literature Review (Section 2.11). This section expands on the threats that are relevant to the study area, based on the findings of this research. The examples below illustrate the complex nature of anthropogenic and ecological stressors on wetland systems. These stressors are multi-scalar, with impacts occurring across different spatial and temporal scales at different levels of intensity (Danz *et al.* 2007, Sánchez-Andrés *et al.* 2010). The resultant effect on wetland degradation and loss therefore provides insight into some of the anthropogenic activities occurring in the catchment and, to a degree, the socioeconomic changes that are occurring within the area (as seen by Sánchez-Andrés *et al.* 2010).

Over a third of the wetlands in the NMBM are situated on land that is classified as agricultural (Figure 3-5). This land use is possibly the largest threat to wetlands and loss of biodiversity or wetland function in the NMBM. This biodiversity loss is often due to activities associated with agriculture (such as ploughing and irrigation) and overgrazing (as observed by: Marty 2005, Maltby and Acreman 2011). In addition, the number of natural or near-natural wetlands in the NMBM is also thought to be decreasing due to increasing formal and informal urban and peri-urban development (Pers. Obs.). This is a result of urban expansion, increase and intrusion of alien invasive plants and the increase in agriculture in the region (Stewart 2010). A reduction in natural wetlands (in terms of surface area coverage or wetland numbers) could be associated with an increase in modification to systems or artificial systems (depending on the level of impact), or wetlands could be filled in and lost completely. Consequently, a large number of systems in the NMBM are under direct and indirect threats, as these changes in catchment activities and conditions also influence the hydrodynamics of wetlands (also recorded in: Tiner *et al.* 2002, McCauley and Jenkins 2005, Machtinger 2007).

Artificial drainage or direct abstraction can also result in a reduction in wetland area. Many wetlands within the urban boundary have had artificial drainage lines created to reduce flooding of the surrounding land. Many developments have, at high costs, redirected water to build roads and houses. One such example is the Kings Court Shopping Centre in Walmer Heights, Port Elizabeth, which was built on a large natural wetland that was artificially drained. If there had been adequate knowledge on the extent of the wetland and the hydrodynamics

of the surrounding catchment, construction planning could have taken into account the extent of costs involved in development and road infrastructure. There are also strategies to mitigate the effects of developments that result in wetland/ecosystem loss (see Section 8.4.1).

There was only limited evidence of direct use of wetland resources in the NMBM (in terms of ecosystem services). Direct use was mainly associated with wetlands that were used to supply water for surrounding agriculture and livestock, as well as for direct grazing by ungulates. A depression in the Theescombe conservation area (a complex of six wetlands) (Plate 8-1) is an example of an ephemeral system used recreationally by people for swimming. Litter (mainly plastic items such as garden furniture) was also observed both in and around the wetland. At the end of the sampling season (in 2014), it appeared that the wetland had been illegally stocked with juvenile *Oreochromis mossambicus* (Tilapia). The introduction of this species, upon re-inundation, might affect the macroinvertebrate community (with the introduction of a new predator) and affect water quality through excretion and sediment disturbance (Ferreira *et al.* 2012, O'Neill and Thorp 2014). This wetland is one of the key conservation areas recommended for NMBM (see Table 8-3), and further public education/initiatives are needed to ensure these systems are conserved appropriately. This could include placing several rubbish bins around the outskirts of the area, and one or two set narrow pathways for people to use, to limit trampling over extensive areas. The structural and functional diversity recorded in these systems, combined with the surrounding land use, has highlighted these systems for better informed and increased conservation measures. This is discussed further in Section 8.4.2.

Various salt works are located within the study area. Although they provide a large contribution to the surface area of water in the Municipality, these systems are artificial and hypersaline, and have been built on current or previous floodplains. Therefore, not only has their construction altered the hydrology of surrounding freshwater and estuarine systems (through the construction of these artificial systems), but they also function differently from other wetland systems, such as a reduced vegetation cover that is primarily comprised of halophytes (James *et al.* 2009). This change in vegetation cover can be seen as a loss of a system for plant and animal species that inhabited the same system (or used it as a stepping stone) under different environmental conditions.

Pollution from fertilizers, sewage or industrial sources can also affect the nutrient levels in a wetland (Rossouw *et al.* 2005, Corry 2012). Nutrient enrichment, which can increase algal grown and reed growth, has been observed in several wetlands in the NMBM, especially those that fall within the urban boundary and around informal settlements. For example, the Swartkops Estuary floodplain is a key area of concern. There are several sewage and

industrial inputs into the River, as well as a sewage works that is situated on the floodplain (see Table 8-3).

Overgrazing on agricultural and rural land result in trampling and grazing of the vegetation, potentially altering vegetation community structure. Livestock trampling also increases sediment compaction and soil erosion, which can potentially alter the hydrological dynamics of the system, as well as any of surrounding systems that are connected hydrologically. An example of the impact of these activities was observed along the R75 (Zone 8), where a series of three connected seeps (R75-4a-c) was modified, to differing degrees, by grazing. This modification was reflected in the plant community structure, and is discussed in Chapter 7 and illustrated in Plate 8-2. However, it is noted that some disturbance to systems, especially from low-level grazing, is useful in maintaining biodiversity as it possibly mimics what would have happened when grazers and browsers occurred naturally (Marty 2005).

Some wetlands, classified as “modified” in this study, appear to be successfully carrying out various ecosystem functions. The wetland illustrated in Plate 8-3 is a relic quarry and was previously used to mine gravel, effectively scouring the site. Scouring, draining or shoring up one side of a wetland were found mostly on agricultural lands, next to roads, or were associated with mining activities (such as gravel, clay or salt). Over time, if no further disturbance occurs in these systems, they begin to recover and restore some of their previous functioning, or they can shift to a new ecological state with new functions that relate to the structure of the wetland and the hydrological inputs/outputs. Little research appears to have been conducted on cases such as this relic quarry, and this could be a point for future research as it is unlikely that remediation measures were used to create the wetland system.

In contrast to the relic quarry, other systems have been irreversibly altered by development and anthropogenic activities. For example, a wetland known as “Pond 6” (33.878775 ^{o}S 25.604390 ^{o}E) was most likely originally to have been an ephemeral floodplain system that had intermittent connectivity with the Swartkops River Estuary (located approximately 1 km north of the wetland). The construction of a roads downstream of the wetland (to the east) has prevented water from connecting to other parts of the floodplain and has resulted in a larger (as a result of back flooding), permanent wetland system. In addition, a settlement is situated on the western border of the wetland, which is responsible for large amounts of pollution entering the system. Consequently, this system has extremely poor water quality (unpublished data from WRC project K5/2348). Floodplain wetlands are also largely affected by anthropogenic activities in other regions. For example Sánchez-Andrés *et al.* (2010) indicated that almost 50% of floodplain wetlands in the Upper Guadiana river basin, Spain, were lost in 30 years. Long term investments (financially and from community participation)

would be needed to restore the water quality and vegetation in the system which would effectively create a relatively functioning system that is a permanent depression wetland.

The effect of fires on wetland systems in the NMBM should also be ascertained, as both planned and unplanned fires occur in many of the biomes associated with the NMBM. Fynbos vegetation needs fire to maintain the community structure (for reproduction and for preventing the intrusion of vegetation typical of other biomes). As a result, wetlands located in the fynbos biome may potentially be exposed to planned fires every few years. This would have an effect on the vegetation cover, the physico-chemical properties of both the sediment and water, (e.g. an increase in pH) as well as releasing carbon and nitrogen into the soil directly surrounding the wetland (Wetzel and Likens 1991, Battle and Golladay 2003). An example of the visual effect of an unplanned fire at Hopewell Estate is illustrated in Plate 8-4 and Plate 8-5.

Long-term studies should be carried out in areas where wetlands fall under fire management regimes to establish how the ecosystem functioning changes in response to the reduced vegetation cover, changes in physico-chemical properties, and increased nutrient input into the wetland system (Wetzel and Likens 1991, Battle and Golladay 2003). For example, an increase in pH, electrical conductivity and some of the nutrients measured in the surface water, was recorded at the Hopewell site after the fire (unpublished data). If this has long term changes in vegetation cover, this could alter the available habitats for various faunal and floral species which could result in community shifts (Isacch *et al.* 2004, Sánchez-Andrés *et al.* 2010).

In NMBM, Port Jackson (*Acacia saligna*) was a common invasive tree observed within and around wetlands (Plate 8-6). Alien invasives are a widespread problem in southern Africa, and they pose a threat to both water quality and quantity, as well as biodiversity (Mitchell 2013). Increased alien vegetation cover around the wetland would also increase evapotranspiration rates, thereby reducing the amount of available sub-surface water input into the system (Le Maitre *et al.* 2000).

The flooding that occurred during 2012 had major implications around the Municipality. Many wetlands extended beyond their natural boundaries and, as a result, flooded roads and lands bordering these wetlands. The picture in Plate 8-7 illustrates the “normal” vegetation boundary and Plate 8-8 depicts the same wetland after the 2012 floods. This whole section of property remained under water for over a month after extensive rainfall, resulting in a loss of grazing land and the access route to the farm was blocked. A main road in Port Elizabeth, linking Walmer and Seaview was also affected. The road closed for approximately five

months as the road and neighbouring properties (including a restaurant) were severely flooded. The flooding of the road had happened many times in previous years as the local geomorphology and hydrology create a bottleneck which prevents water from draining away. Aerial photos and the topography also indicates that the location was possibly a relic lake, which would further promote flooding.

In many of the cases above, and others not mentioned, the anthropogenic impact is often not directly observed by the public and/or land developers. However, these changes can have a cumulative effect on a landscape scale, often resulting in larger impact in a more concentrated area (Sánchez-Andrés *et al.* 2010). Two examples of this are the properties that flood below the Theescombe wetland complex and the closure of the Seaview Road. Both of these significantly affected the livelihood of many people with large financial costs to individuals and to the Municipality. In the following section recommendations are provided to mitigate some of the anthropogenic activities that currently negatively impact wetlands in the NMBM. This will hopefully ensure that that wetland ecosystem services (such as those described in Table 2-10, page 28) are sustainably managed for the NMBM.

The effects of climate change in SA was decribed in Section 2.13, page 35. In areas such as the NMBM, it is predicted that rainfall patterns would become increasingly irregular, with more extreme events such as droughts and floods (Mitchell 2013, IPCC 2014). This study has illustrated the extent to which wetlands are directly reliant on rainfall for inundation to occur, and this is especially prominent in the southern parts of the Municipality. The effects are likely to be more noticeable in these areas, as the occurrence of wetland flats and seeps and their associated communities appear to be highly influenced by rainfall. In comparison, wetlands in the drier, northern parts of the study area tend to have more variable environmental processes driving wetland structure and their community structures. This means that any changes in climate, specifically rainfall patterns and evaporation rates (due to increased temperatures) would result in an overall reduction in wetland density, their surface areas and their inundation periodicity. Consequently, these changes would result in increased distances between wetlands which would negatively affect the associated communities (Erwin 2009, Junk *et al.* 2013).

Plate 8-1 Depression in Theescombe (TC1).

Plate 8-2 Degradation of a wetland (R75-4b) as a result of livestock overgrazing and agriculture. Arrow indicates location of seep.

Plate 8-3 Wetland (VSR 1) that was previously scoured (for gravel mining) and bermed. Subsequently, it is "naturalised" and provides many functions/ecosystem services associated with wetlands.

Plate 8-4 **Depression wetland at Hopewell Conservation Estate (HW1), taken in February 2013. Note the clump of *Typha capensis* in the top right of the wetland.**

Plate 8-5 **Depression at Hopewell (HW 1). This picture was taken one week after a fire that occurred in October 2013. Note the lower water level and how the clump of *T. capensis* has been burnt compared to February 2013 (Plate 8-4).**

Plate 8-6 **Depression wetland in Parson's Vlei (PV2) with invasive alien Port Jackson trees. The trees can be seen in the wetland and around the periphery (examples denoted by black arrows).**

Plate 8-7 Site R75-1 before the floods in October 2012.

Plate 8-8 Site R75-1 after the floods in October 2012.

8.4. IMPLICATIONS AND RECOMMENDATIONS FOR MANAGEMENT, CONSERVATION AND RESEARCH

This section addresses the final objective of this thesis which was to provide general management and conservation strategies for wetlands in the NMBM based on the data collected, as well as identify priority areas for conservation, rehabilitation and research.

There are many tools available for evaluating wetland condition, assessing important wetlands and determining which systems should be rehabilitated. Consequently, this section will not address the application of these tools such as those found in the DWAF guidelines

(2005), the WET series and the Wetland Health and Importance (WHI) Series (the latter two being WRC funded projects). This research has highlighted the importance of an inter-disciplinary and multi-scalar approach towards understanding wetlands. Accordingly, successful management strategies should take a similar approach, using expertise from different disciplines.

8.4.1. General management implications and recommendations

This study, along with the WRC Report (No. 2181/1/15), has significantly contributed to the knowledge on ephemeral wetlands in the NMBM. As a result, there are various management implications which have been highlighted below.

- This study has highlighted the need for fine-scale mapping for effective management and conservation, and an extensive wetland database now exists for the NMBM.
  - These data are also freely available on the SANBI National Freshwater Ecosystem Priority Areas (NFEPA) national wetland database (Nel 2011) and at the NMBM offices.
  - The dataset will be integrated into the Second Conservation Assessment and Plan for the Municipality. The first one was published by Stewart (2010).
  - The baseline wetland map and the wetland occurrence model can be used in conjunction with known riparian zones and flood lines to better establish which areas are prone to flooding.
- The mapped data and results from the site studies should be used in the decision making process for future developments, such as housing projects. Many of these wetland systems were not identified previously and are not easily identifiable during dry conditions. Any development that occurs on a wetland area during this dry cycle is at an unknown risk of flooding. This happened in many areas of NMBM during the floods in 2011 and 2012 (as addressed in Section 8.3). Consequently, any development occurring at any time will benefit from having an extensive wetland layer to more accurately predict/manage flood risk and to protect vulnerable wetlands from development.
- Although Environmental Impact Assessments are conducted prior to large developments, there is no legislation in SA that currently mandates offsetting biodiversity losses, as well as the associated long-term socio-ecological consequences (Burge and Ihlanfeldt 2013, Jenner and Balmforth 2015). This is crucial to ensure that valuable ecosystem services are maintained in the

landscape. An alternative approach than enforcing developers to pay would be to subsidise mitigation measures where development is needed to provide incentives for restoration of ecosystem services (Bullock *et al.* 2011).

- A LR wetland occurrence model was applied and could be useful in other semi-arid areas with small, ephemeral and geographically isolated systems. For example, in other data-scarce regions in the Eastern Cape. However, further refinement is needed and possibly the inclusion of more fine-scale variables to improve the accuracy. An example is the use of high resolution soil parameters in LR wetland modelling in KZN (Hiestermann and Rivers-Moore 2015).
- Baseline data on wetland soils (properties and chemistry) and water chemistry have been recorded on a subset of wetlands. These data can then be used to further develop national monitoring tools for water and sediment quality, by providing reference condition data for relevant databases, as well as to assess changes in quality due to various anthropogenic activities in a catchment (in different areas of a catchment, and over time).
- Sites that were dry should be re-sampled when wet (and vice versa) to assess the two extreme sides of the inundation cycle (see the Continuum Concept in Section 8.4.2). This would also provide good baseline data on some of the biological characteristics of these systems and, therefore, ensure that they management recommendations are relevant to the system.
- The sampling of the sites could be repeated at certain intervals (e.g. every 5 years). This would provide more in-depth baseline data of the abiotic variables and the dominant plant, macroinvertebrate and tadpole communities, as well as a more complete species list that includes those that are less frequently observed. This would also provide insight into which wetlands remain inundated for longer periods of time and would, therefore, provide habitat refuges during prolonged dry spells. Systems that appear to be key refuge/source areas for other systems then could have a higher conservation priority.
- There are now site-specific data recorded, along with more detailed hydrological and ecosystem characteristics on a subset of sites as well as the species and species distribution, across a wide area of the Municipality, on:

  - the aquatic and semi-aquatic vegetation with associated terrestrial vegetation;
  - aquatic invertebrates; and
  - frog/toad (tadpole) species.

  In addition, three IUCN species (*Crinum campanulatum*, *Paradiaptomus natalensis* and *Streptocephalus dendyi*) have been recorded at their respective

sites, which should be conserved (see Section 8.4.2). These species lists can now be included into distribution maps and, therefore, monitored and included in future conservation planning initiatives, such as planning biodiversity corridors. This is especially important with any Red List species.

- Along with endangered species, the presence and distribution of alien invasive invertebrate species have been documented for two snail species, *Cochlicella barbara*, and *Theba pisana*. These species recordings can aid in the documentation of the spreading of these species to help with control and management of alien invasives.
- The plant and macroinvertebrate community patterns highlight, once more, the importance of accurately identifying and classifying systems. The classification of wetlands by a HGM unit implies key hydrological and geomorphological similarities. However, most studies fail to link the HGM unit to ecosystem functioning beyond each individual site (even though it is implied in a hierarchical classification technique). This study has shown that using the CS by Ollis *et al.* (2013) provides a good basis for understanding wetland ecosystems in SA, by classifying a system from a broad landscape level (Level 1), to a site-level (Levels 5 and 6 of the CS). However, stopping at the site-scale results in data that is site-specific and difficult to use when trying to implement conservation and management strategies in a region. If this data is grouped within the respective HGM units, there are underlying processes that create certain community structures that supersede variations in individual environmental features (such as rainfall or underlying geology). Therefore, management strategies aimed at key systems within each wetland type should be considered, as they are indicative of certain ecosystem functions.

  In addition, it might not be as useful to compare individual wetland sites to another because different HGM types and the proximity of a wetland to another system, might result in different capacities to provide ecosystem services. Therefore, fieldwork should be strategically planned such that key, representative (of specific ecosystem functions) wetland are sampled within a study area.
- This research has provided necessary information on the formation, structure and some ecological functioning. This knowledge can be used to identify potentially threatened systems (by existing and future anthropogenic activities), such as those described in Chapter 6 (Section 6.4.3, page 115). This is discussed further, in more detail, in the following section (Section 8.4.2).

- This study has also provided useful insight as to the relevance of different data analyses at different spatial scales. As a result, there are several management implications which are outlined in Table 8-2.

8.4.2. Wetland conservation and research priority areas for NMBM

Prioritisation procedures were not conducted according to the WET-Prioritise method described by Rountree *et al.* (2009), as this was beyond the scope of this study. However, the broad-scope of this project, along with the conservation and bioregional plans by Stewart (2010) and DEDEAT (2015), has helped to estimate which wetland areas are of key concern, should potentially be conserved, or where further research is needed in the NMBM. The findings of this study comprise the first stages of the systematic conservation planning approach. As the name implies, this technique systematically addresses conservation goals through a six stage processes (Margules and Pressey 2000, Kukkala and Moilanen 2013). This research covered the first two stages. Biodiversity and species data now exist for plants, macroinvertebrates and (to a certain degree) some aquatic and semi-aquatic frogs and toads (Stage 1). Various conservation goals have been suggested and are described in this section (Stage 2). Other aspects of systematic conservation planning are part of other assessments and plans that have been documented for NMBM. This includes the 2009 Conservation Assessment and Plan for the NMBM by Stewart (2010). Recently, the Department of Economic Development Environmental Affairs and Tourism (2015) has also published a Bioregional Plan for the NMBM. This Gazette (Provincial Notice No. 13: Gazette No. 3362) provides further guidelines for biodiversity conservation and land-use planning. These government documents should be in line with one another and used in conjunction with more specific resource management strategies, such as those described in this chapter.

The vulnerability map (Figure 6-9, page 110) was used to assess the surrounding land condition. Recommended areas for conservation and/or rehabilitation, are suggested below based on the knowledge gained during this study (Table 8-3).

Table 8-4 highlights specific sites where further research is needed. This study has emphasised the importance of multi-scalar interactions from the site to the catchment scale. As a result of these interactions, conservation approaches need to look beyond hydrological and ecological responses, but also to the underlying geomorphic processes that affect these systems (Ralph *et al.* 2015).

Stewart (2010) suggests that the existing network of protected areas in the NMBM does not adequately or sustainably conserve biodiversity. The definitions of what are considered priority areas are described in Stewart (2010) and DEDEAT (2015). Figure 6-2 (page 111)

illustrated the number of wetlands per HGM type associated with the various Critical Biodiversity Area (CBA) categories, which should all be conserved or protected, according to Municipal regulations. Many of these important zones coincide with vulnerable areas in the NMBM (Section 6.3.2), highlighting the need to continue to conserve these areas of known ecological importance. The CBAs (from Stewart (2010)) and the vulnerable areas (from this research) have been used to create a map of wetland conservation priority areas for NMBM (Figure 8-1).

Some of these systems mentioned in Table 8-3 and Table 8-4 below are currently highly affected by anthropogenic activities. Other systems are much larger wetlands that are unique to the area and, accordingly, should be researched further, as they represent part of the diversity of systems found in the region. Some of these systems of interest were discussed in an ICLEI – Local Governments for Sustainability Workshop for Wetland Prioritisation. This workshop was held at Pine Lodge, Port Elizabeth on 5-6 May 2015. As a result, several of these conservation measures mentioned below will hopefully be implemented as part of this wetland prioritisation project for the Municipality.

Baseline data on the systems mentioned in Table 8-3 and Table 8-4 should form an important part of future conservation planning for NMBM, to ascertain what conservation targets are obtainable for these wetlands and how systems should be sustainable managed and conserved. Ecosystem services should also be identified and valued for key systems to assist in specific management decisions and goals.

Table 8-2 Management implications and the relevance of data that is collected and analysed at different spatial scales, as well as techniques that are relevant to that scale. ANN = average nearest neighbour.

Management spatial scale	Information that can be obtained	Techniques used	Relevance for management and conservation
Municipality	Wetland distributions; predictive models	Desktop analysis, remote sensing and statistical modelling	Can provide useful insight into overall distribution and state of wetlands at a provincial level for water resource management strategies. Limited at a local scale due to data variability
Quaternary catchment	Wetland densities & distribution	Desktop analysis (mapping)	Limited as there can be large variations in the geomorphological structure of the landscape and the surrounding land use Good for managing impacts of surrounding anthropogenic activities
Quinary catchment	Wetland densities; ANN, hotspots & wetland clusters	Spatial statistical analyses; connectivity & landscape suitability analyses (e.g. directional biotic movements – see Chapter 6)	Good resolution for determining key areas of wetlands Can manage anthropogenic activities and establish priority areas for conservation (including those highlighted using mapping and modelling techniques – e.g. Section 6.3.2. Smaller catchments can be disproportionately high or low in terms of wetland density
Wetland mosaic	Wetland connectivity; vegetation patterns	As above; as well as field visits and sample collection	Good to excellent. Especially in smaller ephemeral systems that are more dynamic and vary in their inundation patterns. Species are consequently adapted to migrate between these systems Species conservation
Individual wetland	Site specific abiotic & biotic data	Field visits and sample collection	Good, but often impractical unless there is a specific function the system performs. In smaller systems it is unlikely that one individual system is important in itself, especially in ephemeral systems Species conservation

Table 8-3 Key wetland conservation and rehabilitation areas recommended for NMBM. Code number refers to the wetland area on Figure 8-1. CBA = Critical Biodiversity Area; CESA = Critical Ecological Support Area; MOSS = Metropolitan Open Space System.

Code	Location	Conservation/ Rehabilitation	Reason/Comments	Conservation network
1	Grass Ridge	Part of the Coega Industrial Development Zone. Some areas are zoned for conservation	A large number of depressions are situated on a stretch of thicket/Bontveld associated with alluvial gravel (Bluewater Bay Formation). Vegetation is becoming increasingly degraded from overgrazing and anthropogenic activities such as increased access routes, illegal dumping and settlements. It is thought that there have already been systems lost along similar ridges in the Motherwell area due to development. Vegetation type is difficult to restore once lost. Limestone mining also occurs in the area (SRK Consulting 2014).	None
2	Redhouse/ Swartkops Estuary	Conservation and rehabilitation	Several wetlands are situated on alluvium associated with a relic floodplain. These systems are downslope of an industrial area with many other poorly managed developments in the area. The surrounding land and the estuary is severely degraded due to prevalence of overgrazing, pollution, nutrient enrichment, sand mining and dumping (industrial and building rubble) (SRK Consulting 2014). These systems need to be rehabilitated due to their unique setting and potential for ecosystem service provision. The wetlands can act as a buffer between the industrial area and the Swartkops River, reducing the influx of water into the system (flood attenuation) and absorb pollution from industrial area (reducing nutrient inputs into the river) (SRK Consulting 2014). The Swartkops Estuary-Redhouse and Chatty salt pans complex is an Important Bird and Biodiversity Area (IBA), supporting ~14 500 birds every year (Marneweck *et al.* 2015). Note: boundaries for the IBA extend past the location square on Figure 8-1.	CBA & CESA 2
3	Hopewell Conservation Estate & the neighbouring MOSS	Conservation and increased protection	Site of IUCN Red List species (*Crinum campanulatum*). Area within and outside reserve are under increasing measures of overgrazing. This should be managed and possibly reduced to prevent degradation of the wetland vegetation and surrounding fynbos.	CBA & Hopewell Conservation Estate

Code	Location	Conservation/ Rehabilitation	Reason/Comments	Conservation network
4	Parson's Vlei	Conservation and rehabilitation	Site of IUCN Red List species (*Streptocephalus dendyi)* unique to ephemeral systems Area should remain non-developed (except for a few access roads) as there are many pristine wetland systems. Alien vegetation (*Acacia saligna)* clearing is needed around the wetland systems. The Parson's Vlei system is upslope of a large development. Degradation of these headwater systems could potentially result in an increased flood risk for the Bethelsdorp community below and affect water quality and quantity feeding into the Swartkops Estuary.	CBA & CESA 2
5	Progress airfield	Rehabilitation and possible conservation	Removal of extensive alien vegetation. Reduce number of access roads which are increasing run-off across the landscape. The amount of surface water present despite the density of alien vegetation indicates that there are important hydrological processes that need to be examined more closely.	None
6	Theescombe	Conservation and rehabilitation	Continue to protect with increased awareness and more signage indicating the conservation area. Prevent the stocking of fish in the depression and pedestrian activity through other systems in the complex. Removal of alien vegetation upslope is also recommended. However, further studies should be conducted first as there are settlements downslope which might be affected by changes in flow patterns.	CBA & Theescombe wetland conservation area
7	Seaview	Conservation of system to maintain connectivity of seeps and to control hydrological dynamics	Coastal seeps dominated by P*hragmites australis*. These seeps are unique due to the associated stromatolites that are situated below the systems. These types of stromatolites are only found between PE and St Francis Bay and therefore, should be conserved (Perissinotto *et al.* 2014). Residential development and access roads have already increased the vulnerability of these systems.	CBA

Code	Location	Conservation/ Rehabilitation	Reason/Comments	Conservation network
			The seeps are also within a coastal dune system and the destruction of systems might lead to changes in sediment dynamics and flow of water towards the coast. This could possibly result in flooding of the coastal road (a main access route to residential areas).	
8	NMMU South Campus Reserve	Conservation	The Reserve is a highly utilised area for walking, birding and education and, should continue to be conserved.	PA1

Table 8-4 Wetland systems that should be prioritised for further research. See Figure 8-1 for the locations of the codes of these systems/areas.

Code	Wetland system	Location	Reason
A	**Addo Elephant National Park**	Extending north of the Municipality	More research needs to be conducted on wetlands in the more arid parts of the region, especially in the thicket biome. It is a Protected Area
B	**Springs**	North of Uitenhage	The Table Mountain Group aquifer is responsible for providing a large portion of water to the surrounding areas in the NMBM. It is also one of the largest aquifers in the region and one of the most important artesian groundwater basin in SA with a yield of 1400 mL/yr (Maclear 2001). Some wetlands fall within PA1, CBA and CESA1s
C	**Progress airfield**	Greenbushes area	A large, ephemeral wetland of approximately 30 ha, is located next to the airfield. This system is unique and should be researched further.
D	**St Alban's wetland**	North of St Alban's prison, off the Rocklands Road	A large ephemeral system (~18 ha) that has undulating topography. It is surrounded by small holdings that appear to utilise the wetland for recreation and other activities. Some wetlands fall within CBAs
E	**Lake Farm**	Kragga Kamma/Colleen Glen	The lake is the largest in the Municipality and the only true valley bottom lake system. Indirect impacts from surrounding farm lands is possibly large, especially runoff from a piggery which contributes to elevated nutrient levels and frequent blue-green algal blooms in the lake. Wetland in a CBA
F	**Urban systems**	Various locations in the urban boundary	Systems within the urban boundary are highly affected by surrounding anthropogenic activities and, as a result, many are polluted. Several systems are now being investigated as part of WRC project number K5/2348. Some wetlands are CBAs

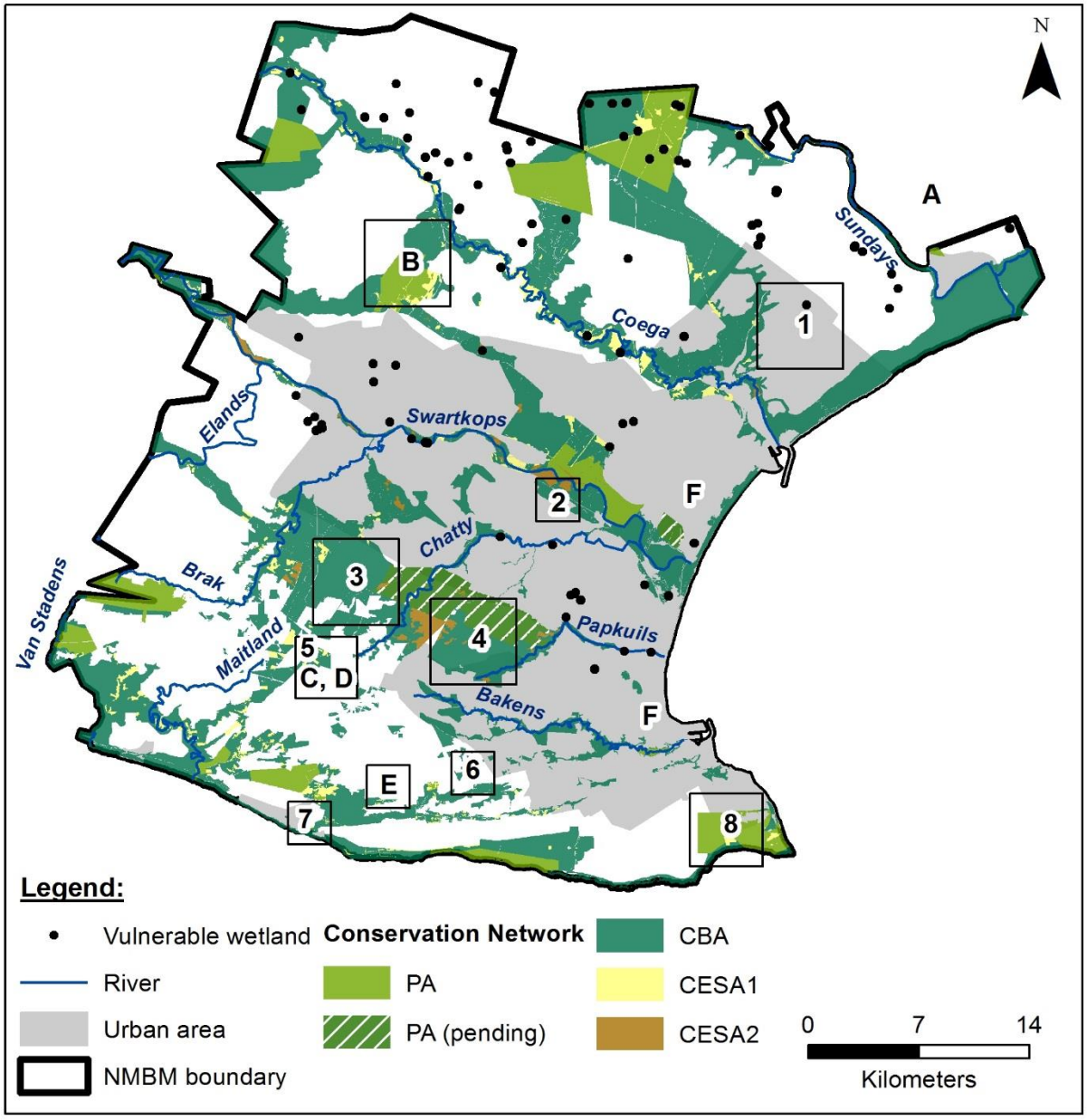

Figure 8-1 **Map of the key conservation and research priority areas for the NMBM. Actual boundaries of sites or areas are not portrayed, only the general location of the area of interest. Numbers refer to key areas for further conservation and research (based on Table 8-3 and Table 8-4). PA = Protected Area; CBA = Critical Biodiversity Area; CESA = Critical Ecological Support Area. (1 is agricultural land that provides some function or connectivity, 2 is disturbed or transformed areas that requires rehabilitation).**

8.4.3. Future research

Further research should be conducted on changes in wetland coverage in the Municipality over the last few decades. This will serve as a useful baseline for how changes in land use have impacted these systems in the past, what proportion has been lost or modified from anthropogenic activities, and to establish which systems are (and will be) most vulnerable to various types of anthropogenic or climate changes (Johnson *et al.* 2005, McCauley and Jenkins 2005, Ralph *et al.* 2015).

The limited success of the LR model provided a good base on the potential to model wetland occurrence in other semi-arid areas where small wetlands dominate. Many of the successful models that were looked at had various soil attribute data. Therefore, further research on the landscape morphology and soils should be done before more modelling is done in the region, as well as the inclusion of any other environmental features where spatial data is available. There is also scope to try different occurrence modelling techniques, especially those using satellite imagery. Although obtaining satellite imagery can be financially costly, the success recorded in other regions suggests that a combination of modelling methods can be used to cover much larger areas with more accuracy (Koneff and Royle 2004, Martin *et al.* 2012, Hiestermann and Rivers-Moore 2015). This would aid in understanding wetland distribution beyond the borders of the current study area, as well as some of the important environmental processes occurring at a local scale that affect the abiotic and biotic characteristics of wetlands, as was seen in this study.

Petrie *et al.* (2015) discuss the importance of small rainfall events (less than 5 mm) on maintaining grassland ecosystems. Their study showed that the absence of small rainfall events between drought and flood cycles results in a significant loss of vegetative cover and above-ground net primary productivity. Therefore, the timing and duration of inundation of a system has an associated influence on the ecological structure and function of the broader landscape (Bunn *et al.* 2006, Kobayashi *et al.* 2015). This concept should be applied to small ephemeral systems that occur in aseasonal and variable rainfall areas to establish when inundation will occur at a site. Furthermore, rainfall should be monitored and linked to the onset of inundation in a monitored system until desiccation occurs. This can only be done through monitoring systems from the onset of inundation until desiccation occurs, as well as recording rainfall events (amount and intensity) before and during inundation of the associated wetland. Site monitoring data does exist for six wetland sites. Some of the data have been analysed and are described in the report by Schael *et al.* (2015), which highlighted the value of collecting this form of data.

In addition to the importance of precipitation, this study has also indicated the prevalence of perched systems (clay, calcrete and bedrock), across the main HGM sites. This is likely a crucial component to wetland development in the NMBM and possibly other semi-arid areas. Therefore, the extent of these systems should be explored further.

Long term monitoring should also include looking at seeds and egg banks in the sediment. If the ephemeral systems are inundating at different stages, the egg bank might provide an indication of the effects of isolation/connectivity between wetland systems. An example would be to ascertain whether similar species are found in samples collected from the same area versus those found in wetlands in other catchments (Brendonck *et al.* 2000). The egg bank also harbours several generations of macroinvertebrates that have been deposited into the sediment, which could potentially host a wider species diversity than that collected in the water at a given point in time (Brendonck and De Meester 2003).

This research has highlighted the prominence of wetland clustering and the presence of a variety of mosaics. Papers by Soranno *et al.* (1999) and Zhang *et al.* (2014), for example, illustrate the spatial complexity and dynamics of a system of lakes and wetlands within a landscape. This concept can be applied to wetlands in the NMBM in two ways. Firstly, an entire set of wetland mosaics should be studied (or a subset thereof). As this study was aimed at sampling across the NMBM, the complexity of wetland mosaics could not be adequately researched. A complex of wetlands offers a wide variety of habitats that facilitate biotic diversity and incorporates migrations that occur between wetlands (Roe and Georges 2007, Kobayashi *et al.* 2015), especially those with different HGM types within close proximity. A good example of where such monitoring could occur would be in the Theescombe Conservation Area that is comprised of a number of different HGM types, with different plant communities, in a relatively small area (Table 8-3 and Figure 8-1). The NMMU South Campus Reserve (Table 8-3 and Figure 8-1) also has many small wetland flats and depressions that are highly variable in their inundation periodicity and timing which could provide some useful information on inundation patterns and the effects of isolation and connectivity between different wetland systems in a complex. The importance of the sequence in which wetlands inundate in an area and the affect it has on biota movements has been indicated by Roshier *et al.* (2001). Therefore, further research should also be conducted on the geomorphological factors that have resulted in different wetland types within such close proximity to each other and have, as a result, affected the timing of inundation and the ecosystem functioning of these systems.

Secondly, a series of wetland systems could be studied from the top of a catchment to its base level (excluding the riverine/estuarine output). Even though systems are geographically

isolated, there is a possibility that the natural environmental gradient occurring down a hillslope will affect these “islands”. This gradient could be abiotic (e.g. changes in nutrient concentrations) or biotic in nature (species composition). This is a concept well covered in fluvial research (Kobayashi *et al.* 2015), and forms the basis of the catena concept decribed initially by Milne in 1936 (as cited in Goudie (2013)). This concept illustrates how soil properties are influenced by hillslope processes, and the associated dynamics between erosion and deposition associated with the topography result in changes the soil properties from the summit to the base of a hillslope (Goudie 2013). There are several areas within the NMBM where this could be studied: Parson’s Vlei, Van Stadens and Coega/Grass Ridge areas (Table 8-3 and Figure 8-1). All of these areas have different HGM units that occur at several points within their respective catchments that can be used to explore this aspect.

The clustering and close average distances between wetlands also indicates that it is important to study the effects of functional connectivity in these systems. This project only collected basic data on tadpoles (as by-catch in invertebrate sampling) and anecdotal observations were made on bird species present. More focused research should be done on key, indicator amphibian species to determine their distribution and movements in the landscape and, as a result, calculate the degree of functional connectivity of these system (Dodd and Cade 1998). For example, *Xenopus laevis* would be an indicator species to determine the connectivity between wetland systems in the NMBM as it is already known to be prevalent in the region (see Section 8.1.3).

Many of the research areas discussed above would also need to be related to the anthropogenic effects on wetlands in the NMBM. Anthropogenic drivers on ecosystem change are complex, but can be assessed using GIS and multi-scalar analysis. For example, a case study in Spain looked at wetland losses in relation to various socio-economic changes over three decades, that resulted in changes in land use (Sánchez-Andrés *et al.* 2010). A similar approach should be used in the NMBM to establish wetland areas that are potentially under greater threat due to current and future socio-economic activities.

On a more-broad scale, birds can also be used to determine wetland connectivity on an inter-basin level. The Swartkops Estuary-Redhouse and Chatty salt pans complex (Table 8-3 and Figure 8-1) is also an Important Bird and Biodiversity Area (IBA) that supports approximately 14 500 birds every year (Marneweck *et al.* 2015), further illustrating the importance of recording avifaunal data.

The questions highlighted in this section would be used to build on the existing baseline data, and, therefore, could be used to help understand how different environmental processes affect wetland structure and function across different spatial and temporal scales.

Despite the new knowledge generated through this research, there are more questions generated than answers. Existing tools should be used to assist future research and to effectively manage the wetlands in the NMBM, based on the knowledge gained during this research. Examples of tools that have been developed for SA include the WET series and the WHI publications. These documents have outlined a series of guidelines for effective wetland management and rehabilitation, based on current national policies and legislations, and (Dada *et al.* 2007). They also provide guidelines for assessing the environmental condition and the various socio-economic benefits of these systems (Day and Malan 2010). Therefore, these tools are necessary to further establish other baseline information on wetland health and ecosystems services. The applicability of these tools in the Eastern Cape also still needs to be tested.

Some questions for further research direction are outlined below.

- Although the majority of the geographically isolated wetlands appear to be precipitation fed and perched, is there groundwater interaction occurring, specifically in the region of the Uitenhage Aquifer?
- What are the fundamental differences, if any, in the drivers that affect the formation of depressions and wetland flats in the NMBM?
- How important are perched water tables for wetland development in semi-arid areas? And, to what extent do these perched systems exist?
- Could some of the depressions in the northern parts of the NMBM be identified as gilgai-type formations?
- What ecosystem services do small, ephemeral wetlands provide:
  - predominantly ecosystem functioning; or
  - direct services and goods; as well as
  - what proportion of each?
- How many systems need to be conserved within each area or HGM type? Do these conservation measures need to also include land corridors between important systems, and if so, what does the condition of the corridors need to be to ensure “connectivity”?
- What urban and per-urban anthropogenic activities currently (and in the future) pose the greatest threat to wetlands in the NMBM, and how can these effects be mitigated?
- In the face of global climate change, what is the effect of higher variability in rainfall periodicity and duration on the resilience and sustainability of ephemeral wetlands?

- How would these changes affect ecosystem services?
- Can the abiotic and biotic dynamics of ephemeral systems act as models for change in both perennial and non-perennial wetlands under different climate scenarios?

8.5. CONCLUSIONS

This study has made a significant contribution to ephemeral wetland knowledge in the Eastern Cape. The outcomes of the research objectives are indicated below.

Objective 1: To identify wetlands using visual interpretation of aerial photographs, and to use this output to create a wetland occurrence model

Chapter 5 described the delineation of 1712 wetlands in the NMBM using aerial photographs. There were six HGM types identified across all four of the Landscape Units (Level 3 of the CS). These wetlands ranged in size and distribution patterns, with more wetlands located in the southern portion of NMBM than in the north. This study has emphasised the importance of conducting local studies and that broad scale databases have limited relevance that can be applied to management and conservation practices. This study has also made an important contribution to the National Wetland Map and to the NMBM.

Objective 2: To determine whether a logistic regression (LR) modelling technique can be used to accurately predict the likelihood of wetland occurrence and whether there are key environmental variables that are associated with wetland distribution in a predominantly semi-arid climate such as NMBM

A LR model was created that highlighted several key environmental variables that can be used to predict wetland occurrence (in Chapter 5). These were: elevation, flow accumulation, flow direction, mean annual precipitation, temperature, evapotranspiration and groundwater occurrence. These variables also related to wetland functioning (Chapter 7) and, consequently, would provide insight on the variables that should be included and measured to establish wetland functioning in other regions.

Although this model wasn't as successful as other predictive wetland models, this can be attributed to the environmental variability, available data, and specifically the dominance of small, ephemeral systems. Therefore, this technique would still provide an invaluable tool in other semi-arid, data-scarce areas to improve wetland databases for management and conservation.

Objective 3: To describe patterns of wetland distribution using spatial statistics and identify whether wetlands are clustered and form mosaics within the surrounding landscape in relation to wetland size and HGM type

Spatial statistics quantify the link between broader distribution patterns and what is observed within a catchment or wetland. Performing these statistics was an important step in establishing what scale these systems operate and interact. In Chapter 6, ANN spline interpolation and Gi* optimised hotspot analyses were conducted and revealed that the wetlands in the study area were highly clustered. This clustering was more prominent in smaller systems and was more pronounced than that analysed in other geographically isolated wetland studies. The extent of this clustering meant that structural connectivity between wetlands is high and that biotic connectivity should be researched to establish the value of this proximity. In addition, 43% of the wetlands were located within 200 m of another wetland system and could be considered as part of a wetland mosaic, which ranged from two to twelve wetlands. There was also variability among HGM types with mosaics most common in wetland flats, and depressions were more isolated. The importance of clustering and wetland complexes on plant, macroinvertebrate and tadpole communities needs to be further examined as the spatial distribution of these systems indicates that there are complex interactions that occur within these systems. Several macroinvertebrate species identified in this study are endemic to ephemeral wetlands, and the aquatic *X. laevis* uses these systems as stepping stones to other aquatic habitats. In terms of ephemeral systems, it is suggested that management occur at a wetland mosaic level that would incorporate the variations in inundation patterns that occur within a series of ephemeral systems.

A mosaic should be defined such that it also takes into account the surrounding land use. The dominance of these smaller and more-clustered systems in the NMBM indicate that these systems are at a much higher risk of being lost/destroyed if the surrounding land is altered (e.g. from natural to agriculture). The degree of isolation of the various HGM types also indicates that these systems should be managed differently as they require different

environmental factors to sustain themselves. I.e. a depression wetland can be more isolated than a seep in order to maintain the current limits of structural “connectivity”.

Objective 4: To determine whether potentially vulnerable (in terms of anthropogenic activities and changes in climate) wetlands can be quantifiably chosen using landscape variables

A least-cost analysis was run to ascertain areas of low to high landscape suitability using six variables: land cover, slope, flow accumulation, evaporation, MAP and annual heat units (Chapter 6). The map output indicated areas of low suitability within the urban boundary and in the northern parts of the Municipality, the latter of which concurs with the LR model. When comparing the scores for wetland locations and non-wetland locations, wetlands had a lower suitability score on average. A combination of landscape suitability map and the LR model output was then used to ascertain potentially vulnerable areas (Figure 6-9, page 110). High suitability and high wetland probability areas were least vulnerable, while those with high scores were considered most vulnerable. The incorporation of these two maps provided insight on areas that were suited for wetland development. Therefore, areas that have been impacted by anthropogenic activities in a “suitable environment” would be considered more vulnerable than those in more undisturbed areas. In addition, scores could then be assigned to known wetland locations. A total of 89 wetlands had a score of over 9, and were considered to be highly vulnerable and potentially key conservation priority areas. These wetlands are highlighted in the management map in Figure 8-1. This method should be further refined and testes as it can be a useful tool to help identify systems that are particularly vulnerable to anthropogenic activities. This would help focus future conservation and management initiatives.

Objective 5: To assess ecosystem functioning of a subset of ephemeral wetlands using abiotic and biotic characteristics to establish whether these features are distinguishable at a HGM level

Chapter 7 describes, in detail, the abiotic and biotic characteristics of the 46 field sites that were comprised of the three most common HGM units in the NMBM: depressions, seeps and wetland flats. These sites were described up to Level 6 of the CS, and included analyses on abiotic parameters such as: the underlying geology and soil composition, sub-surface water, surface water and soil physico-chemical properties. The majority of these sites were in a

natural condition; however, there were impacts observed (such as grazing). Depressions had the longest inundation period, seasonal to intermittent, while wetland flats were more intermittent in nature. It was also newly established that a large portion of the wetlands in this region were perched on either clay, calcrete or bedrock and this has played an important role in the development of wetlands in the study area.

There is now an extensive list of plant and macroinvertebrate species found in ephemeral wetlands in the NMBM that can be used as baseline distribution data and can inform regional conservation plans. A total of 307 species of plants, 144 of aquatic macroinvertebrates and 10 tadpole species were identified at the 46 sites. Various species were listed as endemics and three were on the IUCN Red List. Two alien snail species were also recorded and the spread of these species can now be monitored.

It was acknowledged that rainfall and the timing of sampling influenced the plant and macroinvertebrate community. However, this study has found that patterns in plant, macroinvertebrate and tadpole communities superseded inundation stage and periodicity, surrounding terrestrial vegetation, geology and rainfall zone, and that patterns were evident within individual HGM types. This has important implications for management. The main abiotic and biotic characteristics for each HGM is highlighted in Table 8-1 , and this provides an indication of the ecosystem functioning of these systems.

Objective 6: To describe the relationship between landscape or site level data (or a combination thereof) and the plant and macroinvertebrate community structure in depressions, seeps and wetland flats

As mentioned above, there were patterns in the biotic data within HGM types, and addressing wetlands at a HGM unit was considered successful. This was because some of the variation in the plant and macroinvertebrate community structure could be explained by site level and broad-scale environmental variables. Some of the broader, landscape variables included: precipitation, elevation, evapotranspiration and annual heat units, while hydrological and soil physico-chemical data at the site also explained some of the variance. Although both broad- and site-scale data could be used to explain community patterns, there were differences in the level of the significance of the variables for plants, macroinvertebrates and tadpoles. This knowledge can be used to ascertain how anthropogenic activities occurring at different spatial scales would affect the functioning of these ephemeral systems.

An important finding of this study was directly related to the multi-scalar approach of the research. Data need to be collected at multiple scales in order to sufficiently explain wetland occurrence and why certain wetland characteristics are evident in some systems but not in others. It was broad-scale data that indicated that depressions were driven by different underlying processes than seeps and wetland flats, due to their different distribution patterns. Wetland flats and seeps were found to be primarily precipitation driven, and the lack of direct groundwater input on wetland presence is relatively unique for seeps. This importance of rainfall was primarily discovered through site visits (fine-scale data collection) and map data which suggests an overall low groundwater influence to the region. In contrast, depressions were found throughout the study area, across all rainfall areas. Therefore, different geomorphological processes were needed to facilitate wetland formation. Site studies indicated ferricrete formations, possible karst features, and possible gilgai development (clay shrinking/swelling). Only anecdotal evidence suggests that karst features exist in this region (with other known locations found further north, beyond the Municipality), and there has been no research done on gilgai development anywhere in the region. These new findings provide crucial direction to future research on wetland formation and possible distribution in the Eastern Cape.

In addition to the importance of precipitation, this study has also indicated the prevalence and importance of perched systems (clay, calcrete and bedrock), across the main HGM sites. This is likely a crucial component to wetland development in the NMBM and possibly other semi-arid areas. Therefore, the extent of these systems should be explored further.

Objective 7: To provide general management and conservation strategies for wetlands in the NMBM based on the data collected, as well as identify priority areas for conservation, rehabilitation and research

This Chapter (specifically Section 8.4) has provided an extensive discussion on various implications and recommendations for effective management conservation and research. These outcomes have been built on existing literature (primarily described in Chapter 2) and through knowledge gained through this study, and will be an invaluable tool for focusing future management and conservation strategies. Through the tools developed in this research, a total of 90 wetlands have been identified as vulnerable to current anthropogenic and environmental factors and should be assigned as key conservation priority areas. At present, the overall proximity of wetlands to each other are likely to be sufficient to maintain biodiversity

(i.e. adequate dispersal of fauna and flora). However, these systems are small and more vulnerable to land-use changes than larger systems would be.

This study has highlighted the importance of understanding systems based on their hydrogeomorphological structure and, as a result, it is suggested that research, conservation and management strategies should be implemented such that HGM types are fairly represented across a landscape.

In accordance with the aim of this project, this study has elucidated the factors influencing wetland distribution and structure, as well as some of the underlying processes that reflect aspects of ecosystem functioning for a subset of ephemeral wetlands within the NMBM. This research has highlighted the value of ephemeral wetland research in arid and semi-arid areas. Some of this knowledge could also be used for systems in temperate regions around the world. Several environmental variables, across different spatial scales, have resulted in distinct wetland distribution patterns and community structures.

This study has made a significant contribution to understanding the underlying geomorphological processes in depressions, seeps and wetland flats, and how these systems are fundamentally different in their formation, structure and processes. The effect of different spatial scales on the information obtained on these systems illustrates the importance of conducting studies using this approach in the future, despite the difficulties in establishing trends with the increased data variability that occurs across different scales. Numerous methods developed in this study can provide the necessary tools to prioritise systems of ecological importance. Management, conservation and research cannot be generalised over all wetland types in an area, but need to be addressed at specific spatial and temporal scales that incorporate the key environmental processes that are occurring within each HGM type. Due to the dynamic and closely-related relationships that occur between ephemeral systems, conservation and management strategies need to be implemented across a wetland complex, and not just in a single system. This is because both broad and fine-scale processes are also likely to effect the resultant community structure, and possibly the ecosystem functioning of these systems.

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10. APPENDICES

Appendix A. Diagram of the hydrological patterns associated with HGM types

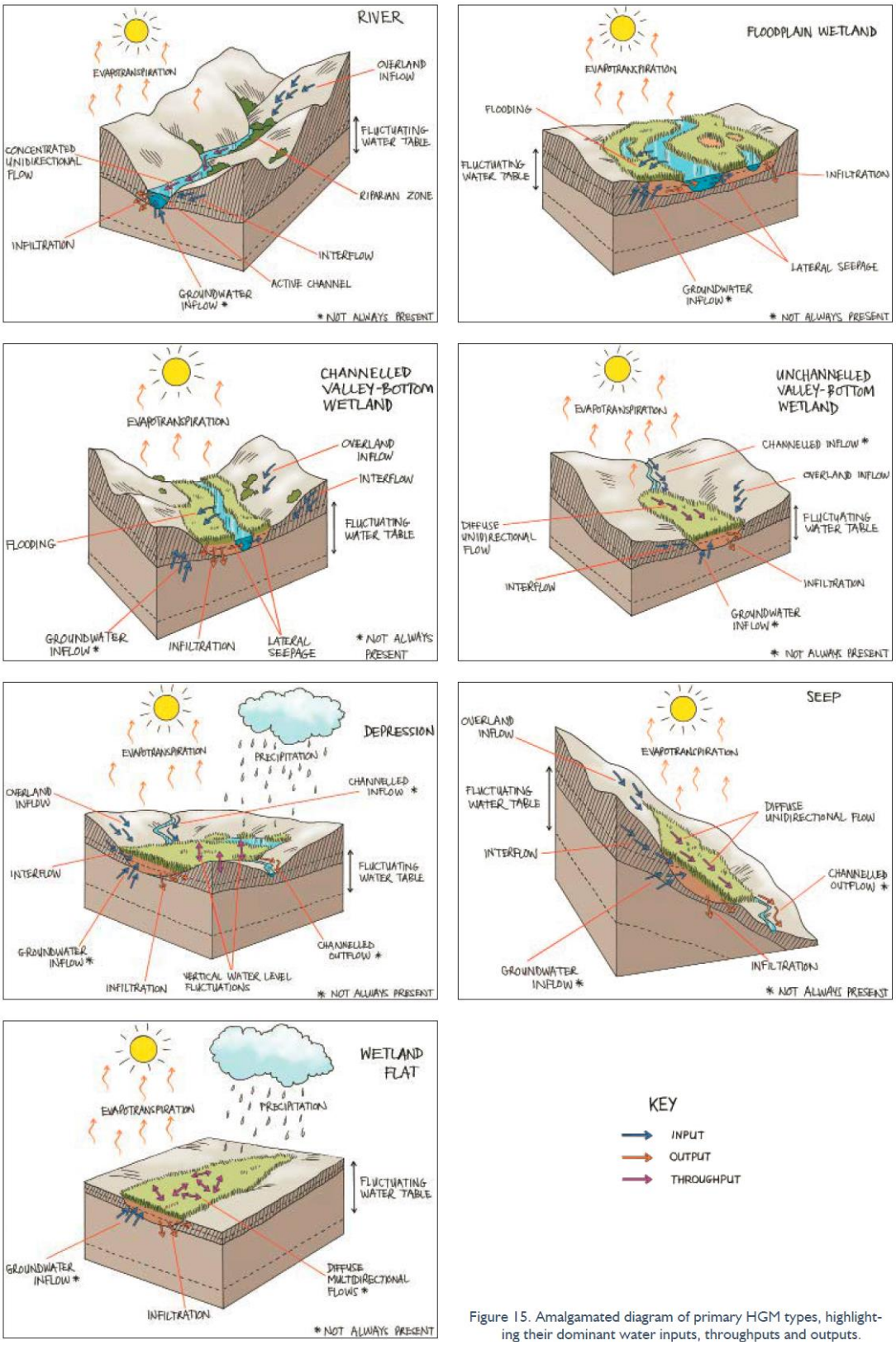

Figure A-1 **Primary HGM types with dominant water inputs, throughputs and outputs highlighted. Taken from pg. 19 of Ollis *et al*. (2013) with permission.**

Appendix B. Further information on the GIS data used during the research

Table B-1 List of data resources used listed by theme (purpose for its use), types of data files, scales and resolution along with the source of the data. HBH = Hartebeesthoek, TM = Transverse Mercator, WGS = World Geodetic System.

Data theme	Spatial data file name	File type	Datum	Scale/Resolution	Area	Source of data
Anthropogenic	Land cover	Polygon vector data	HBH 1994, TM 25	1: 10 000	NMBM	Stewart (2009)
	NMBM Boundary, Roads 2010	Line vector data	HBH 1994, TM 25	Unknown	NMBM	Nelson Mandela Bay Municipality (2011)
	Provinces	Polygon vector data	HBH 1994	Unknown	SA	Municipal Demarcation Board (2013)
Background	Aerial Photos 2009	TIFF raster data	WGS 1984	1 m^2	NMBM	Nelson Mandela Bay Municipality (2012)
	Spot 5 Images 2010	JP2 raster data	WGS 1984	2 m	NMBM	CSIR (2011)
	Digital Elevation Model	DEM	WGS 1984, TM 25	20 m	NMBM	Nelson Mandela Bay Municipality (2011)
Environmental/ Other	1 m and 2 m Contours	Line vector data	HBH 1994, TM 25	N/A	NMBM	From 20 m DEM
	Annual Rainfall	Raster data	WGS 1984	1 km^2	National	Schulze (2007)
	Annual Rainfall	Polygon vector data	D North American 1927	1 km^2	National	Agricultural Research Council (2007)
	Average Relative Humidity	Raster data	WGS 1984		National	Schulze (2007)
	Total Heat Units	Raster data	WGS 1984		National	Schulze (2007)
	Total Radiation	Raster data	WGS 1984		National	Schulze (2007)
	Total Relative Evapotranspiration	Raster data	WGS 1984		National	Schulze (2007)
	Boreholes	Point vector data	GCS WGS 1984	-	NMBM	Department of Water Affairs (2010a)
	Critical Biodiversity Areas	Polygon vector data	HBH 1994, TM 25	1: 10 000	NMBM	Stewart (2009)
	Critical Ecological Processes	Polygon vector data	HBH 1994, TM 25	1: 10 000	NMBM	Stewart (2009)
	Dams	Polygon vector data	GCS WGS 1984		National	Department of Water Affairs Agriculture and Fisheries (2014)
	EC CBA Reserves	Polygon vector data	GCS WGS 1984		Eastern Cape	Berliner and Desmet (2007)

Data theme	Spatial data file name	File type	Datum	Scale/Resolution	Area	Source of data
	EC CBA Terrestrial	Polygon vector data	GCS WGS 1984	Unknown	Eastern Cape	Berliner and Desmet (2007)
	EC Geology	Polygon vector data	GCS Cape	1: 500 000	Eastern Cape	Council for Geosciences (N.D.)
	Elevation	20 m DEM	WGS 1984, TM 25	400 m^2	NMBM	From 20 m DEM
	Evaporation (Pan)	Polygon vector data	GCS Cape	1 km^2	National	Schulze (2007)
	FEPA Sub-Water Management Area (WMA)	Polygon vector data	GCS WGS 1984	Sub-WMA	National	Council for Scientific and Industrial Research (CSIR) (2011)
	FEPA WMA	Polygon vector data	GCS WGS 1984	WMA	National	CSIR (2011)
	Generalised Soil Patterns	Polygon vector data	GCS WGS 1984		National	AGIS (2007)
	Land capability	Polygon vector data	GCS WGS 1984		National	AGIS (2007)
	Land cover	Polygon vector data	HBH 1994, TM 25	1: 10 000	NMBM	Stewart (2009)
	Moisture Availability	Polygon vector data	GCS Cape	1 km^2	National	Schulze (2007)
	Morphology, Rainfall (per Quaternary Catchment), Soils	Polygon vector data	GCS Cape	Quaternary catchment	National	Schulze (2007)
	NFEPA Rivers	Polygon & Line vector data	WGS 1984, Albers	1:500 000	National	CSIR (2011)
	NFEPA Wetland Vegetation	Polygon vector data	GCS WGS 1984	30 m	National	CSIR (2011)
	NFEPA Wetlands	Polygon vector data	WGS 1984	30 m	National	CSIR (2011)
	NMBM land types	Polygon vector data and associated attribute data in PDF files			NMBM	Agricultural Research Council (2007)
	Hydrogeology (Lithology, Groundwater Yield & Rain)	Polygon vector data	GCS Cape, Clark 1880	1: 500 000	NMBM	Council for Geosciences (N.D.)
	Protected Areas	Polygon vector data	HBH 1994, TM 25	1: 10 000	NMBM	Stewart (2009)
	Quaternary Catchments	Polygon vector data	HBH 1994	Unknown	National	DWA (2012)
	Rainfall	Excel with GPS coords	WGS 1984	N/A	National	AGIS (2007)
	Rivers	Line vector data	HBH 1994	1: 50 000	NMBM	Stewart (2009)
	Rivers	Line vector data	GCS Cape	1: 500 000	National	Department of Water Affairs (2012)
	Rivers	Line vector data	HBH 1994	1: 50 000	National	National Geo-Spatial Information (2013)

Data theme	Spatial data file name	File type	Datum	Scale/Resolution	Area	Source of data
	SA Soils	Polygon vector data	GCS Cape, Clark 1880	?	National	Agricultural Research Council (2007)
	Saline & Sodic Soils	Polygon vector data	D North American 1927	1 km^2	National	AGIS (2007)
	Slope Aspect & Gradient	20 m DEM	WGS 1984, TM 25	400 m^2	NMBM	From 20 m DEM
	Slope Form, Morphology etc.	Polygon vector data & Raster data	GCS Cape, Clark 1880	?	National	Schulze (2007)
	Soils	Polygon vector data	GCS WGS 1984	1: 250 000	National	Agricultural Research Institute for Soil Climate and Water (2004)
	SOTER Soil Association Map	Polygon vector data	D North American 1927	1 km^2	National	AGIS (2007)
	Strategic Water Supply Areas	Polygon vector data	GCS WGS 1984	Unknown	National	CSIR (2011)
	Sub-Quaternary Catchments	Polygon vector data	GCS WGS 1984, Albers	1: 500 000	National	Schulze (2007) & Council for Scientific and Industrial Research (CSIR) (2011)
	Temperature	Excel with GPS coords	WGS 1984	N/A	National	AGIS (2007)
	Urban boundary (2005)	Line vector data	WGS 1984	Unknown	NMBM	NMBM (2011)
	Various - vegetation	Polygon vector data	HBH 1994, TM 25	1: 10 000	NMBM	Stewart (2009)
	Vegetation biomes	Polygon vector data	HBH 1994	1: 250 000	National	Mucina and Rutherford (2006). Spatial data obtained from Biodiversity GIS (2007)
	Protected Areas	Polygon vector data	HBH 1994, TM 25	1: 10 000	NMBM	Stewart (2009)

Appendix C. Geological sequence for NMBM

Table C-1 Geological sequence associated with wetlands in the NMBM. Formations are listed youngest to oldest.

Group (sub-group)	Formation	Lithology
Quaternary Recent deposits	Recent deposits	Aeolian sand, Alluvium, Intermediate and low-level fluvial terrace gravel
Algoa	Salnova	Marine terrace deposit
Algoa	Bluewater Bay	Alluvial gravel, sand, silt
Algoa	Nanaga	Semi-consolidated to consolidated calcareous sandstone and sandy limestone with large-scale cross-bedding
Algoa	Kinkelbos	Silt, sand, calc-tufa, minor gravel
Algoa	Alexandria	Calcareous sandstone, conglomerate, coquinite
Grahamstown	Grahamstown	Silcrete
Uitenhage	Kirkwood	Variegated (reddish-brown and greenish) silty mudstone and sandstone, subordinate grey shale and sandstone
Bokkeveld (Ceres)	Ceres	Three sandstone and three shale units
Bokkeveld (Ceres)	Tra-Tra	Mudstone, siltstone, subordinate sandstone
Bokkeveld (Ceres)	Hex River	Feldspathic arenite, wacke, mudrock
Bokkeveld (Ceres)	Voorstehoek	Grey shale, siltstone and fine-grained sandstone
Bokkeveld (Ceres)	Gamka	Fine-grained, feldspathic sandstone, subordinate mudrock
Bokkeveld (Ceres)	Gydo	Mudrock, siltstone
TMG (Nardouw)	Baviaanskloof	Fine- to medium-grained, dark to light grey, feldspathic sandstone, shale
TMG (Nardouw)	Skurweberg	Thick-bedded, medium- to coarse-grained, cross-bedded, white-weathering, quartzitic sandstone
TMG (Nardouw)	Goudini	Brownish-weathering, quartzitic sandstone, subordinate shale and siltstone
TMG	Peninsula	Quartzitic sandstone, minor conglomerate and shale
TMG	Sardinia Bay	Quartzitic sandstone, phyllitic shale, subordinate small-pebble conglomerate
Gamtoos	Van Stadens	Quartzite, arkose, phyllite, conglomerate
Gamtoos	Kleinrivier	Phyllite, quartzite, conglomerate, arkose, greywacke

Appendix D. Attribute data and metadata information for the NMBM wetlands layer

Table D-1 Attribute descriptions for the NMBM wetlands vector layer created. Full metadata report given in Table D-2.

Attribute	Description
Certainty	A level of certainty of the presence of a wetland was assigned: "1" indicated a possible wetland (contours and/or vegetation indicated the possible presence of one), certainly = Low; "2" if there were strong vegetation and contour indicators of a wetland, certainly = Medium; or "3" if there was the presence of water as well as vegetation and contour indicators, certainly = High.
NAT_ART	Three levels of modification were assigned: "Natural" if the wetland illustrated no signs of man-made structures. No apparent modification in terms of hydrogeomorphology. "Modified" if the wetland illustrated some signs of man-mad structures (e.g. a berm), however, there is a high possibly that wetlands in this category were existing before; or "Artificial" for wetlands that are highly modified (e.g. dams) such that it is not possible to determine whether these wetlands existed before the man-made structures were implemented.
NWCS L3	Level 3 (Landscape Unit) of the CS was determined as follows: "Slope"; "Valley floor"; "Plain"; or "Bench"
NWCS L4	Level 4 (HGM Unit) of the CS was determined as follows: "Depression"; "Seep"; "Wetland flat"; "Channelled valley bottom wetland" "Unchannelled valley bottom wetland"; or "Floodplain wetland"
SANBI_DB	This field was used to indicate whether the wetland was identified in the SANBI database. The following codes were used: "Y" for an identified SANBI wetland; or "N" if the wetland was not digitised previously.
RIV_EST	This field was used to indicate if the wetland is situated alongside a river or estuary.
COMMENTS	Any further comments on the wetland
PERIMETER	Perimeter of the wetland

Attribute	Description
AREA	Area of the wetland in square metres
HECTARE	Are of wetland in hectares
X, Y	X and Y coordinates of the centre of the polygon

Table D-2 Metadata report that applies to the NMBM wetland database created by the project. This report has been done according to SANBI guidelines and is on the SANBI BGIS website.

South African National Biodiversity Institute

GIS METADATA: DETAILED REPORT

FILE NAME: NMBM_wetlands_WGS84TM25_Nov2014.shp	
Full Path	
Description (detailed)	ArcGIS 10 was used to delineate the ephemeral/temporary wetland types in the NMBM up to Level 4 of the NWCS (Ollis *et al.* 2013). Wetlands were digitized for NMBM in a vector format as discrete polygon units with associated attribute data. Aerial photos obtained from the Municipality, as well as existing shape files of the national SANBI wetlands database, rivers and 2 m contours, were overlaid onto the map as guidelines for identifying wetlands. The study area (NMBM) was scanned from east to west at a 1: 2500 scale. Mapping occurred at a 1:2000 m scale. This file comprises the **wetland database for the Nelson Mandela Metropolitan Municipality**. Data compiled under the auspices of a Water Research Commission study K5-2181.
Copyright Holder	None
Data Origin	
Capture Source	Nelson Mandela Metropolitan University
Scale Digitised	1:2000
Date Captured	2012-2014
Data Copyright	No

Distributed?	Yes, available on BGIS

DATA INFORMATION AND METADATA INFORMATION	
Owner Organisation	NMMU
Contact Person	Brigitte Melly, Denise Schael
Position of Contact Person	PhD student, Project leader
Contact Address	Botany Department, South Campus NMMU, Admiralty Way
Contact Number	
Contact Email	brigittemelly@gmail.com; denise.schael@nmmu.ac.za

LEGEND PROPERTIES	
Legend Title	Wetland
Feature Type	Polygon
Scale Parameters	

PROJECTION	
Transverse_Mercator	
False_Easting:	0.00000000
False_Northing:	0.00000000
Central_Meridian:	25.00000000
Scale_Factor:	1.00000000
Latitude_Of_Origin:	0.00000000
Linear Unit:	Meter
Projection Name	Transverse Mercator
Central Meridian	25
Upper Parallel	
Lower Parallel	

DATUM	
Geographic Coordinate System:	GCS_WGS_1984
Datum:	D_WGS_1984
Prime Meridian:	Greenwich
Angular Unit:	Degree
Name	WGS 84
Semi Major Axis	0
Semi Minor Axis	0
Inverse Flattening	0

DETAILED NOTES
Purpose: No extensive research has been conducted on wetlands in the NMBM. This study aimed to digitize and classify wetlands in the NMBM. This forms part of a Water Research Commission project (K5-2181) to be published in 2015. **Methods:** In order to locate, delineate and classify wetlands to Level 4a of the Classification System a variety of data sources were used. The available maps, primary and secondary data sources for the NMBM region used were: aerial photos, NMBM boundary, NMBM roads, 2 m contours, rivers, SANBI NFEPA wetlands. A simple map of the study area with the relevant quaternary catchments is illustrated Figure 3.1. Wetlands within the NMBM were digitised using aerial photos obtained from the Municipality as well as existing shape files of the national SANBI wetlands database. Rivers and 2 m contours were overlaid on the map as guidelines for identifying wetlands (Table 3.3). A new polygon shape file was created in order to digitise the wetlands observed. A 500 m by 500 m grid was also created to ensure scanning over the aerial photos was done in a methodical manner. The study area (NMB) was scanned from east to west at a 1: 2500 scale, overlapping at the top and bottom of the screen to confirm all areas were covered. A wetland was digitised if water was present or vegetation/contour indicators were present. Wetlands were then digitised at a scale of 1: 2000. Field verification of the classification at Levels 3 and 4a was done as per methods outlined in Ollis *et al.* (2013). Based on the preliminary desktop classification, regions of the NMBM were targeted for verification. Wetlands that were given a certainty level of “1” and some “2” (Table 3.4) were grouped into regions and the wetlands were visited to validate the Level 3 and 4 classifications. **Available documentation:** Full report regarding wetlands in the NMBM will be published by the Water Research Commission project (K5-2181) in 2015. Title of report: Ephemeral Wetlands of the Nelson Mandela Bay Metropolitan Area: Classification, Biodiversity and Management implications by Schael, Gama and Melly.

ATTRIBUTE FIELDS

Field Name	Description	Alias
ID	Wetland ID for Nelson Mandela Bay Municipality (NMBM)	Wetland ID
Certainty	A level of certainty of the presence of a wetland was assigned: “1” indicated a possible wetland (contours and/or vegetation indicated the possible presence of one) CS = Low; “2” if there were strong vegetation and contour indicators of a wetland, CS = Medium; or “3” if there was the presence of water as well as vegetation and contour indicators, CS = High.	

NAT_ART	Three levels of modification were assigned: “Natural” if the wetland illustrated no signs of man-made structures “Modified” if the wetland illustrated some signs of man-made structures (e.g. a berm), however, there is a high possibly that wetlands in this category were existing before; or “Artificial” for wetlands that are highly modified (e.g. dams) such that it is not possible to determine whether these wetlands existed before man-made structures were implemented.	
NWCS_L3	The updated the Classification System (CS) from Ollis *et al.* (2013) was used. Level three of the classification system was added to this field which are as follows: “Slope”; “Valley floor”; “Plain”; or “Bench”	
NWCS_L4	The updated CS from Ollis *et al.* (2013) was used. Level four of the classification system was added to this field which are as follows: “Channel”; “Seep”; “Depression”; “Unchannelled valley bottom wetland”; “Floodplain wetland”; or “Wetland Flat”	
SANBI_db	This field was used to indicate whether the wetland was identified in the SANBI database. The following codes were used: “Y” for an identified SANBI wetland; or “N” if the wetland was not digitised previously.	
RIV_EST	This field was used to indicate if the wetland is situated alongside a river or estuary.	
Comments	Any further comments on the wetland	
Perimeter	Perimeter of polygon	
AREA	Area of polygon in square metres	
Areakm2	Area of polygon in square kilometres	
Hectares	Area of polygon in hectares	
X2	X coordinate of centre of polygon	
Y2	Y coordinate of centre of polygon	

Appendix E. Third and fourth iterations for the logistic regression model

Table E-1 **Coefficients and standard errors for the significant variables used in the 3rd logistic regression model. See Table 5-2 for acronyms. P-values are significant at a 0.05 level.**

	Coefficient	Std. error	P- value
(Intercept)	-11.75000	2.17500	< 0.0001
elevation	-0.00266	0.00047	< 0.0001
flow.accum	-0.00947	0.00359	0.0083
flow.dir	0.00809	0.00146	< 0.0001
eto	0.00543	0.00143	0.0002
map	0.00591	0.00067	< 0.0001
gw	0.49800	0.07770	< 0.0001

Table E-2 **Coefficients and standard errors for the significant variables used in the 4th logistic regression model. See Table 5-2 for acronyms. P-values are significant at a 0.05 level.**

	Coefficient	Std. error	P- value
(Intercept)	-3.554985	0.239252	< 0.0001
elevation	-0.002076	0.000436	< 0.0001
flow.accum	-0.009887	0.003593	0.0059
flow.dir	0.008184	0.001463	< 0.0001
map	0.004084	0.000456	< 0.0001
gw	0.484548	0.076732	< 0.0001

Appendix F. Details on the 46 field sites including their position and Levels 3 and 4 of the CS

Table F-1 **List of field sites by GIS database code, field code, geographic coordinates (Coord) and classification at Level 3 and Level 4 of the Classification System. Sites are arranged by area in the NMBM (See Figure 4-1), and the year in which they were sampled. Sites were sampled between September and December of each year, with the exception of * and **, which were sampled in March and May 2013 respectively. Depression HGMs were further classified into three sub-types at Level 4a of the CS. W/O Ch = without channel, W/Ch = with channel, N/A = not applicable for the HGM type.**

						Level 3	Level 4: HGM Unit			
Wetland ID	**Field Code**	**X-Coord**	**Y-Coord**	**Area**	**Year**	**Landscape Unit**	**4A**		**4B**	**4C**
1593	CR1	25.65959	-34.00777	1	2012	Plain	Wetland flat		N/A	N/A
1595	CR2	25.65826	-34.00753	1	2012	Plain	Depression	Inter-dune	Endorheic	W/O Ch Inflow
1596	CR3	25.68600	-34.00584	1	2012	Plain	Depression	Pan	Dammed	W/O Ch Inflow
1624	NMMU1	25.68444	-34.00694	1	2012	Plain	Wetland flat		N/A	N/A
1626	SBG1	25.66291	-34.01336	1	2012	Plain	Wetland flat		N/A	N/A
1627	DuD1	25.64535	-34.00046	1	2012	Valley floor	Depression	Inter-dune	Endorheic	W/O Ch Inflow
1641a**	Res-A	25.65568	-34.01411	1	2013	Plain	Seep		W/Ch Outflow	N/A
1641b**	Res-B	25.65671	-34.01363	1	2013	Plain	Depression	Pan	Endorheic	W/O Ch Inflow
326	TC2	25.48374	-33.98322	2	2012	Slope	Wetland flat		N/A	N/A
329	TC1	25.48184	-33.98550	2	2012	Slope	Depression	Pan	Exorheic	W/O Ch Inflow
1344	CC1	25.38273	-33.97307	2	2013	Valley floor	Depression	Pan	Dammed	W/O Ch Inflow
1647	DFTN	25.32904	-33.94909	2	2013	Slope	Depression	Pan	Dammed	W/O Ch Inflow
1654	SV2	25.36622	-34.01732	2	2013	Slope	Seep		W/O Ch Outflow	N/A
1655	SV1	25.36819	-34.01784	2	2013	Slope	Seep		W/O Ch Outflow	N/A
683	PV2	25.47138	-33.91230	3	2012	Slope	Depression	Pan	Exorheic	W/O Ch Inflow
1699	PV4	25.47032	-33.92215	3	2013	Bench hilltop	Wetland flat		N/A	N/A

						Level 3	Level 4: HGM Unit			
Wetland ID	**Field Code**	**X-Coord**	**Y-Coord**	**Area**	**Year**	**Landscape Unit**	**4A**		**4B**	**4C**
789a	PV3a	25.48831	-33.90878	3	2013	Bench hilltop	Depression	Pan	Exorheic	W/O Ch Inflow
789b	PV3b	25.48801	-33.90770	3	2013	Slope	Seep		W/O Ch Outflow	N/A
790a	PV1a	25.48551	-33.90562	3	2013	Bench hilltop	Seep		W/O Ch Outflow	N/A
790b	PV1b	25.48581	-33.90509	3	2012	Slope	Wetland flat		N/A	N/A
910*	HW3	25.40828	-33.88168	4	2013	Bench hilltop	Depression	Pan	Endorheic	W/O Ch Inflow
944	HW1	25.40724	-33.87354	4	2012	Bench hilltop	Depression	Bowl	Endorheic	W/O Ch Inflow
947	HW2	25.41190	-33.87525	4	2012	Bench hilltop	Depression	Pan	Endorheic	W/O Ch Inflow
1016	RH4	25.54663	-33.83190	5	2013	Valley floor	Wetland flat		N/A	N/A
1017	RH3	25.54470	-33.82998	5	2013	Valley floor	Wetland flat		N/A	N/A
1019	RH1	25.54057	-33.82971	5	2013	Valley floor	Depression	Pan	Endorheic	W/O Ch Inflow
1648	RH2	25.54439	-33.82872	5	2013	Valley floor	Wetland flat		N/A	N/A
743	VSR1	25.21528	-33.91320	6	2013	Slope	Depression	Pan	Dammed	W/O Ch Inflow
1668	VSM2	25.22572	-33.91622	6	2013	Bench shelf	Wetland flat		N/A	N/A
1675	YW1	25.22877	-33.91290	6	2013	Bench shelf	Wetland flat		N/A	N/A
1679	VSM1	25.23575	-33.95090	6	2013	Slope	Wetland flat		N/A	N/A
749	VSR2	25.22253	-33.91369	6	2013	Slope	Wetland flat		N/A	N/A
1310	EW1	25.68759	-33.73170	7	2013	Slope	Depression	Pan	Endorheic	W/O Ch Inflow
1311	CZ6-1	25.39075	-33.73305	7	2013	Bench hilltop	Depression	Bowl	Endorheic	W/O Ch Inflow
1359	PL1	25.66212	-33.71678	7	2013	Bench hilltop	Depression	Pan	Endorheic	W/O Ch Inflow
1649	CDD1	25.79942	-33.73520	7	2013	Plain	Depression	Inter-dune	Endorheic	W/O Ch Inflow
1650	CDD2	25.79981	-33.73540	7	2013	Plain	Depression	Inter-dune	Endorheic	W/O Ch Inflow
1651	CDD3	25.79658	-33.73422	7	2013	Plain	Depression	Inter-dune	Endorheic	W/O Ch Inflow
1380	R75-2	25.45338	-33.70309	8	2012	Valley floor	Depression	Pan	Dammed	W/O Ch Inflow
1381	R75-3	25.45341	-33.70228	8	2012	Valley floor	Wetland flat		N/A	N/A

						Level 3	Level 4: HGM Unit			
Wetland ID	**Field Code**	**X-Coord**	**Y-Coord**	**Area**	**Year**	**Landscape Unit**	**4A**		**4B**	**4C**
1625	R75-1	25.45845	-33.69553	8	2012	Valley floor	Depression	Bowl	Endorheic	W/O Ch Inflow
1691	BED1	25.42619	-33.67663	8	2013	Slope	Seep		W/O Ch Outflow	N/A
1692	BED2	25.42592	-33.67612	8	2013	Slope	Seep		W/O Ch Outflow	N/A
1382a	R75-4a	25.44693	-33.70510	8	2013	Slope	Seep		W/Ch Outflow	N/A
1382b	R75-4b	25.44693	-33.70510	8	2013	Slope	Seep		W/Ch Outflow	N/A
1382c	R75-4c	25.44693	-33.70510	8	2013	Slope	Seep		W/Ch Outflow	N/A

Appendix G. Number of field sites in the different categories for Levels 4 – 6 of the CS, by HGM type

Table G-1 Number and type of different HGMs at Levels 4A-C of the CS (HGM type) for the field sites. W/O Ch = without channel; W/Ch = with channel.

4A	4B	4C	Total
Depression	Dammed	Without channelled inflow	**5**
	Endorheic	Without channelled inflow	**14**
	Exorheic	Without channelled inflow	**3**
Wetland Flat	**-**	-	**14**
Seep	With channelled outflow		**4**
	Without channelled outflow		**6**
Total			**46**

Table G-2 Mean inundation and saturation scores (Level 5 of the CS) by HGM type.

Zone	Depression	Seep	Wetland flat
Permanently saturated	0.7	0.5	0.1
Seasonally inundated	2.2	1.5	0.9
Seasonally saturated	2.2	2.0	1.5
Intermittently inundated	2.3	2.5	2.8
Intermittently saturated	2.5	2.5	2.8
Rarely inundated	1.3	1.5	1.8
Rarely saturated	1.3	1.5	1.9
Unknown inundated	0.2	0.6	0.5
Unknown saturated	0.3	0.5	0.7

Table G-3 Underlying geological types (Level 6 of the CS) by HGM type.

Formation	Level 6a: Geology	Depression	Wetland Flat	Seep
Recent deposits	Aeolian sand; Intermediate & low-level fluvial terrace gravel	8	6	1
Bluewater Bay	Alluvial gravel, sand, silt	3		
Nanaga	Semi-consolidated to consolidated calcareous sandstone & sandy limestone with large-scale cross-bedding	2	2	
Kirkwood	Variegated (reddish-brown and greenish) silty mudstone & sandstone, subordinate grey shale & sandstone	2	1	

Formation	Level 6a: Geology	Depression	Wetland Flat	Seep
Skurweberg	Medium to coarse grained quarzitic sandstone	2		
Goudini	Brownish-weathering, quartzitic sandstone, subordinate shale & siltstone	1		
Van Stadens	Quartzite, arkose, phyllite, conglomerate		1	
Peninsula	Quarzitic sandstone, minor conglomerate and shale	4	4	7
Kleinrivier	Phyllite, quartzite, conglomerate, arkose, greywacke			2

Table G-4 Summary of substratum types (Level 6 of the CS) by HGM type.

6a: Substratum types	HGM		
Primary	**Depression**	**Wetland Flat**	**Seep**
Pebbles/Gravel/Sand	1		
Gravel/Clay	1		
Sandy	10	8	6
Sandy/Clay		3	
Sand/Silt	1	1	
Silt	4	1	
Silt/Clay	1		
Clay	4	1	4

Table G-5 Sample sizes for the number of "wet" (inundated) and dry sites where samples were taken. Number of sites where SW (surface water), SSW (sub-surface water) and invertebrates were sampled are also below.

	Dry	Inundated ("wet") sites	No. of sites where SW sampled	No. of sites where SSW sampled	No. of sites invertebrates sampled
Depression	4	18	18	17	15
Seep	4	7	7	6	7
Wetland flat	5	8	8	6	8

Table G-6 Dominant vegetation characteristics for Level 6 of the CS.

Vegetation Cover	Vegetation Form		HGM		
A	**B**	**C - D**	**Depression**	**Seep**	**Wetland Flat**
Unvegetated			3		
Unvegetated/Vegetated	Herbaceous	Herbs & Forbs	1		
	Aquatic	Submerged	1		
Vegetated	Aquatic/Herbaceous	Submerged/Sedges	3		
		Free-floating/Sedges/Restios			1
		Floating-attached/Rushes	1		
	Herbaceous	Grasses	4	1	4
		Grasses/Herbs & Forbs	1	1	
		Grasses/Sedges	1	1	1
		Reeds	1	2	1
		Restios		2	1
		Rushes			1
		Sedges	6	2	3
		Sedges & Rushes		1	1
	Shrubs & Thicket/Herbaceous	Grasses/Rushes/Shrubs			1

Appendix H. Physico-chemical data for soils, surface water and sub-surface water by HGM type. Various soil parameters also given for all sites

Table H-1 **Summary of the water chemistry and physico-chemical properties of the field sites. SW = surface water, SSW = sub-surface water, PC = physico-chemical properties, EC = electrical conductivity, TDS = total dissolved solids, TSS = total suspended solids, ppt = parts per thousand, SR = soluble reactive, TOxN = total oxidised nitrogen.**

		All			Depression		Seep		Wetland flat	
Water chemistry	**Unit**	**Sample size**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
Soil PC										
Soil moisture	%	46	17.5	2.7-35.6	18.4	4.93-32.04	20.2	7.64-35.59	14.2	2.72-29.28
Soil organic matter	%	46	3.5	1.0-7.7	3.4	1.13-5.37	3.7	1.02-7.66	3.4	1.12-6.05
EC	µS/cm	46	8329	196-304000	16246.6	331-304000	1526.2	1.88-2.3	746.2	201.5-4.04
pH		46	7.2	4.3-8.6	7.3	4.25-8.58	7	5.55-8.12	7.4	6.7-8.24
Surface water PC										
Maximum depth	cm	46	43	4-125	60	6-125	14	4-41	27	11-40
Water temp.	ºC	32	20.5	13.3-29.9	20.1	13.3-27.3	24.5	18.1-29.4	18.7	14.7-29.9
EC	µS/cm	32	8063.5	179.3-89510.0	11961	212-89510	6183.4	614.8-32741.7	702.2	179.3-2423.3
pH		32	7.4	4.6-9.8	7.7	6.1-9.8	6.5	4.6-7.8	7.5	6.7-8.1
TDS	mg/L	32	1471.8	12.4-19346.7	2288.8	19.1-19346.7	399.8	12.4-797.5	437.8	94.2-1525.7
DO	mg/L	32	8.3	0.5-57.9	6.7	0.8-16.6	10.4	0.5-49.1	10.4	1.4-57.9
Salinity	ppt	32	5.7	0.1-63.71	8.1	0.1-63.7	5.3	0.3-29.3	0.4	0.1-1.5
TSS	mg/L	32	0.85	0.02-3.82	0.55	0.02-2.95	2.13	0.16-3.80	0.37	0.07-1.50
Sub-surface water PC										
EC	µS/cm	29	4711.5	96.2-66100.0	6647.1	96.2-66100.0	2761.5	183.7-14910	8822.2	133-3450

			All		Depression		Seep		Wetland flat	
pH			6.9	5.0-9.0	7	5.31-9.0	6.7	5.6-8.2	6.7	5.0-7.6
TDS	mg/L		2179.1	60.2-41000.0	2984.6	60.2-41000.0	1449.9	332-3418.8	610.3	83.8-2170
Salinity	ppt		3.8	0.1-43.2	5.3	0.1-43.2	2.3	0.2-10.8	0.3	0.1-0.6
Surface water nutrients										
Total phosphorus	µg/L	32	154.2	1.9-1665.9	53.6	3.8-314.2	624.1	1.9-1666.0	28.3	8.3-62.1
SR phosphorus	µg/L	32	121.7	0.2-1405.4	20.2	0.58-70.2	528.6	0.2-1405.5	45.1	9.2-158.4
Total nitrogen	µg/L	32	7236.8	0-12478.8	7778.4	0.0-59566.2	7941	355.6-12478.8	5744.2	30.4-20865.9
Nitrite	µg/L	32	26.3	0-161.6	27.3	0-161.6	11.1	0-52.7	35.6	0-122.7
TOxN	µg/L	32	38.8	0-975.7	9.1	0-59.2	1.4	0-7.5	119.9	0-975.7
Ammonium	µg/L	32	14.4	0-54.6	13.2	0-34.01	14.6	0-32.4	16.7	0.2-54.6
Silica	µg/L	32	7.3	0-50.6	5.5	0-26.2	1.4	0.4-2.7	16.1	0.2-50.6
Sub-surface water nutrients										
Total phosphorus	µg/L	29	43.3	0-185.5	43	0-185.5	72.4	35.0-125.5	25.5	0-55.8
SR phosphorus	µg/L	29	49.9	1.16-488.6	57.1	1.4-350.6	36	17.28-64.8	44.8	13.8-115.8
Total nitrogen	µg/L	29	15940.3	0-179854.7	21643.4	0-179854.7	9239.9	5156.8-14461.5	6481.9	31.5-25768.0
Nitrite	µg/L	29	44.4	0-412.6	63.2	0-412.6	1.3	0-7.1	37.5	0.0-172.6
TOxN	µg/L	29	495.4	0-12903.1	834.7	0-12903.1	3.5	0-20.1	25.9	4.5-55.7
Ammonium	µg/L	29	34.7	0-348.0	38.3	0-348.0	40.7	4.9-171.2	19	8.2-44.4
Silica	µg/L	29	10.8	0.1-43.9	10.2	0.1-43.9	6	2.2-9.7	17.1	4.9-34.4
Other										
Elevation	m	46	117.3	1-298	111.7	1-228	144.2	1-298	106.9	8-225
Gradient	^{o}	46	1.9	0.1-10.1	1.3	0.1-4.573	4.6	0.5-10.1	0.9	0.1-3.3
Wetland area	m^2	46	15396.5	75.2-450700.3	28655.7	387.6-450700.3	3761.7	460.4-11148.2	2871.2	75.2-7151.6

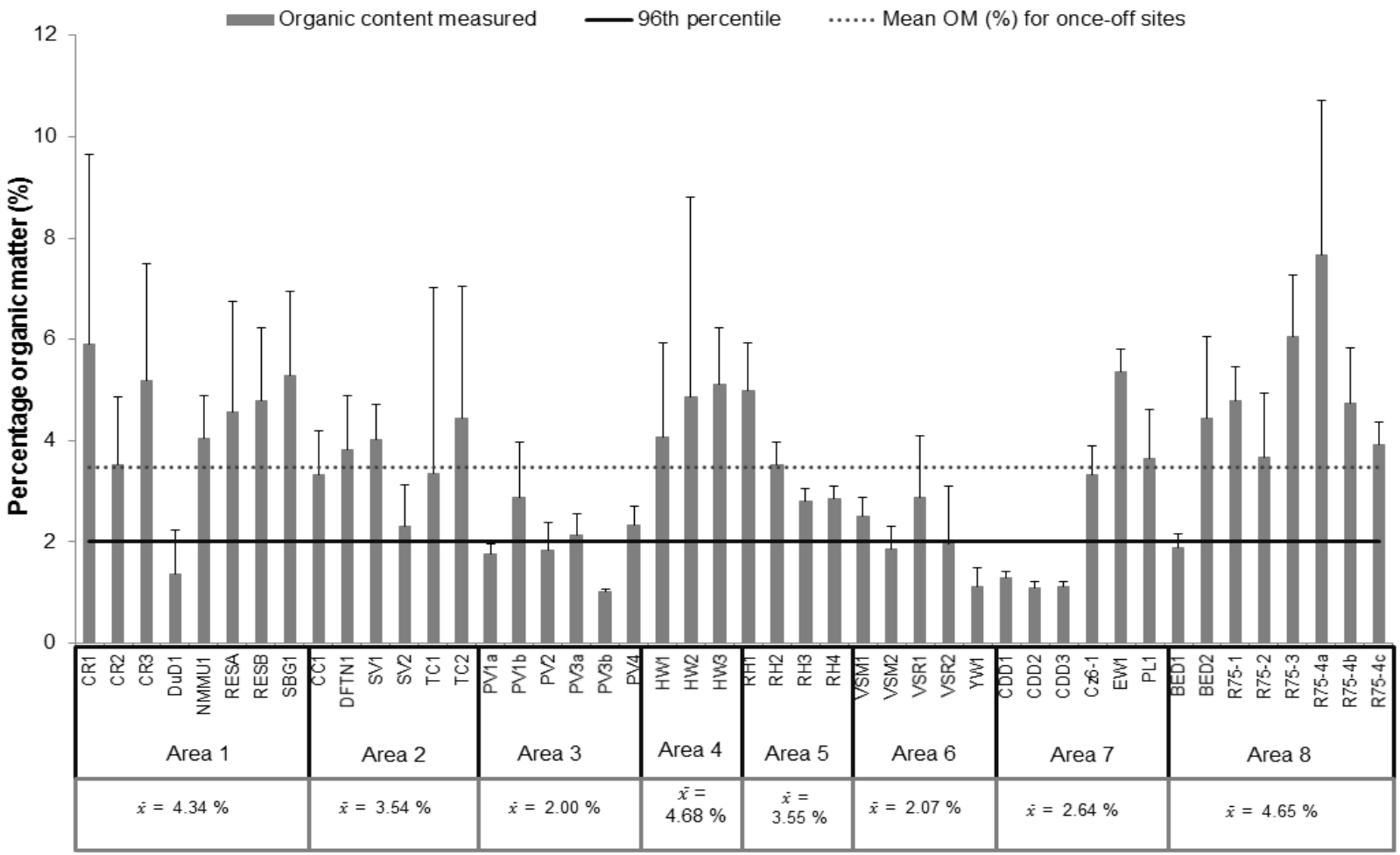

Figure H-1 **Organic matter (OM) (%) and standard deviations (SD) for field sites grouped in geographic areas (Figure 3.2). Means for each area are indicated at the base of the graph; overall mean is indicated as a dotted line on the graph. The solid line represents the 96th percentile.**

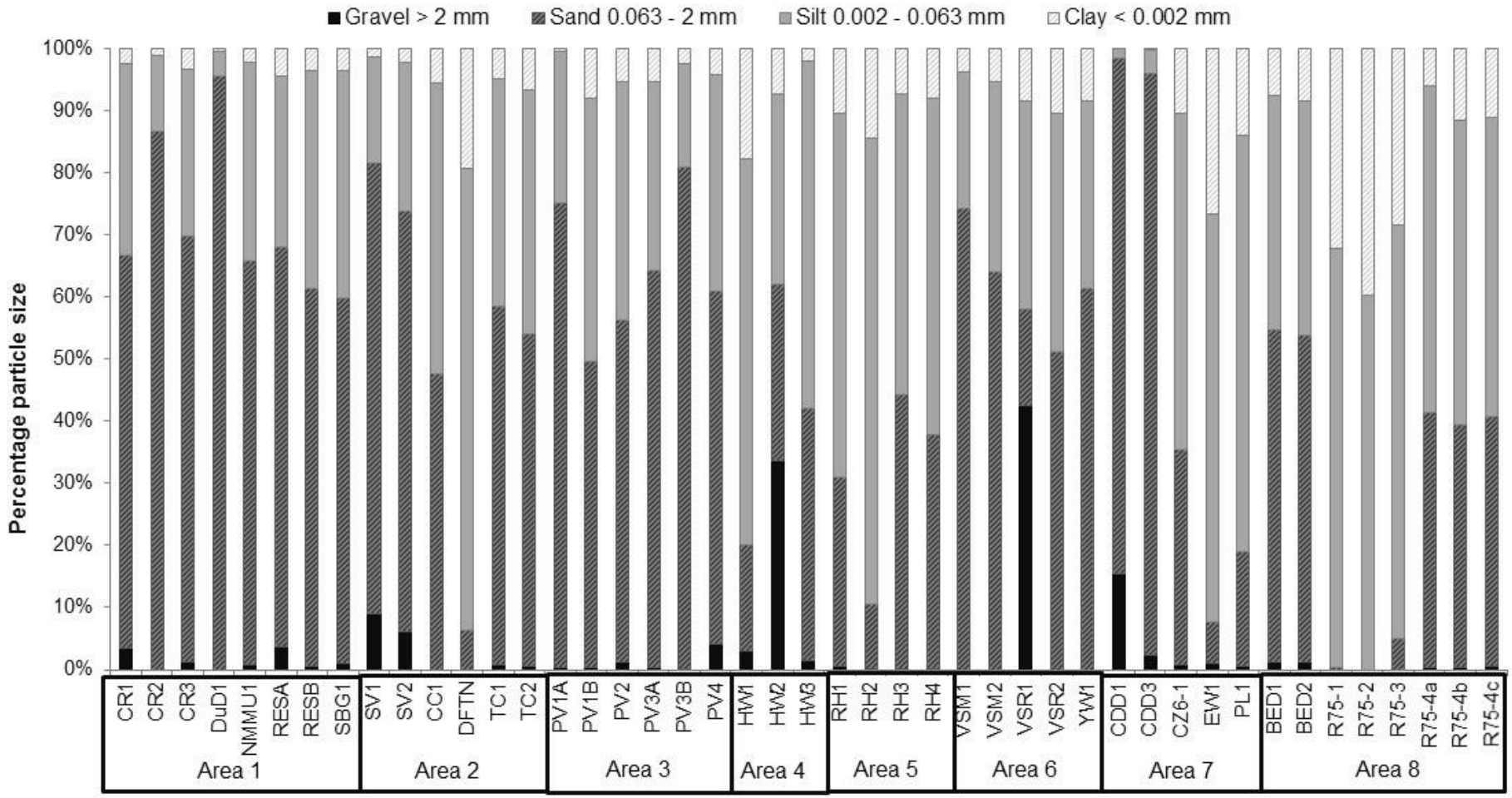

Figure H-2 Particle size distribution (PSD) for all once off wetland sites (average percentages illustrated).

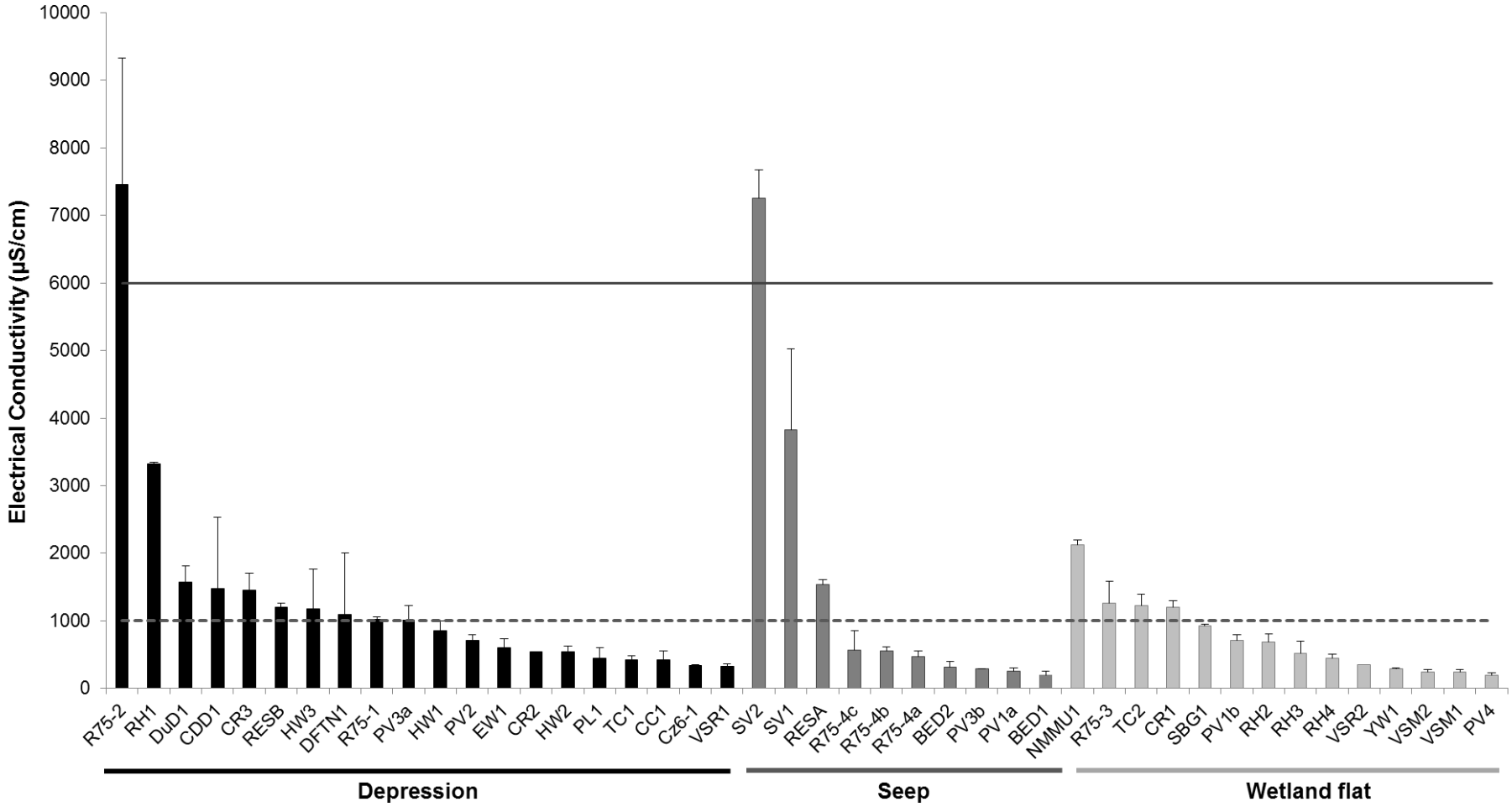

Figure H-3 **Sediment electrical conductivity for all field sites. Horizontal grey line indicates the freshwater/brackish boundary (dashed line) and the brackish/saline boundary (solid line) (values based on Taylor et al. 2007).**

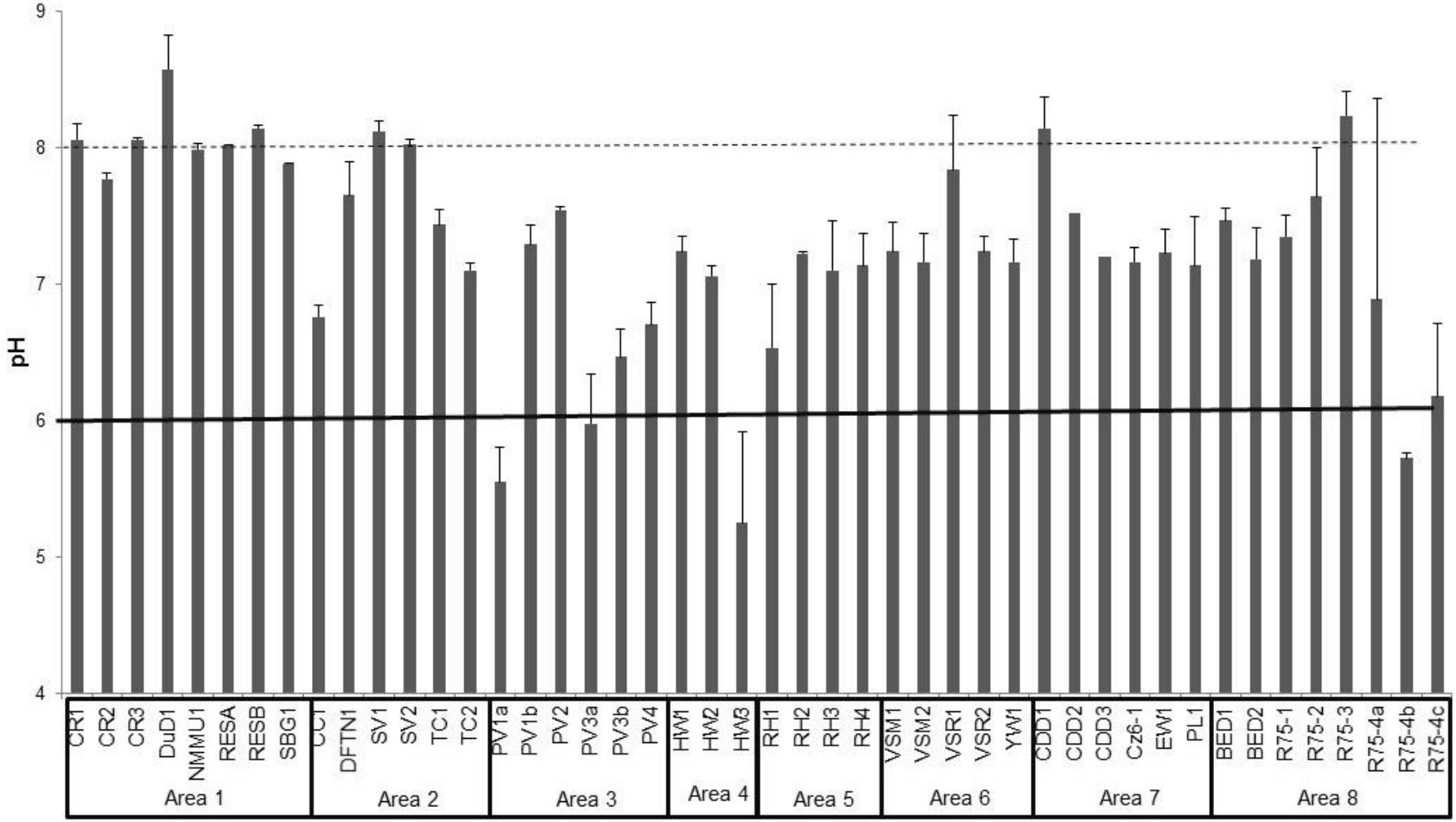

Figure H-4 **Soil pH for all field sites. Values below the solid line indicate acidic soils (pH < 6.0) and values above the dotted line indicate alkaline soils (pH > 8.0). pH values between 6.0 and 8.0 indicate circum-neutral soils.**

Appendix I. Taxonomic lists for vegetation, macroinvertebrates and amphibian (tadpole) data collected and identified to the lowest practical level

Table I-1 Presence/absence species list for plant species. Sites from areas 1, 2, 3 and 4 are represented here (see Figure 4-1 for general locations). See Table F-1 for further information on each site.

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Acanthaceae	*Hypoestes aristata*											+												
Agavaceae	*Agave sisalana*																							
Aizoaceae	*Aizoon rigidum*						+																	
Aizoaceae	Unidentified sp.															+								
Aizoaceae	*Tetragonia fruticosa*			+															+				+	
Aizoaceae	*Tetragonia* sp.												+											
Amaranthaceae	*Amaranthus* sp.																							
Amaranthaceae	*Atriplex* sp.										+													
Amaranthaceae	*Guilleminea densa*						+																	
Amaranthaceae	*Salicornia quinqueflora*																							
Amaranthaceae	*Salicornia* sp.																							
Amaryllidaceae	*Crinum campanulatum*																						+	+
Amaryllidaceae	*Scadoxus multiflorus*											+												
Anacardiaceae	*Searsia glauca*	+		+			+		+	+				+						+				
Anacardiaceae	*Searsia longispina*																							
Anacardiaceae	*Searsia lucida*																						+	
Anacardiaceae	*Searsia undulata*																				+			
Apiaceae	*Centella asiatica*							+		+	+			+			+		+	+		+	+	+
Apiaceae	*Cyclospermum leptophyllum*																							
Apiaceae	*Dasispermum suffruticosum*																							
Apocynaceae	*Asclepias physocarpa*																							

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Apocynaceae	*Carissa bispinosa*																							
Apocynaceae	*Cynanchum obtusifolium*					+																		
Aponogetonaceae	*Aponogeton junceus*																+							
Aponogetonaceae	*Aponogeton* sp.			+		+												+	+			+	+	+
Araceae	*Zantedeschia aethiopica*									+		+			+									
Arecaceae	*Phoenix reclinata*					+																		
Asparagaceae	*Albuca* sp.																					+		
Asteraceae	*Anthemis cotula*																							
Asteraceae	*Arctotheca calendula*																							
Asteraceae	*Arctotis stoechadifolia*																							
Asteraceae	*Chrysanthemoides monilifera*				+							+	+											
Asteraceae	*Chrysanthemoides* sp.						+																	
Asteraceae	*Cineraria lobata*																							
Asteraceae	*Cirsium vulgare*																		+					+
Asteraceae	*Conyza bonariensis*						+	+		+	+													
Asteraceae	*Conyza canadensis*						+																	
Asteraceae	*Conyza* sp.																							
Asteraceae	*Cotula coronopifolia*											+												
Asteraceae	*Cotula zeyheri*																							
Asteraceae	*Eclipta prostrata*																							
Asteraceae	*Felicia fascicularis*																							
Asteraceae	*Gamochaeta* sp.																							
Asteraceae	*Gazania krebsiana*																							
Asteraceae	*Gazania pectinata*															+	+			+	+			
Asteraceae	*Gazania* sp.															+								
Asteraceae	*Gnaphalium group* sp.										+													
Asteraceae	*Helichrysum arenarium*																					+	+	+
Asteraceae	*Helichrysum foetidum*									+														

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Asteraceae	*Helichrysum odoratissimum*																							
Asteraceae	*Helichrysum oxyphyllum*										+													
Asteraceae	*Helichrysum* sp.									+						+								
Asteraceae	*Helichrysum subglomeratum*						+			+							+					+		+
Asteraceae	*Nidorella ivifolia*					+																		
Asteraceae	*Oedera squarrosa*																							
Asteraceae	*Pentzia incana*																							
Asteraceae	*Picris echioides*																							
Asteraceae	*Printzia polifolia?*																							
Asteraceae	*Pseudognaphalium luteo-album*										+													
Asteraceae	*Pseudognaphalium* sp.			+																				
Asteraceae	*Relhania pungens*																							
Asteraceae	*Senecio angulatus*																							
Asteraceae	*Senecio bonariensis*																							
Asteraceae	*Senecio cineraria*																							
Asteraceae	*Senecio crenatus*									+														
Asteraceae	*Senecio erubescens*									+					+									
Asteraceae	*Senecio glutinosus*										+													
Asteraceae	*Senecio ilicifolius*																						+	
Asteraceae	*Senecio inaequidens*										+						+		+					
Asteraceae	*Senecio lanceus*																							
Asteraceae	*Senecio latifolius*																							
Asteraceae	*Senecio linifolius*																							
Asteraceae	*Senecio litorosus*																							
Asteraceae	*Senecio madagascariensis*																							
Asteraceae	*Senecio oederiifolius*	+									+			+	+									
Asteraceae	*Senecio* sp.			+		+																+		

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Asteraceae	*Senecio* sp.1															+			+					
Asteraceae	*Senecio* sp. 2															+				+				
Asteraceae	*Seriphium plumosa*																				+			
Asteraceae	*Seriphium* sp.																	+						
Asteraceae	*Sonchus asper*																							
Asteraceae	*Sonchus dregeanus*																							
Asteraceae	*Sonchus oleraceus*			+																				
Asteraceae	*Syncarpha loganiana*																		+		+			
Asteraceae	*Taraxacum officinalis*																							
Asteraceae	*Vellereophyton velleum*																							
Asteraceae	*Xanthium strumarium*																							
Asteraceae	*Xanthium spinosum*																							
Boraginaceae	*Amsinckia* sp.																							
Boraginaceae	*Lobostemon trigonus*																							
Boraginaceae	*Trichodesma zeylanicum?*																							
Brassicaceae	*Canola* sp.			+																				
Brassicaceae	*Erucastrum austroafricanum*						+																	
Bryophyta	*Liverwort*							+																
Bryophyta	*Moss* 2																							
Bryophyta	*Moss* sp.	+					+	+			+												+	
Cactaceae	*Cactus* sp.																							
Campanulaceae	*Wahlenbergia procumbens*																						+	
Campanulaceae	*Wahlenbergia stellarioides?*																							
Caryophyllaceae	*Polycarpon tetraphyllum*																							
Caryophyllaceae	*Spergularia media?*																							
Caryophyllaceae	*Polycarpon* sp.																							
Celastraceae	*Gymnosporia buxifolia*																					+		
Characeae	*Chara* sp.	+		+			+	+						+				+				+	+	+

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Characeae	*Nitella* sp.																+		+				+	
Chenopodiaceae	*Atriplex nummularia?*																							
Chenopodiaceae	*Chenopodium album*						+				+								+					
Chenopodiaceae	*Chenopodium carinatum*							+																
Chenopodiaceae	*Chenopodium* sp.																							
Chlorophyceae	*Chlorophyte* sp.				+		+	+	+									+					+	
Chlorophyceae	*Oedogonium* sp.																							
Colchicaceae	*Wurmbea stricta*																+							
Commelinaceae	*Commelina benghalensis*																							
Compositae	*Hertia kraussii*																							
Convolvulaceae	*Convolvulus arvensis*												+											
Convolvulaceae	*Falkia repens*					+	+							+					+					+
Crassulaceae	*Crassula expansa*	+																						
Crassulaceae	*Crassula inanis/natans?*																							
Crassulaceae	*Crassula rubricaulis*																							
Crassulaceae	*Crassula* sp.	+																				+	+	
Crassulaceae	*Crassula tetragona*										+													
Cyperaceae	*Bolboschoenus maritimus*			+										+			+					+		
Cyperaceae	*Bolboschoenus* sp.												+											
Cyperaceae	*Carex glomerabilis*	+																						
Cyperaceae	*Carex* sp.									+														
Cyperaceae	*Carpha glomerata*																							
Cyperaceae	*Cyperaceae* sp.	+													+	+						+		
Cyperaceae	*Cyperus congestus*							+		+														
Cyperaceae	*Cyperus denudatus*			+										+			+		+					+
Cyperaceae	*Cyperus marginatus*																							+
Cyperaceae	*Cyperus nataliensis*									+														
Cyperaceae	*Cyperus* sp.								+										+					+

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Cyperaceae	*Cyperus* sp.1															+								
Cyperaceae	*Cyperus* sp. 2																							
Cyperaceae	*Cyperus thunbergii*																							
Cyperaceae	*Eleocharis dregeana*								+	+				+								+		
Cyperaceae	*Eleocharis limosa*														+							+		
Cyperaceae	*Eleocharis* sp.		+			+	+		+		+						+		+				+	
Cyperaceae	*Eleocharis* sp.2																							
Cyperaceae	*Epischoenus gracilis*																		+	+	+			
Cyperaceae	*Epischoenus* sp.																+							
Cyperaceae	*Ficinia capillifolia*						+	+		+														
Cyperaceae	*Ficinia nodosa*																+		+	+			+	
Cyperaceae	*Ficinia* sp.		+						+								+	+				+		+
Cyperaceae	*Ficinia* sp.1															+								
Cyperaceae	*Fimbristylis complanata*																	+						
Cyperaceae	*Fimbristylis dichotoma*																	+						
Cyperaceae	*Fimbristylis*																							
Cyperaceae	*Fuirena hirsuta*	+																				+	+	
Cyperaceae	*Fuirena* sp.																+							
Cyperaceae	*Fuirena* sp.1																							
Cyperaceae	*Isolepis sp.*					+																		
Cyperaceae	*Isolepis cernua*								+								+		+				+	
Cyperaceae	*Isolepis fluitans*						+	+				+					+					+	+	+
Cyperaceae	*Isolepis levynsiana*																					+		
Cyperaceae	*Isolepis marginata*	+																						
Cyperaceae	*Isolepis sepulcralis*																							
Cyperaceae	*Isolepis setacea*																					+	+	
Cyperaceae	*Isolepis* sp.		+						+		+			+		+		+		+				+
Cyperaceae	*Isolepis* sp.1	+														+			+	+				

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Cyperaceae	*Isolepis striata*																		+					
Cyperaceae	*Kyllinga erecta*																					+		+
Cyperaceae	*Pycreus nitidus*																							
Cyperaceae	*Pycreus* sp.																		+				+	
Cyperaceae	*Schoenoplectus brachyceras?*																							+
Cyperaceae	*Schoenoplectus decipiens*	+	+	+			+	+	+									+	+			+	+	+
Cyperaceae	*Schoenoplectus* sp.1											+	+											
Cyperaceae	*Schoenoplectus* sp.							+	+					+		+	+	+	+			+	+	
Cyperaceae	*Schoenoplectus triqueter*																	+						
Cyperaceae	*Schoenus nigricans*																+							
Cyperaceae	*Scirpoides* sp.	+																						
Cyperaceae	*Scleria nigra*																+							
Cyperaceae	*Scleria* sp.																+							
Cyperaceae	Sedge sp.		+																					
Cyperaceae	Sedge sp. 1																		+					
Dracaenaceae	*Dracaena hookeriana*											+												
Droseraceae	*Drosera* sp.																							
Ebenaceae	*Euclea undulata*																							
Ericaceae	*Erica chamissonis*																							
Ericaceae	*Erica copiosa*		+								+													
Ericaceae	*Erica* sp.	+	+												+					+				
Euphorbiaceae	Euphorb sp.																							
Euphorbiaceae	*Euphorbia bothae*																							
Euphorbiaceae	*Euphorbia mauritanica*																							
Fabaceae	*Acacia cyclops*			+																				
Fabaceae	*Acacia karoo*																							
Fabaceae	*Acacia longifolia*		+							+														
Fabaceae	*Acacia saligna*								+									+						

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Fabaceae	*Acacia* sp.								+									+						
Fabaceae	*Argyrolobium sericeum*																							
Fabaceae	*Argyrolobium* sp.																							
Fabaceae	*Aspalathus chortophila*								+								+							
Fabaceae	*Aspalathus* sp.																	+		+				
Fabaceae	*Aspalathus vulpina*																		+	+	+			
Fabaceae	*Calpurnia aurea*										+													
Fabaceae	*Crotalaria obscura*																							
Fabaceae	*Lessertia brachystachya*																							
Fabaceae	*Medicago* sp.																							
Fabaceae	*Trifolium repens*																							
Fabaceae	*Trifolium* sp.																							
Fabaceae	*Vicia cracca*										+													
Fabaceae	*Vicia* sp.																			+				
Frankeniaceae	*Frankenia repens?*						+																	
Gentianaceae	*Chironia* sp.																							
Geraniaceae	*Erodium moschatum*																							
Geraniaceae	*Geranium molle*																							
Geraniaceae	*Pelargonium pulverulentum*																							
Geraniaceae	*Pelargonium* sp.	+	+																					
Graphidaceae	Lichen sp. 1																							
Haemodoraceae	*Wachendorfia paniculata*																+							
Hydrocharitaceae	*Elodea nuttallii*																							+
Hydrocharitaceae	*Elodea* sp.																					+	+	
Hypoxidaceae	*Hypoxis* sp.															+			+	+				
Hypoxidaceae	*Hypoxis villosa*																							
Hypoxidaceae	*Spiloxene aquatica*																+					+		
Iridaceae	*Watsonia angusta*																							

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Iridaceae	Watsonia -like							+		+											+			
Iridaceae	Unidentified													+										
Juncaceae	*Juncus dregeanus*									+												+		+
Juncaceae	*Juncus effuses*																							
Juncaceae	*Juncus krausii*																							
Juncaceae	*Juncus rigidus*														+									
Juncaceae	*Juncus* sp.																							+
Juncaceae	*Juncus* sp.1																							
Juncaceae	*Juncus* sp. 2																							
Lamiaceae	*Salvia africana-lutea*									+														
Lamiaceae	*Stachys byzantina*						+	+																
Lamiaceae	*Teucrium africanum*																							
Lemnaceae	*Lemna gibba*			+				+		+					+									
Lobeliaceae	*Lobelia anceps*																						+	
Lobeliaceae	*Lobelia flaccida*															+								
Lobeliaceae	*Lobelia* sp.																					+		
Lobeliaceae	*Lobelia tomentosa*																							+
Lobeliaceae	*Monopsis scabra*																		+					
Lobeliaceae	*Monopsis* sp.															+			+					+
Lobeliaceae	*Wimmerella* sp.																							
Lygodiaceae	*Lygodium* sp.																							
Malvaceae	*Abutilon sonneratianum*																							
Malvaceae	*Hermannia* sp.*?*																							
Malvaceae	*Hibiscus grandifolia*																							
Malvaceae	*Hibiscus pusillus*									+														
Malvaceae	*Hibiscus trionum*									+														
Malvaceae	*Malva parviflora*						+	+			+													
Malvaceae	*Malva* sp.																		+					

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Malvaceae	*Sida rhombifolia*								+															+
Marsileaceae	Marsilea sp. 1																							
Marsileaceae	*Marsilea macrocarpa*																							
Marsileaceae	*Marsilea* sp.	+	+															+						
Mesembryanthemaceae	*Carpobrotus deliciosus*		+				+			+														
Mesembryanthemaceae	*Carpobrotus mellei*													+	+									
Mesembryanthemaceae	*Carpobrotus* sp.												+											
Mesembryanthemaceae	*Drosanthemum hispidum*																							
Mesembryanthemaceae	*Dysphemia* sp.																							
Mesembryanthemaceae	*Lampranthus* sp.																							
Mesembryanthemaceae	*Mesembryanthemum aitonis*																							
Mesembryanthemaceae	*Mesembryanthemum parviflorum*																			+	+			
Mesembryanthemaceae	*Mestoklema* sp.																							
Mesembryanthemaceae	*Ruschia cymbifolia*																							
Myoporaceae	*Myoporum tenuifolium*			+																				
Myricaceae	*Morella quercifolia*	+												+					+					
Myrsinaceae	*Rapanea* sp.																							
Nymphaeaceae	*Nymphaea* sp.																							
Ochnaceae	*Ochna serrulata*									+														
Orchidaceae	*Cyrtorchis arcuata*	+																						
Orchidaceae	*Disa bracteata*																			+				
Oxalidaceae	*Oxalis incarnata*																							
Oxalidaceae	*Oxalis latifolia*																							
Oxalidaceae	*Oxalis pes-caprae*																							
Oxalidaceae	*Oxalis* sp.									+														
Plantaginaceae	*Plantago lanceolata*																							
Plantaginaceae	*Plantago major?*																							

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Plantaginaceae	Plantago sp.					+		+		+	+								+					+
Plumbaginaceae	*Limonium linifolium*											+												
Plumbaginaceae	Plumbago sp.																							
Poaceae	*Ammophila arenaria*											+												
Poaceae	*Andropogon* sp.			+					+								+		+				+	
Poaceae	*Andropogon* sp.1															+			+	+	+			
Poaceae	*Andropogon* sp. 2															+			+	+	+			
Poaceae	*Bromus catharticus*																					+	+	
Poaceae	*Bromus* sp.																							
Poaceae	*Cynodon dactylon*	+		+		+	+	+	+	+	+		+						+			+		+
Poaceae	*Dactyloctenium* sp.																							
Poaceae	*Digitaria argyrograpta*																							
Poaceae	*Digitaria* sp.										+													+
Poaceae	*Digitaria ternata*							+																
Poaceae	*Echinochloa* sp.																							
Poaceae	*Ehrharta* sp.1																							
Poaceae	*Ehrharta* sp.				+																			
Poaceae	*Eragrostis* sp.?																							
Poaceae	*Eragrostis planiculmis*																+							
Poaceae	*Eragrostis* sp.									+														
Poaceae	*Eragrostis tef*																							
Poaceae	*Hemarthria altissima*																							
Poaceae	*Hordeum murinum*								+															
Poaceae	*Imperata cylindrica*	+	+	+		+	+	+	+		+											+	+	
Poaceae	*Imperata* sp.																							
Poaceae	Lawn Grass	+																						
Poaceae	*Leersia hexandra*										+												+	+
Poaceae	*Lolium* sp.																							

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Poaceae	*Merxmuellera disticha*													+										
Poaceae	*Panicum coloratum*										+													
Poaceae	*Panicum deustum*																							
Poaceae	*Panicum ecklonii*																							
Poaceae	*Panicum* sp.											+							+	+				
Poaceae	*Paspalum distichum*			+			+		+									+						
Poaceae	*Paspalum* sp.	+	+							+				+									+	+
Poaceae	*Paspalum vaginatum*																+							
Poaceae	*Pennisetum clandestinum*		+	+		+						+	+				+						+	
Poaceae	*Pennisetum* sp.										+					+			+	+	+			
Poaceae	*Pennisetum thunbergii*																		+					
Poaceae	*Pentaschistis heptamera*																							
Poaceae	*Phalaris minor*	+																						
Poaceae	*Phragmites australis*			+								+	+		+									
Poaceae	*Setaria incrassata*																							
Poaceae	*Setaria lindenbergiana*										+													
Poaceae	*Setaria* sp.																		+	+	+			
Poaceae	*Setaria sphacelata*																					+		
Poaceae	*Sporobolus africanus*	+																+						
Poaceae	*Sporobolus centrifugus*							+																
Poaceae	*Sporobolus fimbriatus*																					+		
Poaceae	*Sporobolus* sp.	+	+					+						+				+					+	+
Poaceae	*Stenotaphrum secundatum*					+		+		+	+			+			+							
Poaceae	*Stipagrostis* sp.															+								
Poaceae	*Stipagrostis zeyheri*										+													
Poaceae	*Tenaxia disticha?*																							
Poaceae	*Themeda* sp.															+			+	+	+	+		
Poaceae	*Themeda triandra*								+								+	+				+		

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Poaceae	*Trachypogon spicatus*																					+		
Poaceae	Water grass																							
Polygalaceae	*Muraltia ericaefolia*																	+						
Polygalaceae	*Muraltia* sp.																+							
Polygalaceae	*Polygala myrtifolia var. pinifolia?*																							
Polygonaceae	*Emex australis*																							
Polygonaceae	*Persicaria orientalis*						+	+						+										
Polygonaceae	*Persicaria serrulata*									+														
Polygonaceae	*Rumex crispus*	+		+																				
Potamogetonaceae	*Potamogeton* sp.	+							+													+	+	+
Primulaceae	*Anagallis arvensis*																		+					
Proteaceae	*Leucadendron* sp.																+							
Proteaceae	*Leucospermum* sp.															+	+			+				
Pteridophyta	*Pteridium aquilinum*									+														
Pteridophyta	*Pteridium communalis*																							
Pteridophyta	*Pteridophyta* sp.						+	+																
Ranunculaceae	*Ranunculus multifidus*										+													
Restionaceae	*Chondropetalum nudum*																	+						
Restionaceae	*Elegia ebracteata*																		+	+	+			
Restionaceae	*Elegia filacea*																	+						
Restionaceae	*Elegia microcarpa*																	+						
Restionaceae	*Elegia neesii*	+																						
Restionaceae	*Elegia* sp.																+	+						
Restionaceae	*Elegia stipularis*															+	+							
Restionaceae	*Elegia tectorum*																		+					
Restionaceae	*Ischyrolepis* sp.								+										+					
Restionaceae	*Restio capensis*																	+						

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Restionaceae	*Restio dispar*																		+					
Restionaceae	Restio sp.								+				+									+		
Restionaceae	Restio sp.1															+			+	+				
Restionaceae	Restio sp.2															+								
Restionaceae	Restio sp.3																			+				
Restionaceae	*Restio subgen. Ischyrolepis*	+	+																					
Restionaceae	*Restio tetragonus*																+							
Restionaceae	Restio-like											+												
Restionaceae	*Thamnochortus insignis*															+								
Restionaceae	*Thamnochortus insignis*																	+						
Restionaceae	*Thamnochortus lucens*											+												
Restionaceae	*Thamnochortus* sp.															+		+	+	+	+		+	
Restionaceae	*Willdenowia* sp.?		+																					
Rhamnaceae	*Phylica ericoides*	+																					+	
Rhamnaceae	*Phylica lanata*	+																						
Rhamnaceae	*Phylica* sp.															+								
Rhamnaceae	*Scutia myrtina*																							
Rivulariaceae	*Gloeotrichia* sp.	+																						+
Rosaceae	*Cliffortia* sp.													+										
Rosaceae	*Rubus* sp.											+												
Rubiaceae	*Anthospermum* sp.													+										
Rubiaceae	Rubia sp.									+														
Ruppiaceae	*Ruppia maritima*																							
Ruppiaceae	Ruppia sp.			+																			+	+
Rutaceae	*Agathosma* sp.																		+	+				
Rutaceae	*Coleonema pulchellum*	+																						
Salviniaceae	*Azolla* sp.													+										
Santalaceae	*Thesium* sp.															+								

Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	Res-A	Res-B	SBG1	CC1	DFTN	SV1	SV2	TC1	TC2	PV1A	PV1B	PV2	PV3a	PV3B	PV4	HW1	HW2	HW3
Scrophulariaceae	*Halleria lucida*									+														
Scrophulariaceae	*Ilysanthes dubia*										+					+								+
Scrophulariaceae	*Limosella grandiflora*										+													
Scrophulariaceae	*Phyllopodium cuneifolium*																							
Scrophulariaceae	*Sutera campanulata*																							
Scrophulariaceae	*Sutera pauciflora*																			+				
Solanaceae	*Cestrum laevigatum*					+																		
Solanaceae	*Nicandra physalodes*							+																
Solanaceae	*Solanum africanum*																							
Solanaceae	*Solanum americanum*																							
Solanaceae	*Solanum chrysotrichum*						+	+																
Solanaceae	*Solanum mauritianum*									+														
Stilbaceae	*Nuxia floribunda*																							
Tamaricaceae	*Tamarix usneoides?*																				+			
Thymelaeaceae	*Struthiola argentea*																+							
Thymelaeaceae	*Struthiola hirsuta*																				+			
Thymelaeaceae	*Struthiola* sp.																+	+						
Typhaceae	*Typha capensis*			+		+		+		+		+												
Ulvaceae	Ulva sp.											+	+											
Unidentified	*Eragrostis curvula*																							
Urticaceae	Urtica sp.										+													
Viscaceae	*Viscum rotundifolium*																							
Vitaceae	*Cyphostemma cirrhosum*											+												
Xanthorrhoeaceae	*Trachyandra* sp.															+			+					
Zygnemataceae	*Spirogyra* sp.																							
Zygnemataceae/Oedogoniaceae	*Spirogyra/Oedogonium* sp.			+																				
Zygophyllaceae	*Zygophyllum* sp.											+												

Table I-2 Presence/absence species list for plant species. Sites from areas 5, 6, 7 and 8 are represented here (see Figure 4-1 for general locations). See Table F-1 for further information on each site.

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Acanthaceae	*Hypoestes aristata*																						
Agavaceae	*Agave sisalana*				+																		
Aizoaceae	*Aizoon rigidum*	+	+		+							+											
Aizoaceae	Unidentified sp.																						
Aizoaceae	*Tetragonia fruticosa*		+	+	+						+												
Aizoaceae	*Tetragonia* sp.																						
Amaranthaceae	*Amaranthus* sp.	+																					
Amaranthaceae	*Atriplex* sp.																						
Amaranthaceae	*Guilleminea densa*																						
Amaranthaceae	*Salicornia quinqueflora*																		+				
Amaranthaceae	*Salicornia* sp.																						+
Amaryllidaceae	*Crinum campanulatum*																						
Amaryllidaceae	*Scadoxus multiflorus*																						
Anacardiaceae	*Searsia glauca*										+						+	+					
Anacardiaceae	*Searsia longispina*												+										
Anacardiaceae	*Searsia lucida*				+																		
Anacardiaceae	*Searsia undulata*																						
Apiaceae	*Centella asiatica*		+	+	+		+	+	+		+						+					+	+
Apiaceae	*Cyclospermum leptophyllum*																					+	+
Apiaceae	*Dasispermum suffruticosum*									+													
Apocynaceae	*Asclepias physocarpa*									+													
Apocynaceae	*Carissa bispinosa*			+																			
Apocynaceae	*Cynanchum obtusifolium*																						
Aponogetonaceae	*Aponogeton junceus*																						
Aponogetonaceae	*Aponogeton* sp.								+			+											

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Araceae	*Zantedeschia aethiopica*																						
Arecaceae	*Phoenix reclinata*																						
Asparagaceae	*Albuca* sp.																						
Asteraceae	*Anthemis cotula*			+																			
Asteraceae	*Arctotheca calendula*						+						+										
Asteraceae	*Arctotis stoechadifolia*								+														
Asteraceae	*Chrysanthemoides monilifera*							+		+			+										
Asteraceae	*Chrysanthemoides* sp.																						
Asteraceae	*Cineraria lobata*	+	+																				
Asteraceae	*Cirsium vulgare*						+						+									+	
Asteraceae	*Conyza bonariensis*												+										
Asteraceae	*Conyza canadensis*																						
Asteraceae	*Conyza* sp.										+										+	+	+
Asteraceae	*Cotula coronopifolia*																						
Asteraceae	*Cotula zeyheri*	+	+	+	+																+		
Asteraceae	*Eclipta prostrata*																			+			
Asteraceae	*Felicia fascicularis*																+						
Asteraceae	*Gamochaeta* sp.																				+		
Asteraceae	*Gazania krebsiana*									+													
Asteraceae	*Gazania pectinata*																						
Asteraceae	*Gazania* sp.																						
Asteraceae	*Gnaphalium group* sp.																						
Asteraceae	*Helichrysum arenarium*							+												+			
Asteraceae	*Helichrysum foetidum*																						
Asteraceae	*Helichrysum odoratissimum*																						+
Asteraceae	*Helichrysum oxyphyllum*																						
Asteraceae	*Helichrysum* sp.				+								+								+	+	
Asteraceae	*Helichrysum subglomeratum*										+	+	+				+						

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Asteraceae	*Nidorella ivifolia*																						
Asteraceae	*Oedera squarrosa*							+															
Asteraceae	*Pentzia incana*																+						
Asteraceae	*Picris echioides*							+															
Asteraceae	*Printzia polifolia?*	+																					
Asteraceae	*Pseudognaphalium luteo-album*																						
Asteraceae	*Pseudognaphalium* sp.																						
Asteraceae	*Relhania pungens*		+																				
Asteraceae	*Senecio angulatus*						+																
Asteraceae	*Senecio bonariensis*												+										
Asteraceae	*Senecio cineraria*	+	+																				
Asteraceae	*Senecio crenatus*																						
Asteraceae	*Senecio erubescens*																						
Asteraceae	*Senecio glutinosus*					+	+					+	+										
Asteraceae	*Senecio ilicifolius*												+										
Asteraceae	*Senecio inaequidens*	+			+							+	+										
Asteraceae	*Senecio lanceus*						+																
Asteraceae	*Senecio latifolius*																	+					
Asteraceae	*Senecio linifolius*												+										
Asteraceae	*Senecio litorosus*									+													
Asteraceae	*Senecio madagascariensis*																			+			
Asteraceae	*Senecio oederiifolius*	+	+					+	+														
Asteraceae	*Senecio* sp.																						
Asteraceae	*Senecio* sp.1																						
Asteraceae	*Senecio* sp. 2																						
Asteraceae	*Seriphium plumosa*																						
Asteraceae	*Seriphium* sp.																						
Asteraceae	*Sonchus asper*	+	+	+																			

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Asteraceae	*Sonchus dregeanus*																				+	+	+
Asteraceae	*Sonchus oleraceus*																						
Asteraceae	*Syncarpha loganiana*																						
Asteraceae	*Taraxacum officinalis*																					+	+
Asteraceae	*Vellereophyton velleum*									+													
Asteraceae	*Xanthium strumarium*	+																					
Asteraceae	*Xanthium spinosum*																					+	+
Boraginaceae	*Amsinckia* sp.																						+
Boraginaceae	*Lobostemon trigonus*	+																					
Boraginaceae	*Trichodesma zeylanicum?*										+												
Brassicaceae	*Canola* sp.																						
Brassicaceae	*Erucastrum austroafricanum*																						
Bryophyta	*Liverwort*																						
Bryophyta	Moss 2							+	+														
Bryophyta	Moss sp.	+						+	+		+		+										
Cactaceae	*Cactus* sp.		+																				
Campanulaceae	*Wahlenbergia procumbens*																						
Campanulaceae	*Wahlenbergia stellarioides?*					+	+																
Caryophyllaceae	*Polycarpon tetraphyllum*	+																					
Caryophyllaceae	*Spergularia media?*	+																					
Caryophyllaceae	*Polycarpon* sp.																				+	+	
Celastraceae	*Gymnosporia buxifolia*																						
Characeae	*Chara* sp.							+					+					+	+	+			
Characeae	*Nitella* sp.					+																	
Chenopodiaceae	*Atriplex nummularia?*				+																		
Chenopodiaceae	*Chenopodium album*	+										+											
Chenopodiaceae	*Chenopodium carinatum*																						
Chenopodiaceae	*Chenopodium* sp.																					+	+

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Chlorophyceae	*Chlorophyte* sp.											+	+					+	+				
Chlorophyceae	*Oedogonium* sp.																						+
Colchicaceae	*Wurmbea stricta*																						
Commelinaceae	*Commelina benghalensis*					+																	
Compositae	*Hertia kraussii*												+										
Convolvulaceae	*Convolvulus arvensis*											+											
Convolvulaceae	*Falkia repens*		+										+					+	+	+			+
Crassulaceae	*Crassula expansa*														+								
Crassulaceae	*Crassula inanis/natans?*																						+
Crassulaceae	*Crassula rubricaulis*																			+			
Crassulaceae	*Crassula* sp.																						
Crassulaceae	*Crassula tetragona*																						
Cyperaceae	*Bolboschoenus maritimus*																						
Cyperaceae	*Bolboschoenus* sp.																						
Cyperaceae	*Carex glomerabilis*																						
Cyperaceae	*Carex* sp.																						
Cyperaceae	*Carpha glomerata*																+						
Cyperaceae	*Cyperaceae* sp.																						
Cyperaceae	*Cyperus congestus*					+	+	+	+		+						+						
Cyperaceae	*Cyperus denudatus*																						
Cyperaceae	*Cyperus marginatus*																						
Cyperaceae	*Cyperus nataliensis*									+													
Cyperaceae	*Cyperus* sp.							+	+					+	+								
Cyperaceae	*Cyperus* sp.1																						
Cyperaceae	*Cyperus* sp. 2								+						+								
Cyperaceae	*Cyperus thunbergii*										+										+	+	
Cyperaceae	*Eleocharis dregeana*																+						
Cyperaceae	*Eleocharis limosa*								+														

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Cyperaceae	*Eleocharis* sp.							+		+					+						+	+	
Cyperaceae	*Eleocharis* sp. 2																						+
Cyperaceae	*Epischoenus gracilis*																						
Cyperaceae	*Epischoenus* sp.																						
Cyperaceae	*Ficinia capillifolia*																						
Cyperaceae	*Ficinia nodosa*						+			+													
Cyperaceae	*Ficinia* sp.																			+			
Cyperaceae	*Ficinia* sp. 1																						
Cyperaceae	*Fimbristylis complanata*																						
Cyperaceae	*Fimbristylis dichotoma*																						
Cyperaceae	*Fimbristylis*																				+		
Cyperaceae	*Fuirena hirsuta*																			+			
Cyperaceae	*Fuirena* sp.	+		+																	+		
Cyperaceae	*Fuirena* sp.1			+																			
Cyperaceae	*Isolepis sp.*																						
Cyperaceae	*Isolepis cernua*					+														+	+	+	
Cyperaceae	*Isolepis fluitans*																						
Cyperaceae	*Isolepis levynsiana*																						
Cyperaceae	*Isolepis marginata*	+			+																		
Cyperaceae	*Isolepis sepulcralis*																						+
Cyperaceae	*Isolepis setacea*		+																				
Cyperaceae	*Isolepis* sp.						+	+	+	+	+	+								+		+	
Cyperaceae	*Isolepis* sp.1																						
Cyperaceae	*Isolepis striata*																			+			
Cyperaceae	*Kyllinga erecta*																						
Cyperaceae	*Pycreus nitidus*																					+	+
Cyperaceae	*Pycreus* sp.						+																
Cyperaceae	*Schoenoplectus brachyceras?*																						

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Cyperaceae	*Schoenoplectus decipiens*											+	+									+	+
Cyperaceae	*Schoenoplectus* sp.1																						
Cyperaceae	*Schoenoplectus* sp.	+	+												+			+		+			
Cyperaceae	*Schoenoplectus* sp.2														+								
Cyperaceae	*Schoenoplectus triqueter*																						
Cyperaceae	*Schoenus nigricans*																						
Cyperaceae	*Scirpoides* sp.																						
Cyperaceae	*Scleria nigra*																						
Cyperaceae	*Scleria* sp.																						
Cyperaceae	Sedge sp.																						
Cyperaceae	Sedge sp. 1																						
Dracaenaceae	*Dracaena hookeriana*																						
Droseraceae	*Drosera* sp.								+														
Ebenaceae	*Euclea undulata*		+	+																			
Ericaceae	*Erica chamissonis*							+															
Ericaceae	*Erica copiosa*								+														
Ericaceae	*Erica* sp.										+												
Euphorbiaceae	Euphorb sp.			+																			
Euphorbiaceae	*Euphorbia bothae*				+																		
Euphorbiaceae	*Euphorbia mauritanica*			+																			
Fabaceae	*Acacia cyclops*												+										
Fabaceae	*Acacia karoo*															+					+		
Fabaceae	*Acacia longifolia*				+																		
Fabaceae	*Acacia saligna*																						
Fabaceae	*Acacia* sp.																						
Fabaceae	*Argyrolobium sericeum*						+																
Fabaceae	*Argyrolobium* sp.				+																		
Fabaceae	*Aspalathus chortophila*																						

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Fabaceae	*Aspalathus* sp.																						
Fabaceae	*Aspalathus vulpina*																						
Fabaceae	*Calpurnia aurea*																						
Fabaceae	*Crotalaria obscura*														+								
Fabaceae	*Lessertia brachystachya*	+																					
Fabaceae	*Medicago* sp.	+																					
Fabaceae	*Trifolium repens*						+																
Fabaceae	*Trifolium* sp.														+								
Fabaceae	*Vicia cracca*						+																
Fabaceae	*Vicia* sp.										+												
Frankeniaceae	*Frankenia repens?*																						
Gentianaceae	*Chironia* sp.			+	+							+											
Geraniaceae	*Erodium moschatum*	+																					
Geraniaceae	*Geranium molle*																					+	+
Geraniaceae	*Pelargonium pulverulentum*												+										
Geraniaceae	*Pelargonium* sp.																						
Graphidaceae	Lichen sp. 1												+										
Haemodoraceae	*Wachendorfia paniculata*																						
Hydrocharitaceae	*Elodea nuttallii*																						
Hydrocharitaceae	*Elodea* sp.																						
Hypoxidaceae	*Hypoxis* sp.																						
Hypoxidaceae	*Hypoxis villosa*	+	+	+	+																		
Hypoxidaceae	*Spiloxene aquatica*																						
Iridaceae	*Watsonia angusta*								+														
Iridaceae	Watsonia -like																						
Iridaceae	Unidentified																						
Juncaceae	*Juncus dregeanus*			+	+																		
Juncaceae	*Juncus effuses*			+	+																		

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Juncaceae	*Juncus krausii*	+	+	+																			
Juncaceae	*Juncus rigidus*																						
Juncaceae	*Juncus* sp.								+		+												
Juncaceae	*Juncus* sp.1														+								
Juncaceae	*Juncus* sp. 2														+								
Lamiaceae	*Salvia africana-lutea*																						
Lamiaceae	*Stachys byzantina*																						
Lamiaceae	*Teucrium africanum*												+										
Lemnaceae	*Lemna gibba*																			+			
Lobeliaceae	*Lobelia anceps*																						
Lobeliaceae	*Lobelia flaccida*																						
Lobeliaceae	*Lobelia* sp.																				+		
Lobeliaceae	*Lobelia tomentosa*																						+
Lobeliaceae	*Monopsis scabra*			+	+																		
Lobeliaceae	*Monopsis* sp.																						
Lobeliaceae	*Wimmerella* sp.											+											
Lygodiaceae	*Lygodium* sp.																+						
Malvaceae	*Abutilon sonneratianum*					+																	
Malvaceae	*Hermannia* sp.*?*	+																					
Malvaceae	*Hibiscus grandifolia*								+														
Malvaceae	*Hibiscus pusillus*																						
Malvaceae	*Hibiscus trionum*																						
Malvaceae	*Malva parviflora*																						
Malvaceae	*Malva* sp.												+								+	+	
Malvaceae	*Sida rhombifolia*																						
Marsileaceae	Marsilea sp. 1																						+
Marsileaceae	*Marsilea macrocarpa*		+								+												
Marsileaceae	*Marsilea* sp.																	+					

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Mesembryanthemaceae	*Carpobrotus deliciosus*																						
Mesembryanthemaceae	*Carpobrotus mellei*			+																			
Mesembryanthemaceae	*Carpobrotus* sp.																						
Mesembryanthemaceae	*Drosanthemum hispidum*	+	+																				
Mesembryanthemaceae	*Dysphemia* sp.																		+				
Mesembryanthemaceae	*Lampranthus* sp.												+										
Mesembryanthemaceae	*Mesembryanthemum aitonis*					+	+																
Mesembryanthemaceae	*Mesembryanthemum parviflorum*																						
Mesembryanthemaceae	*Mestoklema* sp.				+																		
Mesembryanthemaceae	*Ruschia cymbifolia*			+																			
Myoporaceae	*Myoporum tenuifolium*																						
Myricaceae	*Morella quercifolia*																						
Myrsinaceae	*Rapanea* sp.															+							
Nymphaeaceae	*Nymphaea* sp.							+															
Ochnaceae	*Ochna serrulata*																						
Orchidaceae	*Cyrtorchis arcuata*																						
Orchidaceae	*Disa bracteata*																						
Oxalidaceae	*Oxalis incarnata*																	+		+			
Oxalidaceae	*Oxalis latifolia*	+	+																				
Oxalidaceae	*Oxalis pes-caprae*																					+	
Oxalidaceae	*Oxalis* sp.			+	+																		
Plantaginaceae	*Plantago lanceolata*	+																					
Plantaginaceae	*Plantago major?*												+										
Plantaginaceae	Plantago sp.	+	+												+			+		+			
Plumbaginaceae	*Limonium linifolium*																						
Plumbaginaceae	Plumbago sp.																				+		
Poaceae	*Ammophila arenaria*																						
Poaceae	*Andropogon* sp.		+						+											+	+		

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Poaceae	*Andropogon* sp.1					+																	
Poaceae	*Andropogon* sp.2					+																	
Poaceae	*Bromus catharticus*																						
Poaceae	*Bromus* sp.														+								
Poaceae	*Cynodon dactylon*	+	+	+	+	+	+	+	+		+	+	+		+		+	+		+	+	+	+
Poaceae	*Dactyloctenium* sp.	+																					
Poaceae	*Digitaria argyrograpta*																	+					
Poaceae	*Digitaria* sp.		+								+												
Poaceae	*Digitaria ternata*																						
Poaceae	*Echinochloa* sp.						+										+						
Poaceae	*Ehrharta* sp.1																					+	+
Poaceae	*Ehrharta* sp.2																						+
Poaceae	*Ehrharta* sp.							+															
Poaceae	*Eragrostis* sp.*?*			+																			
Poaceae	*Eragrostis planiculmis*																						
Poaceae	*Eragrostis* sp.	+											+								+		+
Poaceae	*Eragrostis tef*																	+					
Poaceae	*Hemarthria altissima*																		+	+			
Poaceae	*Hordeum murinum*																						
Poaceae	*Imperata cylindrica*								+														
Poaceae	*Imperata* sp.							+															
Poaceae	Lawn Grass																						
Poaceae	*Leersia hexandra*										+		+										
Poaceae	*Lolium* sp.																					+	
Poaceae	*Merxmuellera disticha*																						
Poaceae	*Panicum coloratum*																						
Poaceae	*Panicum deustum*										+												
Poaceae	*Panicum ecklonii*												+										

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Poaceae	*Panicum* sp.																						
Poaceae	*Paspalum distichum*																						
Poaceae	*Paspalum* sp.	+	+					+	+	+					+								+
Poaceae	*Paspalum vaginatum*																						
Poaceae	*Pennisetum clandestinum*														+								
Poaceae	*Pennisetum* sp.																						
Poaceae	*Pennisetum thunbergii*		+	+	+	+	+									+							
Poaceae	*Pentaschistis heptamera*									+													
Poaceae	*Phalaris minor*																						
Poaceae	*Phragmites australis*																						
Poaceae	*Setaria incrassata*										+												
Poaceae	*Setaria lindenbergiana*								+									+					
Poaceae	*Setaria* sp.																			+			
Poaceae	*Setaria sphacelata*																						
Poaceae	*Sporobolus africanus*						+																
Poaceae	*Sporobolus centrifugus*																						
Poaceae	*Sporobolus fimbriatus*																						
Poaceae	*Sporobolus* sp.												+		+								
Poaceae	*Stenotaphrum secundatum*			+	+		+	+	+														
Poaceae	*Stipagrostis* sp.																						
Poaceae	*Stipagrostis zeyheri*																						
Poaceae	*Tenaxia disticha?*						+																
Poaceae	*Themeda* sp.																						
Poaceae	*Themeda triandra*							+									+						
Poaceae	*Trachypogon spicatus*																						
Poaceae	Water grass							+															
Polygalaceae	*Muraltia ericaefolia*																						
Polygalaceae	*Muraltia* sp.																						

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Polygalaceae	*Polygala myrtifolia var. pinifolia?*								+														
Polygonaceae	*Emex australis*												+										
Polygonaceae	*Persicaria orientalis*																						
Polygonaceae	*Persicaria serrulata*																				+	+	
Polygonaceae	*Rumex crispus*																						
Potamogetonaceae	*Potamogeton* sp.								+			+						+					+
Primulaceae	*Anagallis arvensis*					+																	
Proteaceae	*Leucadendron* sp.																						
Proteaceae	*Leucospermum* sp.																						
Pteridophyta	*Pteridium aquilinum*							+															
Pteridophyta	*Pteridium communalis*																				+	+	
Pteridophyta	*Pteridophyta* sp.																						
Ranunculaceae	*Ranunculus multifidus*																						+
Restionaceae	*Chondropetalum nudum*																						
Restionaceae	*Elegia ebracteata*																						
Restionaceae	*Elegia filacea*																						
Restionaceae	*Elegia microcarpa*																						
Restionaceae	*Elegia neesii*																						
Restionaceae	*Elegia* sp.																						
Restionaceae	*Elegia stipularis*																						
Restionaceae	*Elegia tectorum*																						
Restionaceae	*Ischyrolepis* sp.																						
Restionaceae	*Restio capensis*																						
Restionaceae	*Restio dispar*																						
Restionaceae	Restio sp.																						
Restionaceae	Restio sp.1																						
Restionaceae	Restio sp.2																						
Restionaceae	Restio sp.3																						

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Restionaceae	*Restio subgen. Ischyrolepis*																						
Restionaceae	*Restio tetragonus*																						
Restionaceae	Restio-like																						
Restionaceae	*Thamnochortus insignis*																						
Restionaceae	*Thamnochortus insignis*																						
Restionaceae	*Thamnochortus lucens*																						
Restionaceae	*Thamnochortus* sp.								+					+									
Restionaceae	*Willdenowia* sp.*?*																						
Rhamnaceae	*Phylica ericoides*																						
Rhamnaceae	*Phylica lanata*																						
Rhamnaceae	*Phylica* sp.																						
Rhamnaceae	*Scutia myrtina*		+																				
Rivulariaceae	*Gloeotrichia* sp.																						
Rosaceae	*Cliffortia* sp.							+	+														
Rosaceae	*Rubus* sp.																						
Rubiaceae	*Anthospermum* sp.																						
Rubiaceae	Rubia sp.																						
Ruppiaceae	*Ruppia maritima*																		+				
Ruppiaceae	Ruppia sp.																						
Rutaceae	*Agathosma* sp.																						
Rutaceae	*Coleonema pulchellum*																						
Salviniaceae	*Azolla* sp.																						
Santalaceae	*Thesium* sp.																						
Scrophulariaceae	*Halleria lucida*												+										
Scrophulariaceae	*Ilysanthes dubia*							+	+								+						
Scrophulariaceae	*Limosella grandiflora*																						
Scrophulariaceae	*Phyllopodium cuneifolium*						+																
Scrophulariaceae	*Sutera campanulata*																+						

Family	Taxon	RH1	RH2	RH3	RH4	VSM1	VSM2	VSR1	VSR2	CCD3	CZ6-1	EW1	PL1	VSR2	YW1	BED 1	BED 2	R75-1	R75-2	R75-3	R75-4a	R75-4b	R75-4c
Scrophulariaceae	*Sutera pauciflora*																						
Solanaceae	*Cestrum laevigatum*																						
Solanaceae	*Nicandra physalodes*																						
Solanaceae	*Solanum africanum*												+										
Solanaceae	*Solanum americanum*						+																
Solanaceae	*Solanum chrysotrichum*																						
Solanaceae	*Solanum mauritianum*																						
Stilbaceae	*Nuxia floribunda*																+						
Tamaricaceae	*Tamarix usneoides?*																						
Thymelaeaceae	*Struthiola argentea*																						
Thymelaeaceae	*Struthiola hirsuta*																						
Thymelaeaceae	*Struthiola* sp.																						
Typhaceae	*Typha capensis*																						
Ulvaceae	Ulva sp.																						
Unidentified	*Eragrostis curvula*			+																			
Urticaceae	Urtica sp.																						
Viscaceae	*Viscum rotundifolium*				+																		
Vitaceae	*Cyphostemma cirrhosum*																						
Xanthorrhoeaceae	*Trachyandra* sp.																						
Zygnemataceae	*Spirogyra* sp.																					+	
Zygnemataceae/Oedogoniaceae	*Spirogyra/Oedogonium* sp.																						
Zygophyllaceae	*Zygophyllum* sp.																						

Table I-3 Presence/absence species list for macroinvertebrate species. Sites from areas 1, 2 and 3 are represented here (see Figure 4-1 for general locations). See Table F-1 for further information on each site.

Group/Order	Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	RESA	RESB	SBG1	CC1	SV1	TC1	TC2	PV1b	PV2	PV3a
Acarina	**Unspecified**	Acarina sp.	+							+			+			+	
Amphipoda	**Unspecified**	Amphipoda (marine) sp.										+					
Anostraca	**Branchipodidae**	*Branchipodopsis hodgsoni*	+	+	+	+											
Anostraca	**Streptocephalidae**	*Streptocephalus dendyi*													+		
Anostraca	**Streptocephalidae**	*Streptocephalus* sp.															+
Araneae	**Araneidae: Araneinae**	Araneinae sp.								+							
Araneae	**Eresidae**	Eresidae sp.								+							
Araneae	**Lycosidae**	*Lycosidae* sp.															
Araneae	**Lycosidae**	*Wadicosa*? sp.								+							
Araneae	**Pisauridae: Thalassinae**	*Thalassius ?massajae*					+							+	+		
Araneae	**Segestriidae**	*Ariadna*? sp.								+							
Araneae	**Tetragnathidae**	*Tetragnatha vermiformis*	+		+		+						+				
Araneae	**Tetragnathidae**	*Tetrathemis ?polleni*													+	+	
Araneae	**Unspecified**	Araneae sp.	+				+						+				
Calanoida	**Diaptomidae: Paradiaptominae**	*Lovenula falcifera*	+										+			+	
Calanoida	**Diaptomidae: Paradiaptominae**	*Lovenula simplex*															
Calanoida	**Diaptomidae: Paradiaptominae**	*Paradiaptomus lamellatus?*											+				
Calanoida	**Diaptomidae: Paradiaptominae**	*Paradiaptomus natalensis*															
Cladocera	**Chydoridae**	*Eurycercus gr. lamellatus*															
Cladocera	**Daphniidae**	*Daphnia (Ctenodaphnia) barbata*	+														
Cladocera	**Daphniidae**	*Daphnia (Ctenodaphnia) dolichocephala*	+												+	+	
Cladocera	**Daphniidae**	*Daphnia laevis*											+				
Cladocera	**Daphniidae**	*Daphnia obtusa*			+								+				
Cladocera	**Daphniidae**	*Daphnia pulex*	+	+	+	+											
Cladocera	**Daphniidae**	*Simocephalus exspinosus*	+	+	+					+			+	+		+	
Cladocera	**Daphniidae**	*Simocephalus serrulatus*	+														
Cladocera	**Daphniidae**	*Simocephalus vetulus*											+				
Coleoptera	**Curculionidae: Bagoini**	Bagoini sp. larvae															
Coleoptera	**Curculionidae: Bagoini**	*Bagous ?humeralis adults*											+		+		

Group/Order	Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	RESA	RESB	SBG1	CC1	SV1	TC1	TC2	PV1b	PV2	PV3a
Coleoptera	**Dytiscidae: Colymbetinae: Colymbetini**	*Rhantus* sp. adults	+						+								
Coleoptera	**Dytiscidae: Colymbetinae: Colymbetini**	*Rhantus* sp. larvae	+	+	+	+			+	+					+		
Coleoptera	**Dytiscidae: Copelatinae: Copelatini**	*Copelatus* sp. larvae								+							
Coleoptera	**Dytiscidae: Dytiscinae: Cybistrini**	*Cybister* sp. adults	+										+				
Coleoptera	**Dytiscidae: Dytiscinae: Cybistrini**	*Cybister* sp. larvae	+										+		+		
Coleoptera	**Dytiscidae: Dytiscinae: Hydaticini**	*Hydaticus* (Guignotites) sp. 1 larvae													+		
Coleoptera	**Dytiscidae: Dytiscinae: Hydaticini**	*Hydaticus* (Guignotites) sp. 2 larvae												+			
Coleoptera	**Dytiscidae: Dytiscinae: Hydaticini**	*Hydaticus* (Guignotites) sp. adults							+							+	
Coleoptera	**Dytiscidae: Hydroporinae: Bidessini**	*Hydroglyphus* sp. adults	+			+											
Coleoptera	**Dytiscidae: Hydroporinae: Bidessini**	*Leiodytes* sp. 1 adults						+	+								
Coleoptera	**Dytiscidae: Hydroporinae: Bidessini**	*Leiodytes* sp. 2 adults							+								
Coleoptera	**Dytiscidae: Hydroporinae: Bidessini**	*Uvarus/Hydroglyphus*? sp. larvae				+			+	+							
Coleoptera	**Dytiscidae: Hydroporinae: Hydroporini**	*Canthyporus* sp. adults	+	+						+							
Coleoptera	**Dytiscidae: Hydroporinae: Hydrovatini**	*Hydrovatus* sp. adults															
Coleoptera	**Dytiscidae: Hydroporinae: Hydrovatini**	*Hydrovatus* sp. larvae													+		
Coleoptera	**Dytiscidae: Hydroporinae: Hygrotini**	*Herophydrus* sp. adults	+										+		+		
Coleoptera	**Dytiscidae: Hydroporinae: Hygrotini**	*Herophydrus* sp. larvae															
Coleoptera	**Dytiscidae: Hydroporinae: Hygrotini**	Hygrotini sp. Larvae	+														
Coleoptera	**Dytiscidae: Hydroporinae: Hyphydrini**	Hyphydrini sp.	+	+	+	+			+	+			+	+	+	+	
Coleoptera	**Dytiscidae: Laccophilinae: Laccophilini**	Laccophilini sp.	+						+	+			+				
Coleoptera	**Gyrinidae: Gyrininae: Gyrinini**	*Aulonogyrus* sp. adults											+				
Coleoptera	**Gyrinidae: Gyrininae: Gyrinini**	*Gyrinus (s.str.) vcinus*														+	

Group/Order	Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	RESA	RESB	SBG1	CC1	SV1	TC1	TC2	PV1b	PV2	PV3a
Coleoptera	**Gyrinidae: Gyrininae: Gyrinini**	*Gyrinus (s.str.) vcinus adults*	+										+				
Coleoptera	**Gyrinidae: Gyrininae: Gyrinini**	*Gyrinus (s.str.) vcinus larvae*	+														
Coleoptera	**Gyrinidae: Gyrininae: Orectochilini**	*Orectogyrus* sp. larvae		+													
Coleoptera	**Haliplidae**	*Haliplus* sp. adults															
Coleoptera	**Haliplidae**	*Haliplus* sp. larvae															
Coleoptera	**Helophoridae**	*Helophorus (Rhopalohelophorus) aethiops adults*															
Coleoptera	**Helophoridae**	*Helophorus (Rhopalohelophorus) aethiops larvae*	+														
Coleoptera	**Hydraenidae: Ochthebiinae: Ochthebiini**	*Ochthebius* sp. adults															
Coleoptera	**Hydrochidae**	*Hydrochus* sp. adults													+		+
Coleoptera	**Hydrophilidae: Hydrophilinae: Anacaenini**	*Anacaena* sp. adults													+		
Coleoptera	**Hydrophilidae: Hydrophilinae: Berosini**	*Berosus* sp. 1 adults															
Coleoptera	**Hydrophilidae: Hydrophilinae: Berosini**	*Berosus* sp. 2 adults															
Coleoptera	**Hydrophilidae: Hydrophilinae: Berosini**	*Berosus*? sp. larvae													+		
Coleoptera	**Hydrophilidae: Hydrophilinae: Berosini**	*Regimbartia condicta*? sp. adults													+		
Coleoptera	**Hydrophilidae: Hydrophilinae: Chaetarthriini**	*Amphiops globus adults*											+				
Coleoptera	**Hydrophilidae: Hydrophilinae: Chaetarthriini**	*Amphiops* sp. 1 larvae															
Coleoptera	**Hydrophilidae: Hydrophilinae: Chaetarthriini**	*Amphiops* sp. 2 larvae															
Coleoptera	**Hydrophilidae: Hydrophilinae: Chaetarthriini**	*Amphiops*? sp. larvae											+				
Coleoptera	**Hydrophilidae: Hydrophilinae: Hydrophilini**	*Enochrus* sp. adults							+	+			+				
Coleoptera	**Hydrophilidae: Hydrophilinae: Hydrophilini**	*Enochrus* sp. larvae	+							+							
Coleoptera	**Hydrophilidae: Hydrophilinae: Hydrophilini**	*Helochares* sp. adults									+		+				

Group/Order	Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	RESA	RESB	SBG1	CC1	SV1	TC1	TC2	PV1b	PV2	PV3a
Coleoptera	**Hydrophilidae: Hydrophilinae: Hydrophilini**	*Hydrochara* sp. larvae														+	
Coleoptera	**Hydrophilidae: Hydrophilinae: Hydrophilini**	Hydrophilini sp. larvae	+										+		+		
Coleoptera	**Hydrophilidae: Hydrophilinae: Laccobiini**	*Laccobius* sp. adults															
Coleoptera	**Hydrophilidae: Hydrophilinae: Laccobiini**	*Laccobius* sp. larvae	+		+					+							
Coleoptera	**Noteridae**	*Hydrocanthus* (Sternocanthus) sp.															
Coleoptera	**Scarabaeidae?**	Scarabaeidae? sp. adults		+													
Coleoptera	**Scirtidae**	Scirtidae sp. larvae												+			
Coleoptera	**Spercheidae**	*Spercheus ?cerisyi adults*	+		+					+			+				
Coleoptera	**Spercheidae**	*Spercheus ?cerisyi larvae*	+														
Coleoptera	**Staphylinidae**	*Staphylinidae* sp. adults					+						+				
Coleoptera	**Unspecified**	*Coleoptera spp.*	+							+			+		+		
Collembola	**Poduridae**	*Podura* sp.								+							
Conchostraca	**Leptestheriidae**	*Leptestheria*	+		+										+		+
Copepoda	**Unspecified**	*Copepodite* sp.															
Cyclopoida	**Cyclopidae**	*Ectocyclops phaleratus/Paracyclops poppei*															
Decapoda: Macrura	**Palaemonidae**	*Palaemon*? sp.										+					
Decapoda: Macrura	**Upogebiidae**	*Upogenia* sp.															
Diptera	**Chaoboridae**	*Chaoborus (Sayomyia) microstictus larvae*												+			
Diptera	**Chaoboridae**	*Chaoborus (Sayomyia) microstictus pupae*												+			
Diptera	**Chironomidae**	*Chironomidae spp. adults*			+											+	
Diptera	**Chironomidae: Chironominae: Chironomini**	*Chironomus* sp. larvae	+		+	+	+	+	+	+				+			
Diptera	**Chironomidae: Chironominae: Chironomini**	*Chironomus* sp. pupae	+	+													
Diptera	**Chironomidae: Chironominae: Chironomini**	*Polypedilum* sp. E larvae	+			+				+							

Group/Order	Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	RESA	RESB	SBG1	CC1	SV1	TC1	TC2	PV1b	PV2	PV3a
Diptera	**Chironomidae: Chironominae: Chironomini**	*Polypedilum* sp. larvae	+	+	+								+	+			
Diptera	**Chironomidae: Chironominae: Chironomini**	*Polypedilum* sp. U larvae	+														
Diptera	**Chironomidae: Chironominae: Chironomini**	*Polypedilum*? sp. pupae	+														
Diptera	**Chironomidae: Chironominae: Tanytarsini**	*Cladotanytarsus* sp. larvae	+			+											
Diptera	**Chironomidae: Chironominae: Tanytarsini**	*Cladotanytarsus* sp. pupae	+														
Diptera	**Chironomidae: Chironominae: Tanytarsini**	*Tanytarsus* sp. 1 larvae			+									+			
Diptera	**Chironomidae: Chironominae: Tanytarsini**	*Tanytarsus* sp. 2 larvae						+	+								
Diptera	**Chironomidae: Chironominae: Tanytarsini**	*Virganytarsus* sp. larvae											+				
Diptera	**Chironomidae: Chironominae: Tanytarsini**	*Virganytarsus* sp. pupae											+				
Diptera	**Chironomidae: Orthocladinae**	*Cricotopus* sp. larvae					+									+	
Diptera	**Chironomidae: Orthocladinae**	*Nanocladius* sp. larvae							+								
Diptera	**Chironomidae: Orthocladinae**	*Nanocladius* sp. pupae															
Diptera	**Chironomidae: Orthocladinae**	Orthocladinae sp. larvae	+										+				
Diptera	**Chironomidae: Orthocladinae**	*Parakiefferiella*? sp. larvae			+												
Diptera	**Chironomidae: Orthocladinae**	*Psectrocladius*? sp. larvae											+				
Diptera	**Chironomidae: Orthocladinae**	*Psectrocladius*? sp. pupae											+				
Diptera	**Chironomidae: Tanypodinae**	Tanypodinae sp.											+				
Diptera	**Corethrellidae**	*Corethrella harrisoni pupae*											+				
Diptera	**Culicidae: Anophelinae**	*Anophelinae* sp.															
Diptera	**Culicidae: Culicinae**	Culicinae sp.	+	+	+					+			+	+	+		+
Diptera	**Dixidae**	*Dixella ?harrisoni pupae*			+		+										
Diptera	**Dixidae**	*Dixella harrisoni larvae*	+		+		+						+				
Diptera	**Muscidae**	*Lispe* sp. larvae	+														
Diptera	**Stratiomyidae: Stratiomyinae**	*Odontomyia*? sp.					+							+			
Diptera	**Tabanidae**	*Tabanidae* sp. Pupae											+				

Group/Order	Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	RESA	RESB	SBG1	CC1	SV1	TC1	TC2	PV1b	PV2	PV3a
Diptera	**Tipulidae: Limoniinae**	c. f. *Gonomyia* sp. larvae			+												
Diptera	**Tipulidae: Limoniinae**	*Erioptera* sp. larvae															
Diptera	**Tipulidae: Limoniinae**	*Limnophila* sp. pupae					+										
Diptera	**Tipulidae: Limoniinae**	*Limonia* sp. larvae												+			
Diptera	**Unspecified**	*Diptera spp. adults*					+								+		
Ephemeroptera	**Baetidae**	*Cloeon* sp.	+	+	+	+			+	+			+	+	+	+	
Gastropoda	**Ancylidae**	*Ferrissia* sp.											+				
Gastropoda	**Cochlicellidae**	*Cochlicella barbara*	+				+										
Gastropoda	**Helicidae**	*Eobania vermiculata*								+							
Gastropoda	**Helicidae**	*Theba pisana*					+										
Gastropoda	**Lymnaeidae**	*Lymnaea columella*											+				
Gastropoda	**Physidae: Physinae: Physellini**	*Physella acuta*			+		+										
Gastropoda	**Planorbidae: Bulininae**	*Bulinus tropicus*	+					+					+	+			
Hemiptera	**Belostomatidae: Belostomatidae**	*Appasus* sp.	+						+				+		+		
Hemiptera	**Belostomatidae: Belostomatidae**	Belastomatinae sp.								+							
Hemiptera	**Circopidae**	Circopidae sp.	+														
Hemiptera	**Corixidae: Corixinae**	Corixinae sp.	+	+	+	+		+	+	+			+		+	+	
Hemiptera	**Corixidae: Micronectinae**	*Micronecta* sp.															
Hemiptera	**Gerridae: Gerrinae**	*Gerris swakopensis*	+		+								+			+	
Hemiptera	**Gerridae: Gerrinae**	*Neogerris severeni*													+		
Hemiptera	**Hydrometridae**	*Hydrometra* sp.															
Hemiptera	**Mesoveliidae**	*Mesovelia vittigera*											+				
Hemiptera	**Nepidae: Ranatrinae**	*Ranatra* sp.											+				
Hemiptera	**Notonectidae**	Notonectidae sp.											+				
Hemiptera	**Notonectidae: Anisopinae**	*Anisop*s sp.	+	+	+	+			+	+			+		+		
Hemiptera	**Notonectidae: Notonectinae: Notonectini**	*Enithares* sp.											+			+	
Hemiptera	**Notonectidae: Notonectinae: Notonectini**	Notonectini sp.															
Hemiptera	**Pleidae**	*Plea* sp.											+				
Hemiptera	**Unspecified**	*Hemiptera spp. adults*				+	+			+			+				
Hemiptera	**Veliidae: Veliinae**	*Angilia* sp.													+		
Hirudinae	**Glossiphoniidae**	*Alboglossiphonia conjugata*															

Group/Order	Family	Taxon	CR1	CR2	CR3	DUD1	NMMU1	RESA	RESB	SBG1	CC1	SV1	TC1	TC2	PV1b	PV2	PV3a
Hirudinae	**Glossiphoniidae**	*Alboglossiphonia macrorhyncha*															
Hirudinae	**Glossiphoniidae**	*Helobdella conifera*															
Hirudinae	**Glossiphoniidae**	*Helobdella stagnalis*							+				+				
Isopoda	**Oniscidea**	*Oniscidea*	+														
Lepidoptera	**Crambridae: Nymphulinae**	*Nymphula* sp.															
Lepidoptera	**Unspecified**	Lepidoptera sp.											+				
Nematoda	**Unspecified**	*Nematoda spp.*												+			
Notostraca	**Triopsidae**	*Triops granarius*	+												+		+
Notostraca	**Triopsidae**	*Triops* sp.											+				
Odonata: Anisoptera	**Aeshnidae**	*Aeshna minuscula/subpupillata*	+		+		+										
Odonata: Anisoptera	**Aeshnidae**	*Anax* sp.	+											+			
Odonata: Anisoptera	**Libellulidae**	Libellulidae sp	+	+	+	+	+	+	+	+			+			+	
Odonata: Zygoptera	**Coenagrionidae**	Coenagrionidae sp.	+	+	+		+	+	+	+			+	+		+	
Odonata: Zygoptera	**Lestidae**	*Lestes plagiatus/virgatus*															
Oligochaeta	**Lumbriculidae**	*Lumbriculus variegatus*					+						+				
Oligochaeta	**Naididae**	*Nais* sp.											+				
Orthoptera	**Unspecified**	Orthoptera sp.						+									
Ostracoda	**Cyprididae**	Cyprididae sp. 1			+					+			+	+	+	+	
Perciformes	**Cichlidae**	*Tilapia sparrmanii*											+				
Trichoptera	**Hydroptilidae**	*Oxyethira velocipes*											+			+	
Trichoptera	**Leptoceridae**	*Oecetis*? sp. larvae											+				

Table I-4 Presence/absence species list for macroinvertebrate species. Sites from areas 4, 6, 7 and 8 are represented here (see Figure 4-1 for general locations). See Table F-1 for further information on each site.

Group/Order	Family	Taxon	HW1	HW2	HW3	VSR1	VSR2	YW1	CDD2	EW1	PL1	BED2	R75-1	R75-2	R75-3	R75-4A	R75-4B	R75-4C
Acarina	**Unspecified**	Acarina sp.	+	+			+						+		+			
Amphipoda	**Unspecified**	Amphipoda (marine) sp.																
Anostraca	**Branchipodidae**	*Branchipodopsis hodgsoni*																
Anostraca	**Streptocephalidae**	*Streptocephalus dendyi*					+											
Anostraca	**Streptocephalidae**	*Streptocephalus* sp.																
Araneae	**Araneidae: Araneinae**	Araneinae sp.	+										+		+			
Araneae	**Eresidae**	Eresidae sp.	+										+					
Araneae	**Lycosidae**	*Lycosidae* sp.			+													
Araneae	**Lycosidae**	*Wadicosa*? sp.																
Araneae	**Pisauridae: Thalassinae**	*Thalassius ?massajae*	+					+				+	+					
Araneae	**Segestriidae**	*Ariadna*? sp.																
Araneae	**Tetragnathidae**	*Tetragnatha vermiformis*	+															
Araneae	**Tetragnathidae**	*Tetrathemis ?polleni*																
Araneae	**Unspecified**	Araneae sp.						+					+					
Calanoida	**Diaptomidae: Paradiaptominae**	*Lovenula falcifera*	+	+	+		+								+			
Calanoida	**Diaptomidae: Paradiaptominae**	*Lovenula simplex*			+													
Calanoida	**Diaptomidae: Paradiaptominae**	*Paradiaptomus lamellatus?*	+	+			+											
Calanoida	**Diaptomidae: Paradiaptominae**	*Paradiaptomus natalensis*						+										
Cladocera	**Chydoridae**	*Eurycercus gr. lamellatus*											+					
Cladocera	**Daphniidae**	*Daphnia (Ctenodaphnia) barbata*																
Cladocera	**Daphniidae**	*Daphnia (Ctenodaphnia) dolichocephala*		+														
Cladocera	**Daphniidae**	*Daphnia laevis*			+	+												

Group/Order	Family	Taxon	HW1	HW2	HW3	VSR1	VSR2	YW1	CDD2	EW1	PL1	BED2	R75-1	R75-2	R75-3	R75-4A	R75-4B	R75-4C
Cladocera	**Daphniidae**	*Daphnia obtusa*																
Cladocera	**Daphniidae**	*Daphnia pulex*																
Cladocera	**Daphniidae**	*Simocephalus exspinosus*	+	+											+			
Cladocera	**Daphniidae**	*Simocephalus serrulatus*																
Cladocera	**Daphniidae**	*Simocephalus vetulus*				+	+											
Coleoptera	**Curculionidae: Bagoini**	Bagoini sp. larvae											+					
Coleoptera	**Curculionidae: Bagoini**	*Bagous ?humeralis adults*	+										+		+			
Coleoptera	**Dytiscidae: Colymbetinae: Colymbetini**	*Rhantus* sp. adults						+					+					
Coleoptera	**Dytiscidae: Colymbetinae: Colymbetini**	*Rhantus* sp. larvae						+							+			
Coleoptera	**Dytiscidae: Copelatinae: Copelatini**	*Copelatus* sp. larvae																
Coleoptera	**Dytiscidae: Dytiscinae: Cybistrini**	*Cybister* sp. adults	+															
Coleoptera	**Dytiscidae: Dytiscinae: Cybistrini**	*Cybister* sp. larvae	+	+	+								+		+			
Coleoptera	**Dytiscidae: Dytiscinae: Hydaticini**	*Hydaticus* (Guignotites) sp. 1 larvae																
Coleoptera	**Dytiscidae: Dytiscinae: Hydaticini**	*Hydaticus* (Guignotites) sp. 2 larvae						+										
Coleoptera	**Dytiscidae: Dytiscinae: Hydaticini**	*Hydaticus* (Guignotites) sp. adults			+													
Coleoptera	**Dytiscidae: Hydroporinae: Bidessini**	*Hydroglyphus* sp. adults		+				+										
Coleoptera	**Dytiscidae: Hydroporinae: Bidessini**	*Leiodytes* sp. 1 adults																
Coleoptera	**Dytiscidae: Hydroporinae: Bidessini**	*Leiodytes* sp. 2 adults																
Coleoptera	**Dytiscidae: Hydroporinae: Bidessini**	*Uvarus/Hydroglyphus*? sp. larvae																

Group/Order	Family	Taxon	HW1	HW2	HW3	VSR1	VSR2	YW1	CDD2	EW1	PL1	BED2	R75-1	R75-2	R75-3	R75-4A	R75-4B	R75-4C
Coleoptera	**Dytiscidae: Hydroporinae: Hydroporini**	*Canthyporus* sp. adults											+					
Coleoptera	**Dytiscidae: Hydroporinae: Hydrovatini**	*Hydrovatus* sp. adults			+													
Coleoptera	**Dytiscidae: Hydroporinae: Hydrovatini**	*Hydrovatus* sp. larvae											+					
Coleoptera	**Dytiscidae: Hydroporinae: Hygrotini**	*Herophydrus* sp. adults	+	+				+					+		+			
Coleoptera	**Dytiscidae: Hydroporinae: Hygrotini**	*Herophydrus* sp. larvae		+				+					+		+			
Coleoptera	**Dytiscidae: Hydroporinae: Hygrotini**	Hygrotini sp. Larvae																
Coleoptera	**Dytiscidae: Hydroporinae: Hyphydrini**	Hyphydrini sp.	+	+	+	+	+	+					+		+			
Coleoptera	**Dytiscidae: Laccophilinae: Laccophilini**	Laccophilini sp.	+	+	+	+		+							+			
Coleoptera	**Gyrinidae: Gyrininae: Gyrinini**	*Aulonogyrus* sp. adults	+			+												
Coleoptera	**Gyrinidae: Gyrininae: Gyrinini**	*Gyrinus (s.str.) vicinus*																
Coleoptera	**Gyrinidae: Gyrininae: Gyrinini**	*Gyrinus (s.str.) vicinus adults*																
Coleoptera	**Gyrinidae: Gyrininae: Gyrinini**	*Gyrinus (s.str.) vicinus larvae*													+			
Coleoptera	**Gyrinidae: Gyrininae: Orectochilini**	*Orectogyrus* sp. larvae																
Coleoptera	**Haliplidae**	*Haliplus* sp. adults		+		+							+					
Coleoptera	**Haliplidae**	*Haliplus* sp. larvae		+									+					
Coleoptera	**Helophoridae**	*Helophorus (Rhopalohelophorus) aethiops adults*						+										

Group/Order	Family	Taxon	HW1	HW2	HW3	VSR1	VSR2	YW1	CDD2	EW1	PL1	BED2	R75-1	R75-2	R75-3	R75-4A	R75-4B	R75-4C
Coleoptera	**Helophoridae**	*Helophorus (Rhopalohelophorus) aethiops larvae*																
Coleoptera	**Hydraenidae: Ochthebiinae: Ochthebiini**	*Ochthebius* sp. adults								+								
Coleoptera	**Hydrochidae**	*Hydrochus* sp. adults			+	+												
Coleoptera	**Hydrophilidae: Hydrophilinae: Anacaenini**	*Anacaena* sp. adults			+													
Coleoptera	**Hydrophilidae: Hydrophilinae: Berosini**	*Berosus* sp. 1 adults												+				
Coleoptera	**Hydrophilidae: Hydrophilinae: Berosini**	*Berosus* sp. 2 adults							+									
Coleoptera	**Hydrophilidae: Hydrophilinae: Berosini**	*Berosus*? sp. larvae																
Coleoptera	**Hydrophilidae: Hydrophilinae: Berosini**	*Regimbartia condicta*? sp. adults			+										+			
Coleoptera	**Hydrophilidae: Hydrophilinae: Chaetarthriini**	*Amphiops globus adults*			+	+	+						+					
Coleoptera	**Hydrophilidae: Hydrophilinae: Chaetarthriini**	*Amphiops* sp. 1 larvae											+					
Coleoptera	**Hydrophilidae: Hydrophilinae: Chaetarthriini**	*Amphiops* sp. 2 larvae	+				+											
Coleoptera	**Hydrophilidae: Hydrophilinae: Chaetarthriini**	*Amphiops*? sp. larvae																
Coleoptera	**Hydrophilidae: Hydrophilinae: Hydrophilini**	*Enochrus* sp. adults			+													
Coleoptera	**Hydrophilidae: Hydrophilinae: Hydrophilini**	*Enochrus* sp. larvae										+	+					

Group/Order	Family	Taxon	HW1	HW2	HW3	VSR1	VSR2	YW1	CDD2	EW1	PL1	BED2	R75-1	R75-2	R75-3	R75-4A	R75-4B	R75-4C
Coleoptera	**Hydrophilidae: Hydrophilinae: Hydrophilini**	*Helochares* sp. adults			+													
Coleoptera	**Hydrophilidae: Hydrophilinae: Hydrophilini**	*Hydrochara* sp. larvae																
Coleoptera	**Hydrophilidae: Hydrophilinae: Hydrophilini**	Hydrophilini sp. larvae			+													
Coleoptera	**Hydrophilidae: Hydrophilinae: Laccobiini**	*Laccobius* sp. adults								+								
Coleoptera	**Hydrophilidae: Hydrophilinae: Laccobiini**	*Laccobius* sp. larvae			+								+					
Coleoptera	**Noteridae**	*Hydrocanthus* (Sternocanthus) sp.			+													
Coleoptera	**Scarabaeidae?**	Scarabaeidae? sp. adults																
Coleoptera	**Scirtidae**	Scirtidae sp. larvae																
Coleoptera	**Spercheidae**	*Spercheus ?cerisyi adults*				+	+	+							+			
Coleoptera	**Spercheidae**	*Spercheus ?cerisyi larvae*					+					+						
Coleoptera	**Staphylinidae**	*Staphylinidae* sp. adults	+		+													
Coleoptera	**Unspecified**	*Coleoptera spp.*			+		+	+					+					
Collembola	**Poduridae**	*Podura* sp.																
Conchostraca	**Leptestheriidae**	*Leptestheria*																
Copepoda	**Unspecified**	*Copepodite* sp.											+					
Cyclopoida	**Cyclopidae**	*Ectocyclops phaleratus/Paracyclops poppei*								+								
Decapoda: Macrura	**Palaemonidae**	*Palaemon*? sp.																
Decapoda: Macrura	**Upogebiidae**	*Upogenia* sp.							+									
Diptera	**Chaoboridae**	*Chaoborus (Sayomyia) microstictus larvae*	+	+	+													
Diptera	**Chaoboridae**	*Chaoborus (Sayomyia) microstictus pupae*																

Group/Order	Family	Taxon	HW1	HW2	HW3	VSR1	VSR2	YW1	CDD2	EW1	PL1	BED2	R75-1	R75-2	R75-3	R75-4A	R75-4B	R75-4C
Diptera	**Chironomidae**	*Chironomidae spp. adults*																
Diptera	**Chironomidae: Chironominae: Chironomini**	*Chironomus* sp. larvae										+				+		
Diptera	**Chironomidae: Chironominae: Chironomini**	*Chironomus* sp. pupae																
Diptera	**Chironomidae: Chironominae: Chironomini**	*Polypedilum* sp. E larvae																
Diptera	**Chironomidae: Chironominae: Chironomini**	*Polypedilum* sp. larvae	+	+	+	+	+				+	+	+		+			
Diptera	**Chironomidae: Chironominae: Chironomini**	*Polypedilum* sp. U larvae																
Diptera	**Chironomidae: Chironominae: Chironomini**	*Polypedilum*? sp. pupae																
Diptera	**Chironomidae: Chironominae: Tanytarsini**	*Cladotanytarsus* sp. larvae																
Diptera	**Chironomidae: Chironominae: Tanytarsini**	*Cladotanytarsus* sp. pupae																
Diptera	**Chironomidae: Chironominae: Tanytarsini**	*Tanytarsus* sp. 1 larvae			+	+												
Diptera	**Chironomidae: Chironominae: Tanytarsini**	*Tanytarsus* sp. 2 larvae														+		
Diptera	**Chironomidae: Chironominae: Tanytarsini**	*Virganytarsus* sp. larvae																
Diptera	**Chironomidae: Chironominae: Tanytarsini**	*Virganytarsus* sp. pupae																
Diptera	**Chironomidae: Orthocladiinae**	*Cricotopus* sp. larvae				+		+							+			
Diptera	**Chironomidae: Orthocladiinae**	*Nanocladius* sp. larvae						+					+					
Diptera	**Chironomidae: Orthocladiinae**	*Nanocladius* sp. pupae											+					
Diptera	**Chironomidae: Orthocladiinae**	Orthocladiinae sp. larvae																

Group/Order	Family	Taxon	HW1	HW2	HW3	VSR1	VSR2	YW1	CDD2	EW1	PL1	BED2	R75-1	R75-2	R75-3	R75-4A	R75-4B	R75-4C
Diptera	**Chironomidae: Orthocladiinae**	*Parakiefferiella*? sp. larvae																
Diptera	**Chironomidae: Orthocladiinae**	*Psectrocladius*? sp. larvae																
Diptera	**Chironomidae: Orthocladiinae**	*Psectrocladius*? sp. pupae																
Diptera	**Chironomidae: Tanypodinae**	Tanypodinae sp.			+	+					+					+		
Diptera	**Corethrellidae**	*Corethrella harrisoni pupae*																
Diptera	**Culicidae: Anophelinae**	*Anophelinae* sp.											+					
Diptera	**Culicidae: Culicinae**	Culicinae sp.						+			+	+				+		
Diptera	**Dixidae**	*Dixella ?harrisoni pupae*																
Diptera	**Dixidae**	*Dixella harrisoni larvae*	+										+					
Diptera	**Muscidae**	*Lispe* sp. larvae																
Diptera	**Stratiomyidae: Stratiomyinae**	*Odontomyia*? sp.											+					
Diptera	**Tabanidae**	*Tabanidae* sp. Pupae																
Diptera	**Tipulidae: Limoniinae**	c. f. *Gonomyia* sp. larvae																
Diptera	**Tipulidae: Limoniinae**	*Erioptera* sp. larvae											+					
Diptera	**Tipulidae: Limoniinae**	*Limnophila* sp. pupae																
Diptera	**Tipulidae: Limoniinae**	*Limonia* sp. larvae																
Diptera	**Unspecified**	*Diptera spp. adults*																
Ephemeroptera	**Baetidae**	*Cloeon* sp.	+	+	+	+	+	+		+	+	+	+	+				
Gastropoda	**Ancylidae**	*Ferrissia* sp.	+															
Gastropoda	**Cochlicellidae**	*Cochlicella barbara*											+					
Gastropoda	**Helicidae**	*Eobania vermiculata*																
Gastropoda	**Helicidae**	*Theba pisana*																
Gastropoda	**Lymnaeidae**	*Lymnaea columella*			+	+	+											
Gastropoda	**Physidae: Physinae: Physellini**	*Physella acuta*	+								+							
Gastropoda	**Planorbidae: Bulininae**	*Bulinus tropicus*	+	+	+								+		+			

Group/Order	Family	Taxon	HW1	HW2	HW3	VSR1	VSR2	YW1	CDD2	EW1	PL1	BED2	R75-1	R75-2	R75-3	R75-4A	R75-4B	R75-4C
Hemiptera	**Belostomatidae: Belostomatidae**	*Appasus* sp.	+	+	+	+							+					
Hemiptera	**Belostomatidae: Belostomatidae**	Belastomatinae sp.											+		+			
Hemiptera	**Circopidae**	Circopidae sp.																
Hemiptera	**Corixidae: Corixinae**	Corixinae sp.	+	+	+	+	+	+		+	+	+	+	+	+			
Hemiptera	**Corixidae: Micronectinae**	*Micronecta* sp.	+	+	+					+								
Hemiptera	**Gerridae: Gerrinae**	*Gerris swakopensis*	+										+		+			
Hemiptera	**Gerridae: Gerrinae**	*Neogerris severeni*																
Hemiptera	**Hydrometridae**	*Hydrometra* sp.											+					
Hemiptera	**Mesoveliidae**	*Mesovelia vittigera*			+													
Hemiptera	**Nepidae: Ranatrinae**	*Ranatra* sp.													+			
Hemiptera	**Notonectidae**	Notonectidae sp.																
Hemiptera	**Notonectidae: Anisopinae**	*Anisop*s sp.	+			+	+			+	+		+	+	+			
Hemiptera	**Notonectidae: Notonectinae: Notonectini**	*Enithares* sp.	+	+	+													
Hemiptera	**Notonectidae: Notonectinae: Notonectini**	Notonectini sp.			+													
Hemiptera	**Pleidae**	*Plea* sp.	+	+	+			+										
Hemiptera	**Unspecified**	*Hemiptera spp. adults*			+													
Hemiptera	**Veliidae: Veliinae**	*Angilia* sp.																
Hirudinae	**Glossiphoniidae**	*Alboglossiphonia conjugata*		+														
Hirudinae	**Glossiphoniidae**	*Alboglossiphonia macrorhyncha*		+	+													
Hirudinae	**Glossiphoniidae**	*Helobdella conifera*	+		+					+			+					
Hirudinae	**Glossiphoniidae**	*Helobdella stagnalis*				+				+	+							
Isopoda	**Oniscidea**	*Oniscidea*																
Lepidoptera	**Crambridae: Nymphulinae**	*Nymphula* sp.	+			+												
Lepidoptera	**Unspecified**	Lepidoptera sp.																
Nematoda	**Unspecified**	*Nematoda spp.*																

Group/Order	Family	Taxon	HW1	HW2	HW3	VSR1	VSR2	YW1	CDD2	EW1	PL1	BED2	R75-1	R75-2	R75-3	R75-4A	R75-4B	R75-4C
Notostraca	**Triopsidae**	*Triops granarius*																
Notostraca	**Triopsidae**	*Triops* sp.																
Odonata: Anisoptera	**Aeshnidae**	*Aeshna minuscula/subpupillata*				+												
Odonata: Anisoptera	**Aeshnidae**	*Anax* sp.	+	+	+	+												
Odonata: Anisoptera	**Libellulidae**	Libellulidae sp	+		+	+				+	+		+		+	+		
Odonata: Zygoptera	**Coenagrionidae**	Coenagrionidae sp.	+	+	+	+	+				+	+	+	+				
Odonata: Zygoptera	**Lestidae**	*Lestes plagiatus/virgatus*			+	+	+								+			
Oligochaeta	**Lumbriculidae**	*Lumbriculus variegatus*			+	+	+									+	+	+
Oligochaeta	**Naididae**	*Nais* sp.																
Orthoptera	**Unspecified**	Orthoptera sp.																
Ostracoda	**Cyprididae**	Cyprididae sp. 1	+	+	+		+	+					+	+	+			
Perciformes	**Cichlidae**	*Tilapia sparrmanii*																
Trichoptera	**Hydroptilidae**	*Oxyethira velocipes*			+													
Trichoptera	**Leptoceridae**	*Oecetis*? sp. larvae																

Table I-5 Presence/absence species list for tadpole species. See Table F-1 for further information on each site.

Family	Taxon	CR1	CR2	CR3	NMMU1	SBG1	DuD1	TC2	TC1	PV 1	PV 2	HW1	HW 2	HW3	R75-1	R75-3
Bufonidae	*Amietophrynus ?rangeri*					+	+				+					
Bufonidae	*Amietophrynus pardalis*						+									
Hyperoliidae	*Hyperolius marmoratus*							+	+			+	+	+		
Hyperoliidae	*Semnodactylus wealii*											+	+			

Pipidae	*Xenopus laevis*			+		+			+	+	+	+	+	+	+	+	
Pyxicephalidae	*Cacosternum ?nanum*		+	+		+	+		+	+	+						
Pyxicephalidae	*Cacosternum boettgeri*							+	+		+	+	+		+	+	
Pyxicephalidae	*Strongylopus fasciatus*							+	+								
Pyxicephalidae	*Strongylopus grayii*					+				+							
Pyxicephalidae	*Tomopterna delalandii*	+	+		+	+	+				+		+				