MORPHOLOGY, PATTERNS AND PROCESSES IN THE OYSTER BAY HEADLAND BYPASS DUNEFIELD, SOUTH AFRICA

Thesis submitted in fulfillment of the requirements for the degree of

Master of Science

by

Lauren Elkington

Department of Geography
Rhodes University
Grahamstown
South Africa
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ABSTRACT

Studies of the dunefield systems crossing the Cape St. Francis headland in the Eastern Cape have focused on the role that wind plays in sediment transfer in coastal dunefield systems, with limited consideration of the role of water. The aim of this study was to improve understanding of the morphology, processes and patterns within the Oyster Bay HBD system, focussing particularly on surface water and groundwater interactions and the role of surface water in sediment transfer across the dunefield system. An extensive field survey was conducted, to collect related data, complimented by spatial and temporal analysis of the study area using GIS. The key findings from this research were the apparent differences between the western and eastern regions of the dunefield with regard to specific drivers and the respective processes and responses. Wind is the major driver of change up to and across the crest of the dunefield. In the eastern region water (ground water, surface water and the Sand River System) is the primary agent of sediment flux through processes of aggregation and slumping as well as episodic events including debris flows. This study has highlighted a need for further quantitative studies that investigate the movement of sediment through dunefield systems such as this (where water is at or near the land surface). The paradigm that sediment flux is entirely due to wind is almost certainly simplistic, and deeper understanding of these systems is needed.

DECLARATION

The work described in this research project was carried out, over a period from 2008 – 2012, under the supervision of Ms Gillian McGregor (Geography Department, Rhodes University), Prof. Fred Ellery (Environmental Science Department, Rhodes University) and Prof. Richard Cowling (main funder, Department of Botany, Nelson Mandela Metropolitan University). The research was carried out in fulfilment of the academic requirements for the degree of Master of Science in Geography. This study represents original work by the author, and opinions expressed and conclusions arrived at are those of the author. The author has read and accepted the Rhodes University plagiarism policy. Where use has been made of the work of others it is duly acknowledged.

ACKNOWLEDGEMENTS

I would like to thank my friends and family for their on-going support throughout this research. Many of you helped me with fieldwork, some of you on more than one occasion, often in less than desirable weather – a big thank you to all of you. To my parents and family, thank you for your on-going financial support and encouragement throughout my studies. To Matt, I could not have finished this dissertation without your help in the dunefield and your endless support!

Thank you to Ms Gillian McGregor, my supervisor and friend, for your input into this research and many hours that you helped with the fieldwork. I look forward to drinking tea with you in many more beautiful places. To my co-supervisor, Prof. Fred Ellery, thank you for your invaluable input into this research and for your dedication to helping me finish this dissertation. Thank you to your family too for their help with the field work on more than one occasion. Thanks also go to Prof. Richard Cowling for the initial idea for this research, financial support, academic contribution and co-supervision.

Finally, thank you to everyone else who has contributed in some way to this research: members of the community of Cape St. Francis and surrounds, especially Carol and Bart Logie; the staff and colleagues in the Department of Geography and the Department of Environmental Science at Rhodes University; and the Department of Geography's GIS Honours classes of 2008 and 2009.

To all of you, I hope that when you find fine grains of sand in your pockets, shoes or socks, you think of this beautiful and unique dunefield system!

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ACRONYMS AND ABBREVIATIONS

B&B – Bed & Breakfast

NGI – National Geo-Spatial Information

CDSM – Chief Directorate: Surveys and Mapping

CSIR – Council for Scientific and Industrial Research

DEAT – Department of Environmental Affairs and Tourism

DEDEA – Department of Economic Development and Environmental Affairs

DEIR – Draft Environmental Impact Report

EC – Electrical Conductivity

EIA – Environmental Impact Assessment

GIS – Geographical Information System

GPS – Geographical Positioning System

HB – Herbaceous Bulbous

HBD – Headland Bypass Dunefield

HFR – Herbaceous Forb Rhizomatous

HFT – Herbaceous Forb Tufted

HGR – Herbaceous Graminoid Rhizomatous

HGT – Herbaceous Graminoid Tufted

IDP – Integrated Development Plan

Lo – Longitude of Origin

NB – Northern Boundary

NBP – Northern Boundary Profile

ND – Northern Dunefield

NDP – Northern Dunefield Profile

NPS – Nuclear Power Station

OBHBD – Oyster Bay Headland Bypass Dunefield

P1, P2, etc. – Profile 1, Profile 2, etc.

PRB – Population Reference Bureau

PZ – Piezometer

SAWS – South African Weather Services

SB – Southern Boundary

SBP – Southern Boundary Profile

SD – Southern Dunefield

SDP – Southern Dunefield Profile

UTM – Universal Transverse Mercator

WBR – Woody Broad-leaved Rhizomatous

WBT – Woody Broad-leaved Tufted

WERU – Wind Erosion Research Unit

WNR – Woody Narrow-leaved Rhizomatous

WNT – Woody Narrow-leaved Tufted

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CHAPTER 1: INTRODUCTION

1.1INTRODUCTION

This chapter provides a general introduction to the research undertaken for this dissertation. The research was conducted from 2008 – 2011, with the main field work component taking place between November 2008 and November 2009.

1.1.1 Key Terms

Dunefield systems are 'process-response' systems (Chorley & Kennedy, 1971 and Allen, 1974) that show a strong relationship between the driving forces and their resultant form and processes. At the outset it is important to define the spatial and temporal scales at which a range of processes operate and the appropriate terminology. A conceptual framework illustrating important landforms and processes of change is therefore presented as Figure 1-1.

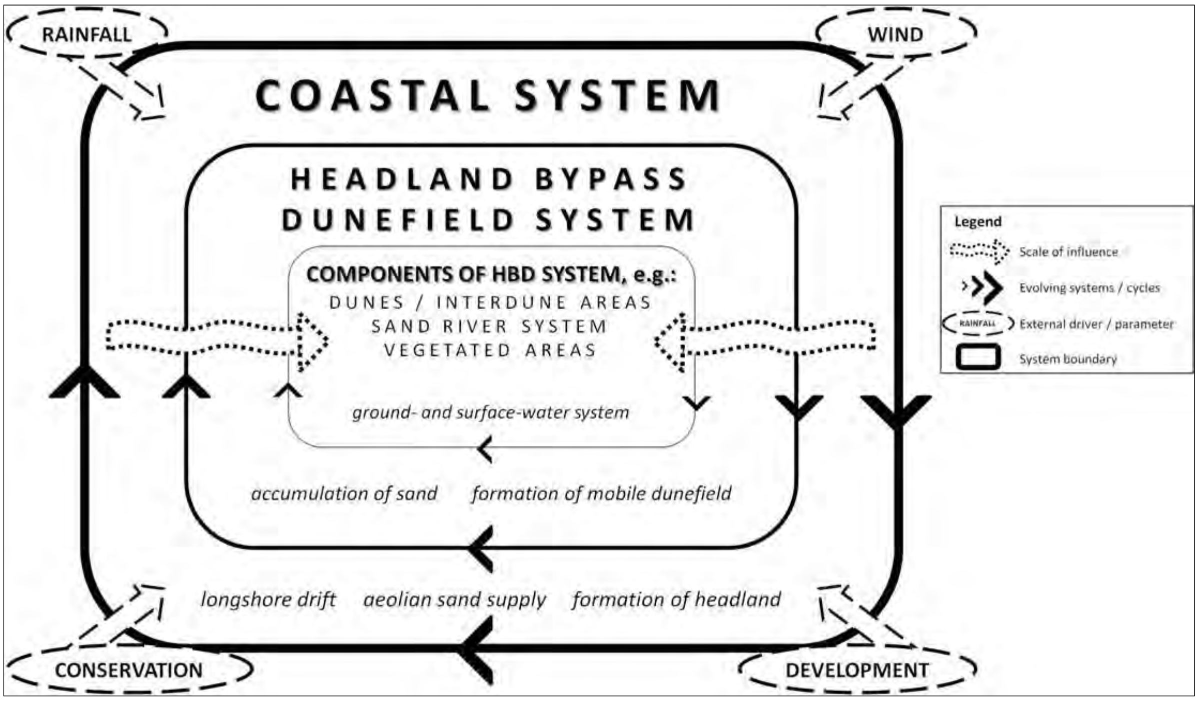


Figure 1-1: Conceptual diagram to show the scales at which systems operate and their spheres of influence on smaller systems' components and dynamics. Typical processes that occur at the various scales are shown in italics; while external drivers / parameters are shown to have an influence at all scales.

The diagram shows that the coastal system is the largest system of influence, incorporating processes such as longshore drift, aeolian sand supply from the sea onto the headland, and persistence of the headland between the sediment supplying and receiving bays. Processes within coastal systems typically occur over a long temporal (tens to hundreds of years) and spatial scales (tens to hundreds of square kilometres). It is this system and its associated processes that have led to the formation and partially govern the functioning of the Headland Bypass Dunefield (HBD) systems that occur across the Cape St. Francis headland.

Within HBD systems, specifically the Oyster Bay HBD system that was examined in this research, there are certain components that can be identified. The dunefield comprises a set of mobile dunes that are bounded by vegetated (stabilised) dunes to the south, and near-horizontal planed rocks of the Cape Supergroup in certain regions to the north that form part of the Post-African I erosion surface to the north. At the scale of the HBD, the system comprises sand dunes and interdune areas that have variable spacing and orientation in relation to the prevailing wind. Groundwater influences the elevation to which the dune system can erode, therefore acting as a base level for wind erosion within the dunefield (wind cannot remove material that is covered with water). Areas of the dunefield are vegetated with various vegetation types that are likely to be related to substratum mobility. The Sand River System located in the north eastern region, which flows intermittently during periods of heavy rain, is an expression of hydrological processes in the dunefield. The Sand River System may also act as an important agent of sediment flux from the dunefield to St Francis Bay.

Considering the various components of HBD systems occurring at smaller scales, while acknowledging the influential processes occurring in the coastal system at larger scales, will prove critical to the overall understanding of HBDs and their associated components. Contextualising external drivers or parameters such as rainfall and wind or physical infrastructural development will also aid in better understanding the functioning of HBD systems over time.

1.2 COASTAL SYSTEMS AND THEIR MANAGEMENT

The coastal zones of the world are under enormous pressure and are undergoing environmental decline (Creel, 2003). This is partly due to the fact that large and growing proportions of the world's population live within close proximity to the coastline. In South Africa, 40% of the population lives within 100 kms of the coastline (Department of Environmental Affairs and Tourism (DEAT), 2006). According to Tibbits (2002), cities within this zone have been continually expanding for the past 50 years. Increasing human and environmental pressure on South Africa's coastal resources has led to a change in both the function and structure of many coastal features (Attwood *et al*., 2002), which has resulted in increased degradation, loss and poorly managed use of coastal resources in many circumstances (Attwood *et al*., 2002 and DEAT, 2006). Unless government and interested and affected parties acknowledge the pressures that an increasing population and associated economic activities have on coastal systems, further degradation is probable (Creel, 2003). A balance between reaping benefits from and conserving coastal resources needs to be established, especially in the case of coastal dunefield systems that are particularly fragile (Carboni *et al*., 2009).

Coastal dunefields are dynamic, sensitive (largely or partially) systems, impacted by many factors, such as sediment supply, hydrological conditions, vegetation cover, climatic factors including episodic events such as large storms, as well as human activities on the coast (Rust & Illenberger, 1996). The dynamic nature of coastal dunefield systems have presented coastal scientists with numerous challenges (Andrews *et al*., 2002). In South Africa, the functioning of coastal dunefields, specifically the movement of aeolian and littoral sand, has been poorly studied, resulting in inappropriate management decisions being made that have been detrimental to the functioning of certain dunefield systems and the associated coastlines – such as dune stabilisation (McLachlan & Burns, 1992 and La Cock & Burkinshaw, 1996). Tinley (1985) noted that approximately 70% of the Southern African coastline consisted of sandy beaches at that time, most of which are associated with stabilised or mobile dune systems and are particularly vulnerable to inappropriate forms of land use.

1.2.1 HBD systems and their management: the case of the Cape St. Francis headland

HBD systems, that are most common along the southern coast of South Africa, have been particularly poorly studied and as a result, poorly managed (Tinley, 1985). HBD systems play an important role in maintaining the coastal sediment budget due to the fact that headlands disrupt the longshore transport of sand (Tinley, 1985: 215 and McLachlan *et al*., 1994). HBDs need to be considered within the context of a greater coastal sediment transport system (Figure 1-1). However, they equally need to be studied and understood as systems functioning in their own right (McLachan, 1990).

Within HBD systems, wave and wind direction is such that sand is blown onshore at the open sandy, upwind bay and is moved towards the downwind bay ending up on the beach (McLachlan & Burns, 1992). These systems tend to be largely unvegetated, allowing for the shifting of transverse dune ridges across headlands in corridors that run parallel to the predominant wind direction (McLachlan *et al.,* 1994), such as between Oyster Bay and St. Francis Bay in the Eastern Cape, South Africa (Figure 1-2 and Figure 2-1), the study area for this research. This area is home to one of the only and possibly best examples of remaining active HBD systems in southern Africa (Illenberger & Burkinshaw, 2008 and La Cock & Burkinshaw, 1996) and it is the Oyster Bay HBD that was investigated in this research.

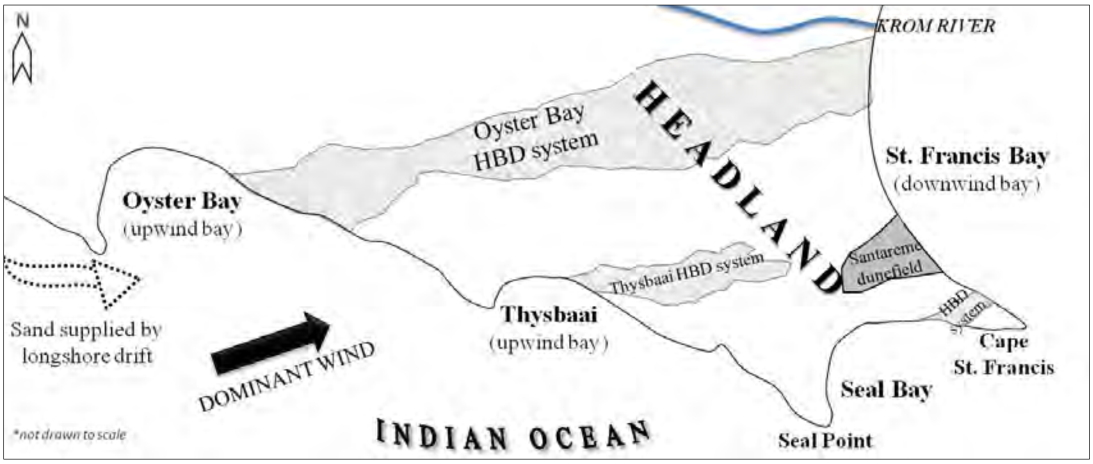


Figure 1-2: Diagram of the Cape St. Francis headland region showing the approximate location of the Oyster Bay HBD, Thysbaai HBD and other places of significance.

Source of figure: Adapted from Burkinshaw (1998).

An example of (mis-)management of this dunefield complex can be observed within the setting of St. Francis Bay, where urban development has occurred in the downwind path of the dunefield, limiting connectivity of the mobile dunefield with the downwind bay. The Santareme Dunefield used to exist to the south and east of the Thysbaai HBD system (Figure 1-2). Between 1970 and 1980 the dunefield was stabilised for the development of the Santareme Village (Illenberger & Burkinshaw, 2008). The importance of the Santareme dunefield system, which supplied between 91 000 m^3 and 150 000 m^3 of sand per year to the beach at St Francis Bay, east of the dunefield system (CSIR, 1991 and McLachlan *et al.*, 1994), is now evident. In a study by Lubke (1985), it was shown that beach erosion was occurring largely due to the stabilisation of the HBD systems. The study by Lubke (1985: 112) recorded the sea level shoreline change as, '$\Delta s = -9$ m'; which revealed that the beach had receded by nine metres between the two surveys conducted in 1975 and 1982 along the St. Francis Bay shoreline. This suggests that the sediment supply to the St Francis Bay beach and coastline had been disrupted, resulting in erosion of the downwind bay (Lubke, 1985). Today, erosion is still occurring along various points of St. Francis Bay (Figure 1-3a, b & c).

Figure 1-3 (a, b & c): Erosion of Ralph Road along the St. Francis Bay shoreline. Photographs 2a and 2b were taken 24 hours apart in March 2007, during which time the width of the road was reduced by erosion.

Source of photographs: Kouga Municipality (2007).

It is generally accepted that the major (mis-)management of these dunefield systems was through the stabilisation of the headland bypass dunes, for the most part as an active attempt to stabilise the dunes using an invasive alien species (*Acacia cyclops* – "Rooikrans") that has been effectively used elsewhere in the world for this purpose (Avis, 1989). Rooikrans has proved to be highly invasive and is a threat to the natural vegetation of the area (Stirton, 1978 and Cowling, 1980). The outcome of the stabilisation is that since 1996, the small dunefield at Cape St. Francis HBD is the only active system supplying sand to the beach of St. Francis Bay (Figure 1-2). The total amount of sand supplied is in the region of 7 000 $m^3.a^{-1}$ (Illenberger & Burkinshaw, 2008), a deficit of approximately 80 000 m^3 compared to what had previously entered the downwind bay from the mobile dunefields.

Other natural features of the Oyster Bay HBD are wetlands and dune pools, as well as the Sand River system that drains the north eastern region of the dunefield. During periods of high rainfall large amounts of water collect in interdune depressions to form pools. The dune pools and wetlands are highly dynamic with some only forming temporarily, while others are more permanent and / or successionally advanced than others. These wetlands attract some wildlife to the dunefield, including otters, crabs, frogs and toads, and an abundance of bird species (including blue cranes).

The Sand River, an important component to the Oyster Bay HBD system, flows from north of the dunefield into the dunefield, and then flows in an easterly direction along the north eastern margin of the dunefield towards the Krom River. This is not however the natural path of the Sand River, which has been diverted to flow more directly and enter the Krom further upstream than it did historically, in order to enable urban development along the lower Krom River and further south (La Cock & Burkinshaw, 1996). Impacts of this diversion are evident during periods of high rainfall, when homes are flooded and infrastructure is damaged. This is to the detriment of the owners of developed properties who find their properties flooded with large amounts of water, debris and sediment (Figure 1-4). The complex relationship between the dunes, the interdune pools / wetlands, and the Sand River System, illustrate the likelihood that sediment flux through the Oyster Bay HBD is not simply a product of interactions between ocean currents, wind and sand. It is likely that fluvial processes are also an important factor that affects sediment flux within the Oyster Bay HBD and thus influence its structure and functioning.

Figure 1-4: Photographs taken after a high rainfall period in November 2007 showing the high sediment flux from the mobile dunefield system that accompanies flooding.
Source of photographs: Peens (2007).

The preceding discussion has described some of the impacts of (mis-)management resulting from a poor understanding of the functional role of HBDs within the coastal zone. Human activities have negatively affected the functioning of the larger coastal system and the more local scale HBD system itself. It is therefore necessary to improve our understanding of the drivers governing the functioning of these systems so that HBD systems can be better managed. Inappropriate development and use of land in and around a complex HBD system has disastrous effects at a broad scale, including destruction of infrastructure along the coastal zone and in terrestrial settings.

Studies in the past, related to the dunefield systems crossing the Cape St. Francis headland, have focused on the role that wind plays in sediment transfer in coastal dunefield systems (Illenberger & Rust, 1988; Burkinshaw *et al.*, 1993 and Burkinshaw, 1998). The role of water in these systems has not been seen as an as important driver, but the role of water in the transfer of sediment within and out of the Oyster Bay HBD, given the impacts shown in Figure 1-4, appears significant. The episodic transfer of sediment by water in the form of debris flows has happened historically as indicated by the presence of debris flows in the sedimentary record (Figure 1-5).

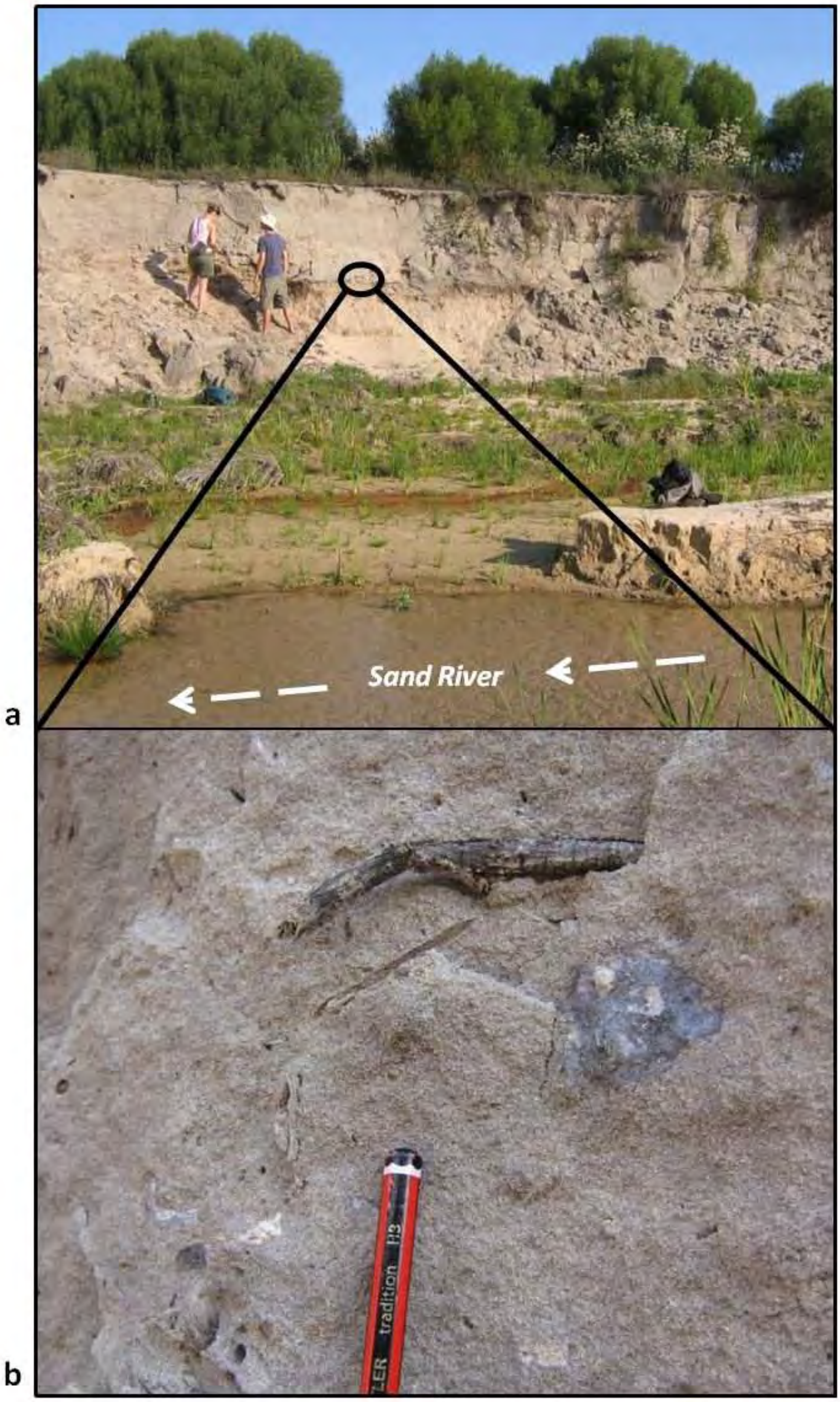


Figure 1-5 (a & b): a: Site along the course of the Sand River System where a debris flow is evident; **b:** A close up view of a section of the site, showing poor sorting within the sediment layer, characteristic of a debris flow.

Source of photographs: a) own photograph (2009); **b)** P. Illgner, 2008.

1.3 AIM

The aim of this study is to improve the understanding of the morphology and dynamics of the Oyster Bay HBD system by focussing particularly on surface water and groundwater interactions and the role of surface water in sediment transfer.

1.4 OBJECTIVES

In order to achieve this aim the following objectives were identified:

1) Mapping of the topography and overall morphology of the Oyster Bay HBD.
2) Measurement of the rates of dune movement as a surrogate measure of sediment flux.
3) Investigation of biophysical attributes as indices of natural processes:
   a) Vegetation – a spatial evaluation of vegetation dynamics over time and a current vegetation classification;
   b) Groundwater and surface water – a spatial and temporal analysis of groundwater levels and water chemistry over an annual cycle; and
   c) Particle size analysis across the dunefield.
4) Development of summary diagrams and tables (related to each objective) and a final summary table and conceptual diagram of dunefield structure and function.

1.5 CHAPTER OUTLINES

Chapter One introduces some initial concepts and provides an explanation of the basic functioning of HBD systems. It justifies the need for more research within HBD settings, specifically within the Oyster Bay HBD system.

Chapter Two places the research in context, showing the location of the dunefield and describing certain important local aspects to help understand the system relative to the surrounding parameters, specifically, those deemed important by Tinley (1985).

Chapter Three provides the theoretical context of the research. It gives perspective on the system at an international and national scale. Part of this section examines the theory (behind the implementation) of Geographical Information Systems (GIS) and some associated tools, which were fundamental to this research.

Chapter Four outlines the methodological approach undertaken to conduct this research. It also describes the methods used both in the field work and the statistical and analytical stages of this research; describing techniques, procedures and tools used to meet the objectives of the research.

Chapter Five presents all the results from the research using various formats: graphs, maps, and tables. A brief description of these further emphasises the most significant outcomes.

Chapter Six presents the discussion and explanation of the results from Chapter Five, in the context of current theory. The chapter relates the findings to the aims and objectives set out at the beginning of the research. The chapter then synthesises and concludes the work carried out in this research and emphasises the key findings. It also contains suggestions for future research.

CHAPTER 2: STUDY AREA

2.1 LOCALITY

The Oyster Bay HBD is situated within the Eastern Cape Province of South Africa. Figure 2-1 shows the spatial relationship of the dunefield to the neighbouring towns of St. Francis Bay, Cape St. Francis, Oyster Bay, Humansdorp and Jeffrey’s Bay. The coastal villages of Cape St. Francis and St. Francis Bay, located south of the mouth of the Krom River, have developed on one of the many isolated capes of the southern and south eastern seaboard of South Africa, in close proximity to one of South Africa’s most extensive and dynamic mobile headland bypass dunefields.

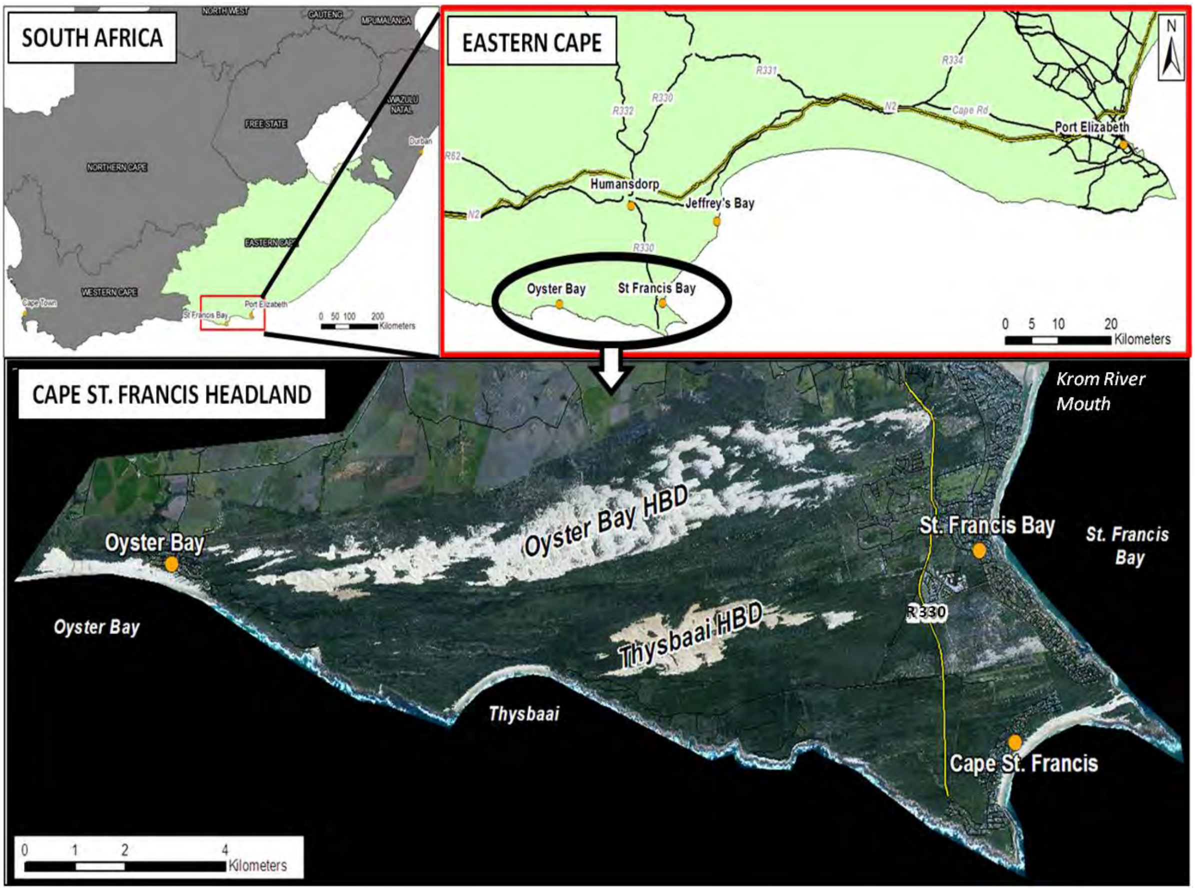


Figure 2-1: The geographical location of the Oyster Bay HBD in the Eastern Cape, South Africa in relation to nearby towns.

Over the period of historical aerial photography (1940 to present) it has been shown that this area was host to four HDBs, one of which has been fully vegetated and developed, such that only three dunefields are visible today. The Oyster Bay HBD, where the field research was undertaken, is the largest and most northern of the four parallel systems. It is approximately 16 kilometres long oriented in a near west-east direction. It is approximately two kilometres wide at its widest point. The other three systems are from north to south: the Thyspunt Dunefield (still visible); the Santareme Dunefield (no longer visible); and the Cape St. Francis dunefield (still visible).

In order to discuss the current context of the coastal mobile dunefield between Oyster Bay and St Francis Bay, it is useful to briefly consider those factors that most broadly affect dune development in coastal areas. According to Tinley (1985) there are seven factors that determine coastal dune development: coast trend and configuration of shorelines; marine processes (wave action and longshore drift); sand supply; wind regime; rainfall regime; plant colonization; and river mouth dynamics (change of flow and sand input). These factors have allowed for the development of, and drive the functioning of, the HBD systems on the Cape St. Francis headland. This chapter will therefore focus on these aspects and their relevance to the Oyster Bay HBD system and the other HBD systems will be explored.

2.2 COASTAL TREND AND CONFIGURATION

The south coast of South Africa extends from Cape Agulhas in the west to Cape Padrone (Algoa Bay) in the east (Tinley, 1985: see Figure 2-2). The majority of this stretch of coastline faces a south to south east direction. It is characterised by many isolated capes and log-spiral bays with sandy beaches bound by low relief rocky headlands of varying lithology. The bays typically form east of coastlines with a strong east-west orientation (Bremner, 1983 and Tinley, 1985). The configuration of the coastline is largely due to the prevailing swell from the south west and the structural control of the headlands in the form of resistant lithologies of the Cape Supergroup.

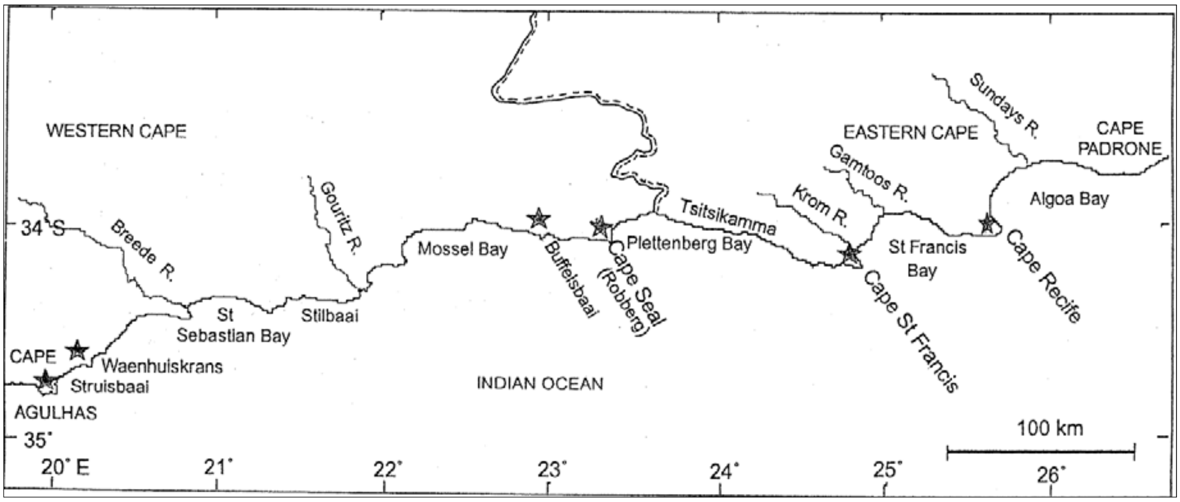


Figure 2-2: The Cape South Coast showing the series of log-spiral bays and associated headlands. Stars indicate the locations of HBDs.

Source of figure: Burkinshaw (1998: 26, after Bremnar, 1983 and Hunter, 1987).

2.3 TOPOGRAPHY AND GEOMORPHOLOGY

The topography of the area is illustrated in Figure 2-3 where the contour lines show an almost symmetrical relationship (dashed line) that is oriented north-west to south-east about the central axis of the headland. These contour lines are not accurate within the extent of the ever-shifting dunefield, but they do give a good indication of the form of the surrounding topography across the headland.

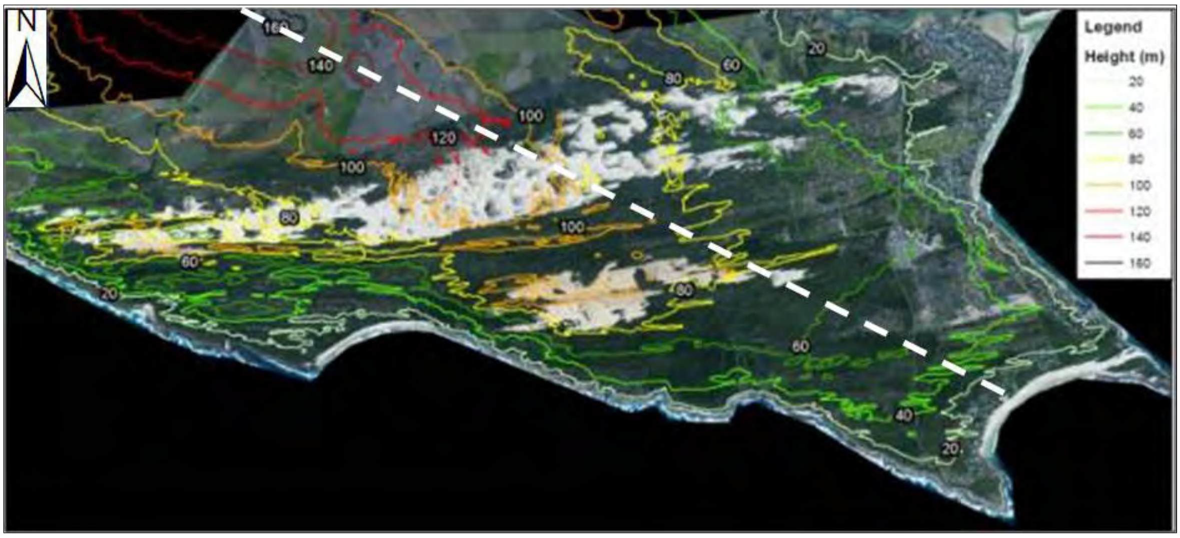


Figure 2-3: Topography of the study area. The dashed white line shows an almost symmetrical topographic relationship about the central axis of the headland.

The Cape south coast comprises several east-facing log-spiral bays of which Slangbaai, Thysbaai and Krombaai (St. Francis Bay) are named on the geological map of the study area (Figure 2-4). Cape St Francis Bay between Seal Point and Cape St Francis is one of these bays although it is not named on the geological map. The lithologies underlying the mobile dunefields that project onto the coastline comprise a folded sequence around the Peninsula Formation (quartzite) that gives way vertically in the original depositional sequence to the Cedarberg Formation (shale), Goudini Formation (shale), Skurweberg Formation (quartzite), Baviaanskloof Formation (quartzite) and the Ceres Group of the Bokkeveld Group (shale).

The shoreline of Krombaai (St. Francis Bay) is co-incident with the Ceres Subgroup, which comprises shales of the Bokkeveld Group that are relatively easily weathered (Figure 2-4). West of the Cape St Francis headland, rocks of the Table Mountain Group project onto the coastline beneath the unconsolidated sediments of the Nanaga and Holocene Formations. Resistant lithologies of the Baviaanskloof and Skurweberg Formations (quartzite) project onto the coastline as rocky shorelines, headlands and peninsulas (Figure 2-4). The bays of Thysbaai and Cape St Francis Bay are associated with less resistant lithologies of the relatively easily weathered shales of the Goudini Formation (Figure 2-4). Between Oyster Bay and the mouth of the Krom River is a cover of sand of the Nanaga Formation and the series of four Holocene mobile dunefields (Figure 2-4).

The topography of the region is related to the underlying lithology in that the highest lying ground is oriented similar to the folded Cape Mountains, although the axis of the anticline is to the west of the highest-lying ground (Figures 2-3 and 2-4). Nevertheless, it must be construed that the underlying lithology exerts a measure of structural control on the overall topography of the peninsula.

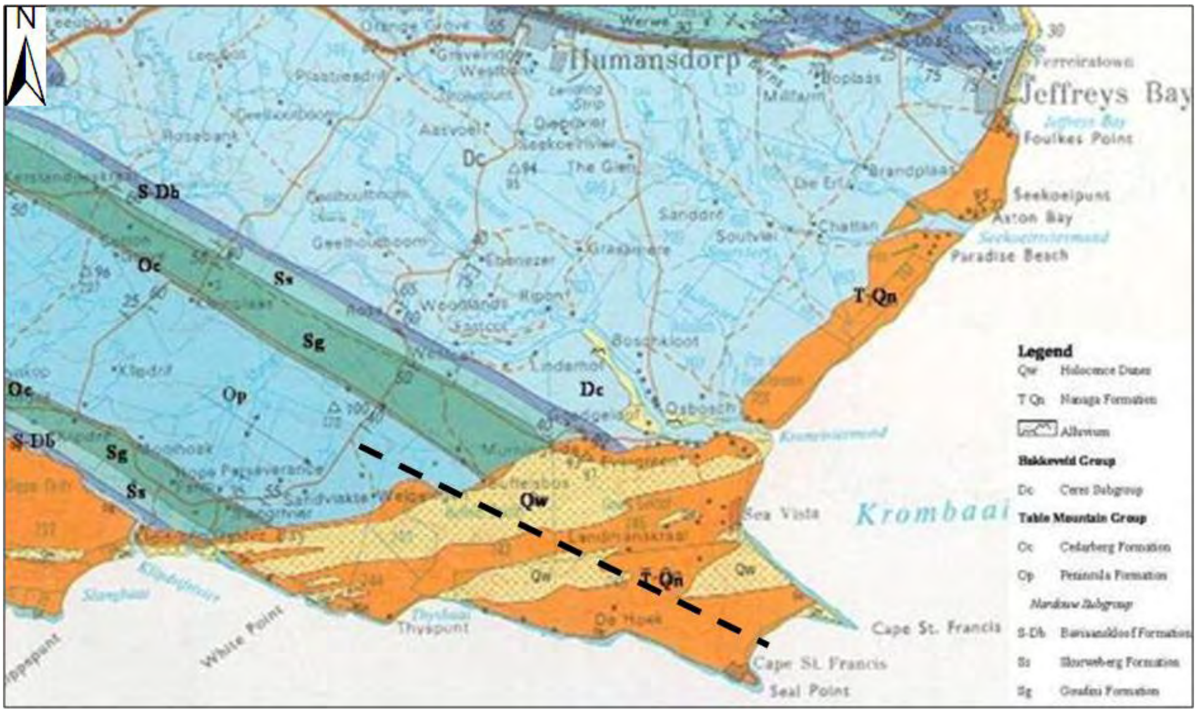


Figure 2-4: Geological map of the Cape St. Francis headland. Drawn dashed line shows an almost symmetrical relationship with regards to elevation about the central axis of the headland.

Source of figure: Geological Survey of South Africa (1991).

2.3.1 Drainage of the headland

The Krom River is the major drainage system north of the Cape St. Francis headland, with its source located some 93 kms to the west in the Tsitsikama Mountains. The mouth of the river opens into Krombaai (St. Francis Bay), north of the town of St. Francis Bay and the Oyster Bay HBD. The river follows the strike of the Table Mountain Group rocks (Burkinshaw, 1998). During periods of high rainfall, the Sand River drains the Oyster Bay HBD and surrounding region and flows in an easterly direction into the Krom River as indicated in Figure 2-5.

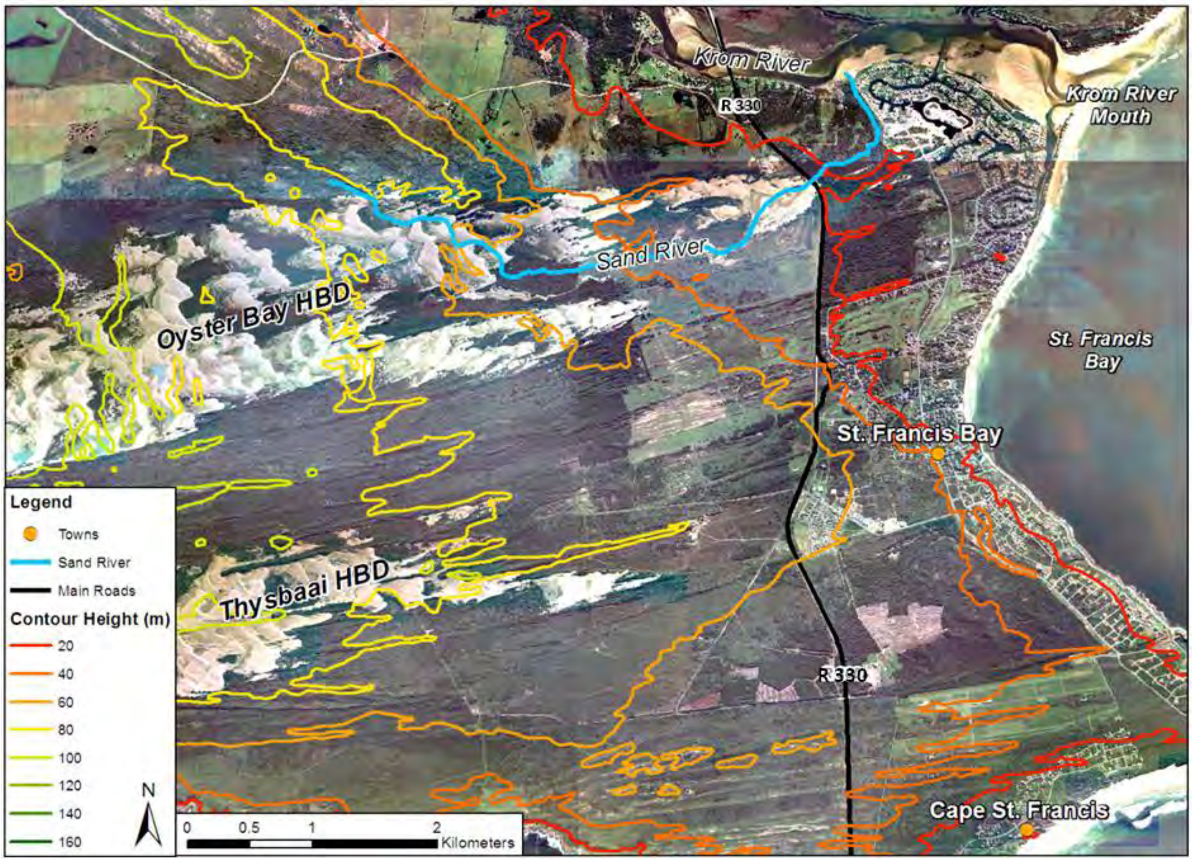


Figure 2-5: Drainage of the Sand River System.

2.4 WAVE ACTION AND LONGSHORE DRIFT

The coast of southern Africa is dominated by dunes and beaches and characterised by extensive sand transport, both littoral and aeolian (Tinley, 1985). The wave regime and predominant winds, both high in energy, mainly approach from a westerly to south-westerly direction, resulting in longshore and aeolian transport towards the east (McLachlan *et al.*, 1994) and more specifically towards Oyster Bay / Thysbaai. Waves and wind generate currents within the near surf zone along the coast which are responsible for the littoral drift, which influences the shape of the coastline through processes such as erosion, transportation or deposition of sediments (Tinley, 1985). Currents and wind regimes are also responsible for the movement of sediments alongshore which ultimately lead to the development of the HBD systems between Oyster Bay and St. Francis Bay. This movement of sand alongshore is essential for the formation of the upwind beaches; which in turn supply sand for mobile dunes that form on the headland between Oyster Bay and St. Francis Bay.

2.5 SAND SUPPLY

In HBD systems, the main source of sand is from the upwind bay supplied initially from marine littoral drift. Sand is transported over the headland and re-joins the marine littoral drift again in the downwind bay. Over the past 100 years however, the impact of humans on these systems has increased dramatically and many dunefields have been modified without understanding the effects on coastal sediment budgets. The dunefields that feed St. Francis Bay have been actively vegetated and the sand source has therefore been cut-off or reduced considerably. The village of Oyster Bay at the head of the Oyster Bay Dunefield has probably diminished the sediment supply from the beach at Oyster Bay (upwind bay), while the town of St. Francis Bay has reduced the rate of movement of sediment into the downwind bay.

2.6 WIND REGIME

The wind rose for Cape St. Francis shows that on average the dominant winds recorded over a period from 2004-2009 at Cape St. Francis, are westerly (Figure 2-6a; South African Weather Services (SAWS), 2010). The main seasonal difference in wind is that in summer (indicated by the wind rose for January), the frequency and strength of easterly winds increases (Figure 2-6b). The easterlies are thought to temporarily reverse the movement of sand and steepen the dunefields within the system (McLachlan, 1990). In general, the land breeze at Cape St. Francis is weakly developed (Tinley, 1985), thus emphasising the role that the coastal winds play in the Oyster Bay HBD.

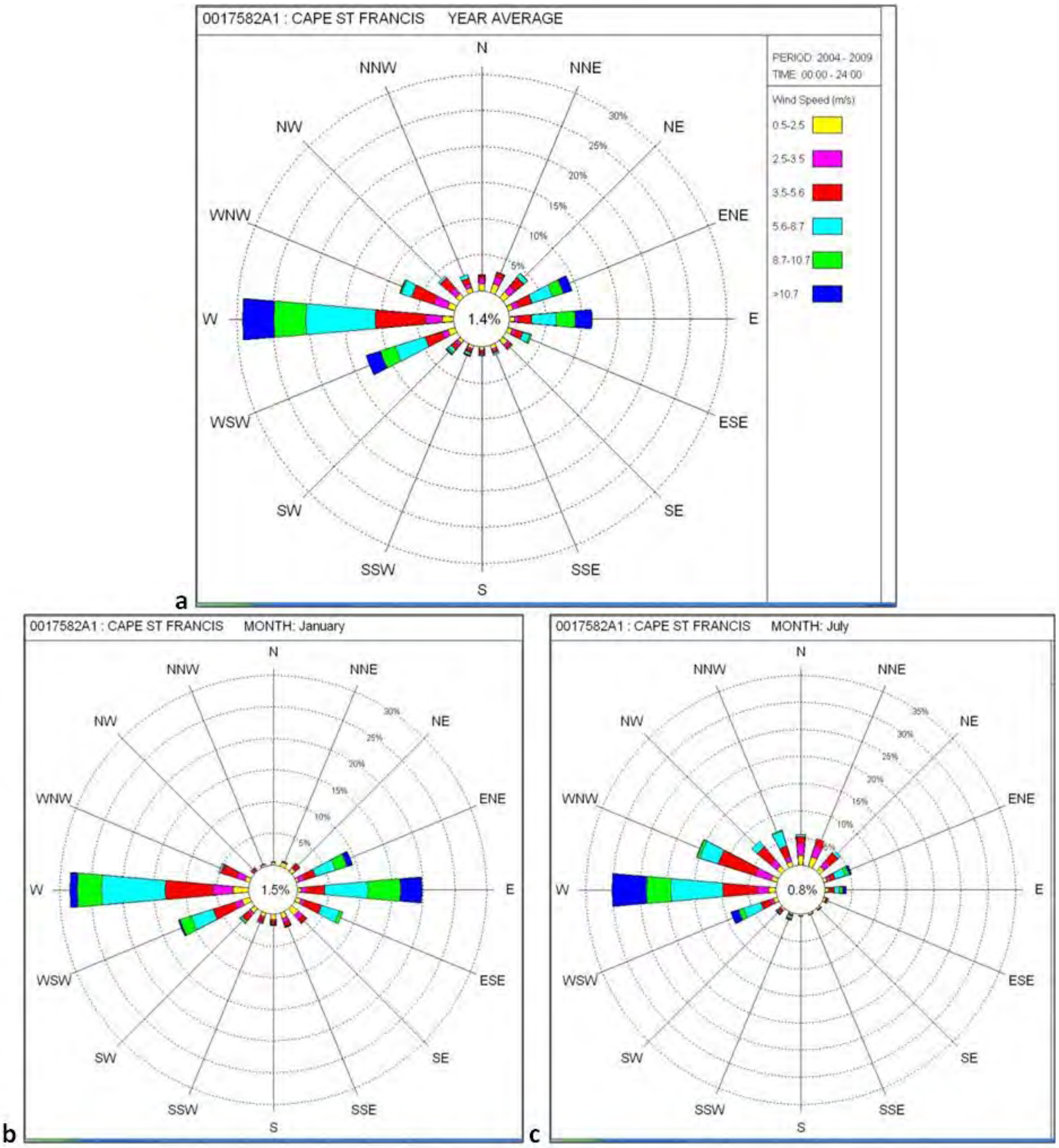


Figure 2-6 (a, b & c): Wind roses for Cape St. Francis showing average wind speeds (m.s^{-1}) and frequency for the period 2004 – 2009. **a:** year average; **b:** average winds for January (summer month); **c:** average winds for July (winter month).

Source of figures: SAWS (2010)

2.7 RAINFALL REGIME AND TEMPERATURE

Mason *et al.* (1999) identified a general 10-year repeating pattern in South Africa's high rainfall years between the years 1931-1990. According to Mason *et al.* (1999: 252), the southern region of the Kouga falls into the category which has experienced increased intensity in 10-year rainfall events since 1931. There is considerable variation in climate across the study area. The climatic data presented here were recorded at the lighthouse in Cape St. Francis. Cooler temperatures and higher rainfall are generally recorded at the lighthouse compared to further inland or within the bay of St. Francis Bay (Lubke, 1985). Rainfall figures for the area show that the rainfall occurs throughout the year with the majority falling in the winter months (Figure 2-7). The average temperatures for the area are approximately 19°C in summer and 15°C in winter. The average mean annual rainfall for the region is approximately 600 mm per annum.

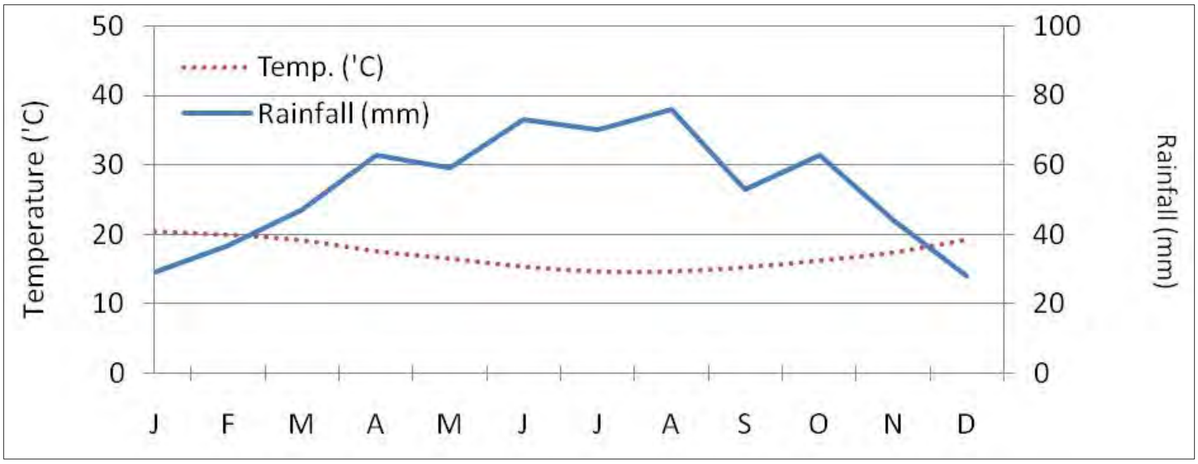


Figure 2-7: Average monthly rainfall (P = 28 years) and temperature (P = 29 years) for Cape St. Francis.

Source of data: SAWS (2010)

2.8 VEGETATION

The main vegetation in the area, as identified by Cowling (1984), is fynbos of the Cape Floristic Region. Three different fynbos vegetation types occur in the area. The headland is dominated by South Coast Dune Fynbos, a type of Coastal Fynbos. In addition there are small areas of dune thicket within the study area (Lubke *et al.,* 1984 cited by Lubke, 1985) and also of Kaffrarian Thicket Mosaic (Cowling, 1984).

South Coast Dune Fynbos is prone to invasion by alien plants (Lubke, 1985). In the past, stabilisation of mobile dunes has been considered a priority. Stabilisation techniques have varied over time but over a lengthy period alien plants were used. The main plants used to stabilise the dunes were *Acacia saligna* (Port Jackson Willow), towards Oyster Bay in the west; and *Acacia cyclops* (Rooikrans), towards the east. Both of these are alien species that have subsequently heavily invaded the low lying areas around and between the Thysbaai and Oyster Bay dunefields to the detriment of much of the indigenous vegetation (Figure 2-8). Rooikrans is currently spreading within the Oyster Bay HBD too, which is of major concern to the local and regional conservation and water management agencies.

Figure 2-8: An area dominated by Rooikrans (*Acacia cyclops)*. This area lies between the northern Thysbaai Dune ridge and the first ridge south of the Oyster Bay dunefield (looking towards St. Franics Bay).

With specific reference to the dunefields, Daines *et al.* (1991) differentiated between the vegetation occurring within the dune wetland ("vlei") habitats as opposed to the dune ridges. They identified that the vegetation within the dune wetland habitat tended to be grassier than the vegetated dune ridges which contained more shrub-like plants (Daines *et al.*, 1991). Today, this is still evident (Figure 2-9a & b).

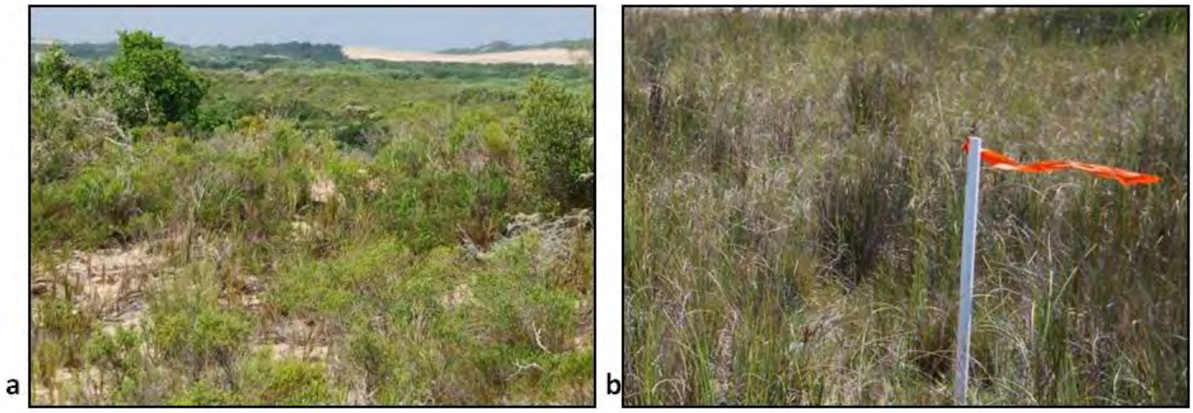


Figure 2-9 (a & b): Vegetation in the Oyster Bay HBD. **a:** dune ridges with shrub-like plants; **b:** grass-like plants within wetland habitats.

2.9 SOCIO-ECONOMIC CHARACTERISTICS

2.9.1 Provincial

The Eastern Cape Province, as was presented in Figure 2-1 of this chapter has an estimated population of between 6.3 and 6.6 million people according to the Department of Economic Development and Environmental Affairs (DEDEA, 2011). The main economic activities include finance, business services, government services and manufacturing, with tourism also considered as very important (DEDEA, 2011). The province is divided into seven districts (Table 2-1), with the study area located in the western part of the province, in the Cacadu District.

Table 2-1: Eastern Cape's population distribution by District Municipality for 2008

	Share of Surface Area (%)	**Share of Population (%)**	**People per km^2**
Cacadu	34.3	5.9	7
Amatole	13.9	26.3	72
Chris Hani	21.9	12.8	22
Joe Gqabi	15.6	5.2	13
OR Tambo	9.1	27.4	114
Alfred Nzo	4.0	6.6	63
Nelson Mandela Bay Metro	1.1	15.8	557

Source of data: DEDEA (2011)

2.9.2 District and municipal Level

The Cacadu District is the largest district in the Eastern Province by area but has the lowest number of people per square kilometre (Table 2-1). The Cacadu District consists of nine local municipalities. The study area falls within the Kouga Municipality.

The population of the Kouga region was estimated to have been 87 thousand people in 2010 with a growth rate of approximately 2.4% per annum between 2000 and 2010 (Draft Environmental Impact Report (DEIR), 2011). The density of the population is estimated at 24 people per km^2 – which is high compared to the district average of seven people per km^2.

2.9.3 Tourism in the region

According to DEDEA (2011), the Kouga Municipality predominantly offers water-based activities. The area is world renowned as a surfing hotspot, for which the most popular tourist destinations include the towns of Jeffrey's Bay, St. Francis Bay and Oyster Bay. The Integrated Development Plan (IDP) for the district shows that tourism has become a key economic driver for the area and as such it is a focus of local economic development strategies (Urban Econ, 2009). A development master plan that focused on tourism for the region has been drafted with an emphasis on obtaining funding to promote and include more tourism-related local initiatives (DEIR, 2011). Table 2-2 is presented to give an indication of the contribution that the 'surfing-tourism' market makes to the economy of the region, based on visitors to the annual ten day Billabong Pro surfing competition (DEIR, 2011).

Table 2-2: The approximate expenditure by visitors during the Billabong Pro

Factor	**Value**
Average number of visitors per day	5 000
Approx. average daily expenditure per visitor	R500
Duration of the competition (days)	10
Approx. total value of visitor spending	**R25 000 000**

Source of data: DEIR (2011).

In addition to events such as the Billabong Pro surfing competition, the Kouga Region is a very popular holiday destination – particularly over the Christmas / New Year period and Easter holiday. Using St. Francis Bay as an example, the 'normal' population rises from 4 000 to 30 000 over the Christmas / New Year period and up to approximately 8 000 over the Easter period. The main source of income is generated from house rentals, bed-and-breakfasts (B&Bs) and guest houses, with average annual occupancy rates estimated at 40% for B&Bs and 5% for house rentals. The following table gives an indication of the value of the hospitality aspect of the tourism market for St. Francis Bay.

Table 2-3: A quantitative representation of the tourism industry for St. Francis Bay

Accommodation type	Indicator / factor	Value
B&Bs	Estimated number of beds	1200
	Average rate per night	R350
	Average annual occupancy (days)	146
	Sub-sector turnover per annum	R61 320 000
House Rentals	Estimated number of houses	300
	Average cost per day	R3 000
	Average annual occupancy (days)	18.25
	Sub-sector turnover per annum	R16 425 000
Combined	Combined total turnover per annum	R77 745 000

Source of data: DEIR (2011).

Other economically significant contributors within close proximity to the study area include: agriculture (mainly dairy farmers), fishing, and retail, with most of the local industry-related contributors being located in the town of Humansdorp to the north of St Francis Bay.

2.9.4 Agricultural industry

Based on information from the Draft Environmental Impact Report of 2010 (DEIR, 2011), the region surrounding Humansdorp is the largest producer of milk in South Africa; with approximately 60 000 cows producing approximately 820 000 litres per day worth approximately R900 million per annum. In addition, the beef cattle industry is worth approximately R37 million per annum while Dohne merino sheep produce wool valued at approximately R1.2 million per annum and mutton at R5.5 million per annum. Wheat production in the region equates to about R1 million per annum. These figures highlight the significant contribution that agriculture makes to the economy of the Kouga Region but also to the Cacadu District and the Eastern Cape as a whole.

2.9.5 Fishing industry

Fishing enterprises within and around St. Francis Bay are part of the fishing industry that make use of the area between Plettenberg Bay (west) and Port Alfred (east), using harbours at Port Elizabeth and St. Francis Bay. The main exploited species are hake and chokka. The hake industry catch is approximately 2 500 tons per annum in the Eastern Cape, of which 800 tons are from the port at St. Francis Bay, with the average prices of €5.50 per kilogram. Over the past 20 years, the chokka industry has taken an average annual catch of 7 000 tons in the Eastern Cape of which 1 000 tons was contributed by companies based at the port at St. Francis Bay, with average prices of €7 per kilogram. Chokka is considered to be the most suitable fishing industry in the region of St. Francis Bay. The Cape Squid Company is an example of the significant contribution this industry makes to the economy of the region. In 2005, the Cape Squid Industry employed about 2 300 fishing crew, 150 management staff and 1 500 factory staff, generating approximately R400 million in foreign exchange per annum (DEIR, 2011).

2.10 PROPOSED ESKOM NUCLEAR POWER STATION AT THYSPUNT

In South Africa, there is a requirement for more than 40 000 MW of new electricity generating capacity over the next 20 years (DEIR, 2011). The additional generating capacity could come from various sources, some of which include coal, hydro, or solar energy. Considering all the possibilities, ESKOM has determined the most appropriate and optimal combination for electricity generation in order to try and meet future demand. Of significance to this research are the proposed nuclear power stations (NPSs). Thermal power stations require large quantities of water for cooling purposes and considering that NPSs do not need to be close to their fuel source, a site at the coast where sea water can be used is therefore a logical solution in a water-stressed country like South Africa. ESKOM has identified certain sites for NPSs based on studies conducted in the 1980s by independent consultants. These sites included Bantamsklip (west coast), Duynefontein (west coast), Brazil (west coast), Schulpfontein (south coast in the Western Cape) and Thyspunt (south coast in the Eastern Cape between Oyster Bay and Cape St Francis). Thyspunt has been identified as the first site to be built and the Environmental Impact Assessment process is currently under way.

2.11 CONCLUDING REMARKS

The information covered in this section aims to shed some light on the region in which the Oyster Bay HBD is situated. It focused on those factors that Tinley (1985) considered to be key in dune development as well as other important information relating to the region. With this information in mind, it is now essential to review some literature in order to put the system into a theoretical context, allowing us to better understand how systems such as this have functioned in the past, how they continue to function today, and the processes which govern their functioning.

CHAPTER 3: THEORETICAL FRAMEWORK

3.1 INTRODUCTION

Coastal dunefields are dynamic, ever-changing (on a daily basis), process-response systems (Chorley & Kennedy, 1971 and Young, 1987), which respond to processes operating at various spatial and temporal scales. The scale at which coastal systems are studied is therefore critical. Literature pertaining to the methods for capturing, monitoring and analysing certain types of data at various scales needs to be reviewed. Similarly, tools that could be used for monitoring and analysing data need to be investigated, and information on the advantages and disadvantages of using certain tools should be explored. There needs to be a balance between the desire for detail and the necessity to collect data that is representative of a larger geographical area. Ultimately, "…the monitoring of changes in coastal dunes has important ramifications for the management of coastal systems" (Andrews *et al.*, 2002: 289-290). These changes need to be understood on both spatial and temporal scales appropriate to the functioning of HBD systems.

3.2 COASTAL DUNEFIELDS

3.2.1 Occurrence and formation

Dunefields vary in form and type and can be found in deserts, on the sea bed and even on Mars (Parteli & Herrmann, 2003), but they are particularly common along the coast (Parteli *et al.*, 2006). The coastal zone occurs at the interface of terrestrial, oceanic and atmospheric systems (Pye, 1983 and Kim *et al.*, 2008). Despite their varying spatial locations, commonly dunefield initiation and maintenance is largely determined by the availability of sand and/or by the strength and appropriate behaviour of wind to transport sand for at least part of the year (Bagnold, 1941 and Parteli & Herrmann, 2003). The interplay of several factors results in dune development and formation, including: the type of sediment, variations in relative sea level, climatic change, vegetation cover, antecedent topography, beach morphodynamic type and processes, and human activities (Carter, 1988; Hesp, 2002 and Martinho *et al.*, 2010: 14).

Aeolian dunes and dunefield systems develop at locations where there is both a sufficient sand supply and wind strength to move sand from the sea to a place in a terrestrial setting where the sand can accumulate (Goldsmith, 1978 cited by Burkinshaw, 1998). The coastline, where sandy beaches and onshore winds are common, therefore creates an ideal setting for the development of coastal dunefields – where sand that constitutes the dunefields comes from the sea (Parteli *et al*., 2006). In coastal dunefield systems the presence of vegetation aids the trapping of sand, and sea waves play a role in replenishing the sand source from the beaches (Carter *et al*., 1990 and Illenberger & Burkinshaw, 2008).

3.2.2 Classification

Dune morphology has been investigated for many years from different research areas since the initial work of Bagnold (Parteli *et al*., 2006). Although no theoretical explanation for the wide variety of dune types exists, it is known that there are key drivers, processes and resultant responses which lead to the various formations. As mentioned in Chapter 1, Tinley (1985: 13) noted that there were seven factors that influence dune development along the coast – all of which were expanded upon in more detail in Chapter 2. It is the combination of these factors, and additional understanding of coastal dunefields through additional research, which led to the morphological classification of coastal dunefields into two broad categories: 'impeded or fixed' and 'transgressive' dunes (Pye, 1983 and Hesp & Thom, 1990: 254). For the purpose of this research the classification presented in Figure 3-1 will be used.

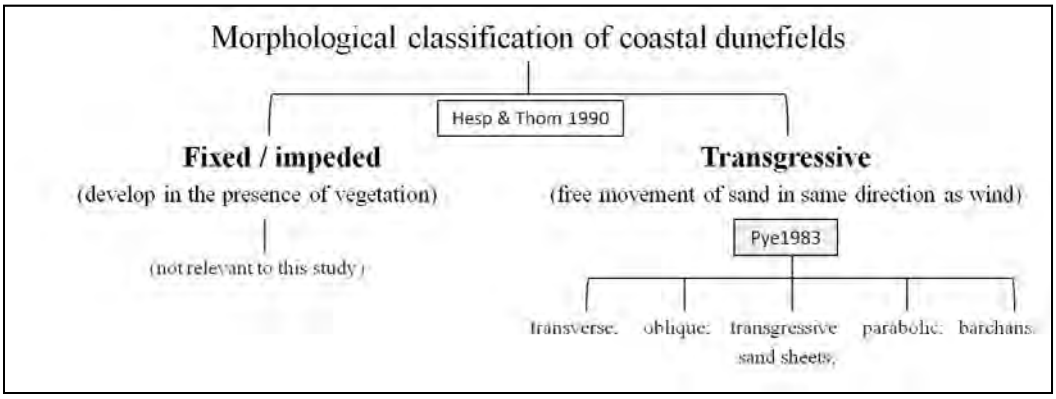


Figure 3-1: The morphological classification of coastal dunefields with an emphasis on transgressive dunefields.

Source of figure: based on Pye (1983) and Hesp & Thom (1990).

Dune heights can range from a few metres to tens of metres such that their spectacular nature forms tourist attractions in coastal zones. More importantly they have key ecological functions within coastal systems, such as working as barriers to waves, and acting as sand reserves to beaches (Parteli *et al*., 2006). Certain types of dunes are more common in certain regions than others. In humid region coastal dunefields, hummock and parabolic dunes are most abundant whereas in arid and semi-arid region coastal dunefields, barchan and transverse barchanoid ridges are most common (Inman *et al*., 1966; Pye, 1984 and Illenberger & Rust, 1988).

3.2.2.1 Transgressive dunefield types

Transgressive dunefields, a term first coined by Gardner (1955), were so named to describe sand deposits which were 'actively migrating' downwind and 'transgressing prior terrain' (Hesp & Thom, 1990: 253). Transgressive dunefield systems differ in size and have varying amounts of vegetation present (Hesp, 2002). They are also typically host to a variety of dune types (Hesp *et al*., 1989). The five dune types which are most commonly referred to are: transverse ridges; barchan dunes; transgressive sand sheets; parabolic dunes and oblique dunes (Pye, 1983). Figure 3-2 provides a representation of some of the transgressive dune types based on the literature cited in this section.

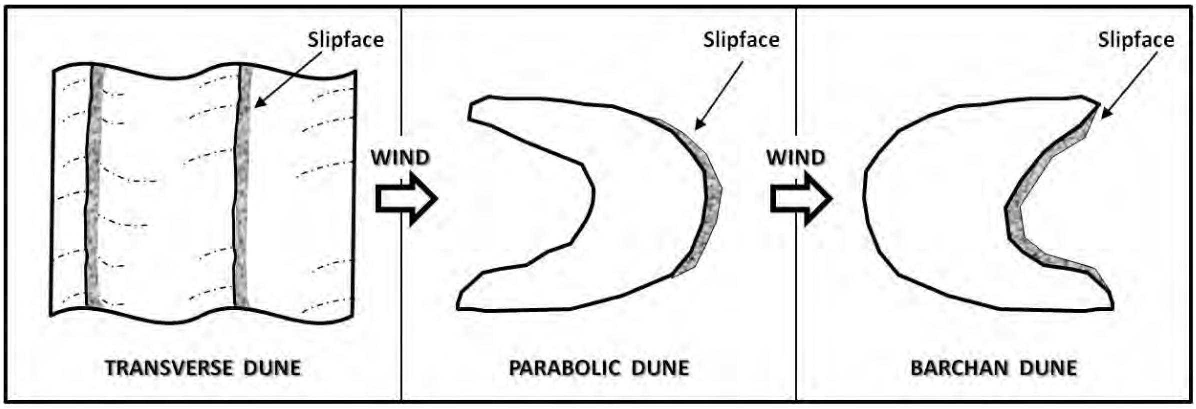


Figure 3-2: Types and views of transgressive dunes.

Source of figure: Adapted from most literature cited in this section.

Transverse dunes cover approximately 40% of the sand seas of our planet (Luna *et al*., 2009). They occur in areas of high sand supply and where the wind is nearly unidirectional.

They appear as a series of parallel ridges which move perpendicular to the wind direction (Figure 3-2). Transverse dunes have been noted to host irregular patterns and hierarchies of smaller dunes (Parteli *et al*., 2006). The typical transverse dune has a gentle windward slope and steep leeward slope (Cooper, 1958). In the last decade there has been increased interest in the investigation of the geomorphological aspect and evolution of transverse dunes, despite this there is still much which is not understood (e.g. Parteli & Herrmann, 2003: 555).

Parabolic dunes in their simplest form are ‘U’-shaped in plan with two trailing arms which point upwind (Figure 3-2). They often have a large sand mound with a steep lee slip face at the downward end. In all cases the outside slopes of the trailing arms are partly or completely vegetated (Pye & Tsoar, 1990: 200). On a larger scale, when parabolic dunes develop in areas prone to strong uni-directional winds, they may become elongated and are then known as *hairpin parabolic dunes* (Tinley, 1985). In addition, parabolic dunes that develop over an expansive area (kilometres long by hundreds of meters wide) are loosely referred to as *megaparabolic dunes* (Illenberger & Burkinshaw, 2008).

In contrast to parabolic dunes, *barchans dunes* are isolated crescent dunes that have ridges which point downwind (Pye & Tsoar, 1990: 175). In areas with barchan dunes that for some reason experience increased sediment supply, individual barchan dunes sometimes link up to form ‘sinuous-crested ridges’ which are oriented perpendicular to the dominant wind (Pye & Tsoar, 1990: 176). Many transverse ridges display alternating barchanoid (downwind facing) and linguoid (upwind-facing) elements.

The transgressive dune and any of its variants, is the dominant dune form within the Oyster Bay HBD (Burkinshaw, 1998: 95) suggesting a large availability of sand and a largely uni-directional wind, which promote the formation of this type of dune. Within the central sections of the Oyster Bay HBD, transverse dunes reach as much as one kilometre in length (north – south / along the crest) and migrate eastwards across the dunefield. This migration is associated with the movement of sand in an easterly direction.

3.2.2.2 Headland bypass dunefields

Tinley (1985: 29) introduced the term "headland bypass dunefield" (HBD). HBDs were classified as dune types that were 'related to topographic boundaries' (Tinley, 1985: 17). They are described as dunefields that involve the development of 'strips' of transverse dunes that cross a 'plateau or undulating plainsland of the headland' in order to replenish the downwind bay with sand (McLachlan *et al*., 1994: Figure 3-3). Therefore, sand supplied by longshore drift, which would otherwise be lost to the downwind bay, is transported overland and re-joins the marine littoral drift, playing an integral role in maintaining the coastal sediment budget (McLachlan *et al*., 1994).

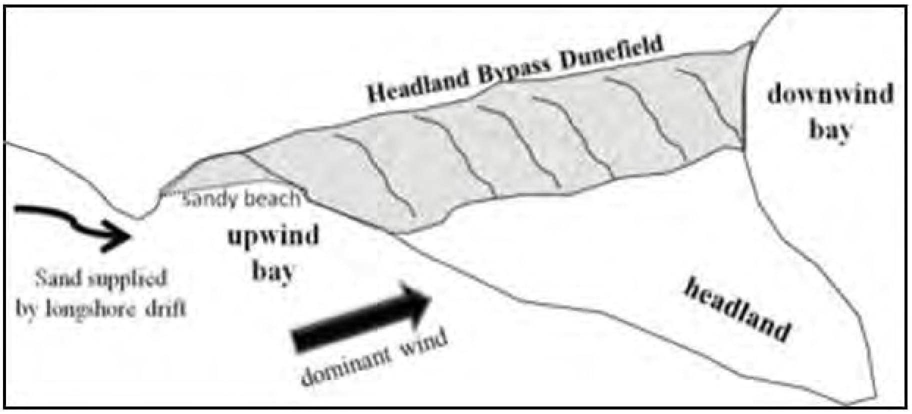


Figure 3-3: Conceptual model of a HBD system.

Source of figure: Adapted from McLachlan *et al.* (1994).

Sandy beaches are integral components of coastal dunefields. Cooper (1958) describes sandy beaches as being 'receptive shores' to littoral sand transported by longshore drift. The location of the 'receptive shore' is determined by shoreline configuration and prevailing wave and wind directions, often occurring updrift of headlands that obstruct and trap sediment transported by longshore drift (Burkinshaw, 1998: 10). These sandy beaches can act as sediment sources to dunefield development – as is the case in HBD systems. The beach is therefore an integral component to the initiation and functioning of this type of dunefield system. Despite being so connected to the coastal sediment transport system, it is important that HBD systems are studied as ecosystems in their own right (McLachlan, 1990).

These systems tend to be largely unvegetated, which therefore allows for the movement of transverse dune ridges across headlands within corridors that run parallel to the predominant wind direction (McLachlan *et al.*, 1994). Often in HBD systems, lateral margins that form over time, parallel to the dominant wind, are evident and create 'precipitation ridges' which border and partially channel the movement of sand through the HBD system (da Silva & Hesp, 2010: 275). These ridges tend to be completely vegetated, such as the southern lateral margin in the Oyster Bay HBD.

Within the main dunefield system, pockets of vegetation occurring within the mobile dunefield system limit the amount of sand that can freely be transported overland into the downwind bays; in a similar manner to that which some human development does. Stabilisation through the planting of vegetation and urban development are the two main ways by which humans have impacted dunefield systems since the end of the nineteenth century. This is the case for many of the HBD systems across the south coast of South Africa particularly at Port Elizabeth and St. Francis Bay.

In places where the HBD systems do not function naturally, the majority of sand is lost to the beaches on the downdrift side of the headland by being trapped in a deep water submarine spit off the rocky points of the headlands (Birch, 1980 cited by Tinley, 1985). This is today exemplified by the increasing loss of sand in the downward beaches at St. Francis Bay and Algoa Bay (McLachlan *et al.* 1994), which is a direct consequence of the stabilisation of the bypass dunes across the respective headlands (Tinley, 1985).

3.3 COMPARATIVE COASTAL DUNEFIELD SYSTEMS

There are some examples of HBD systems along the south coast of South Africa and others elsewhere in the world. On an international level, Brazil and Portugal have a few systems that have similar drivers and processes governing the functioning of the dunefields, to those found on the Cape St. Francis headland (Rebêlo *et al.*, 2002; Castro, 2005; Parteli *et al.*, 2006; Boeyinga *et al.*, 2010 and da Silva & Hesp, 2010). There are also other systems found along the south coast of South Africa, which lend themselves well to being comparative examples of HBD or similar functioning systems (Figure 3-4). These systems include: the

Agulhas Headland / Struis Baai / Waenhuiskrans dunefield system (Swart & Reyneke, 1988 and McLachlan *et al.*, 1994) and the Goukamma Buffelsbaai headland dunes (Burkinshaw, 1998). However, the main system that this section of this review draws attention to is the Cape Recife HBD system south of Port Elizabeth. This is due to the fact that this system is almost a replica of the HBD system occurring across the Cape St. Francis headland particularly as it occurs in the Eastern Cape and is the adjacent system to the Oyster Bay HBD system. It is therefore subjected to similar weather conditions, including longshore drift of sand supplies, rainfall patterns, wind regimes and temperatures.

This part of the theoretical review aims to draw on many aspects from the work conducted on the various examples of dunefield systems along the south coast of South Africa. The intention is to shed light on methodologies used in the research and identify similarities and differences between the HBD systems located across the Cape St. Francis area.

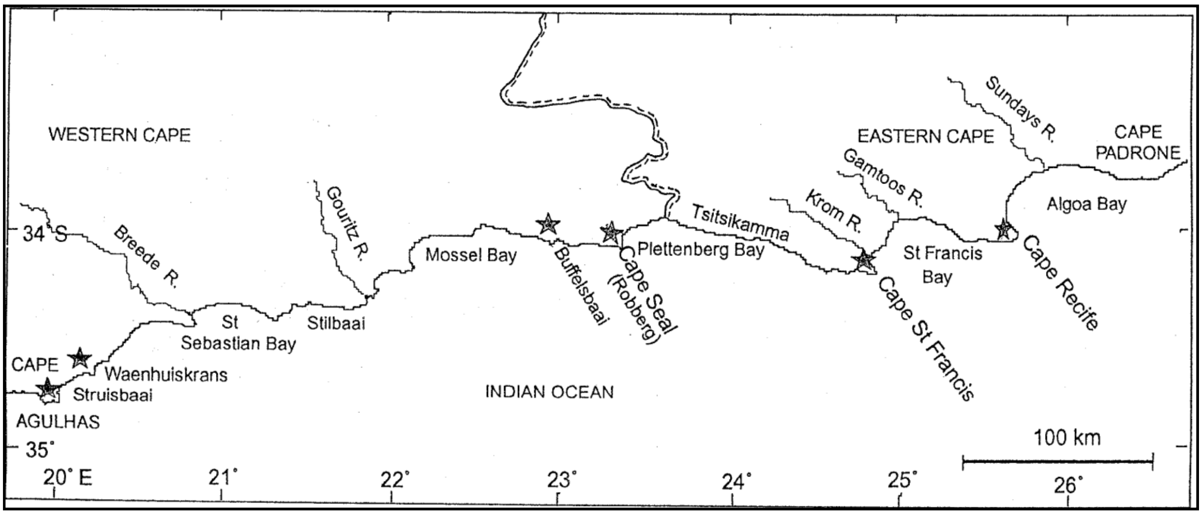


Figure 3-4: The Cape South Coast showing the series of log-spiral bays and associated headlands. Stars indicate the locations of HBDs.

Source of figure: taken from Burkinshaw (1998: 26, after Bremnar*,* 1983 and Hunter*,* 1987).

3.3.1 Local Situation

The Cape Recife headland west of Algoa Bay and the city of Port Elizabeth, hosted three HBD systems in the past, which were similar to those occurring across the Cape St. Francis headland. Each of the Cape Recife mobile dunefields supplied sand to the downwind bay –

Algoa Bay (McLachlan *et al.*, 1994: Figure 3-5). The major dunefield system – 'Driftsands', similar in orientation and size to that of the Oyster Bay HBD system, was approximately 18 kms across when fully functional, while the smaller 'Noordhoek' Dunefield was approximately 600 m across. The Driftsands Dunefield system was stabilised over a number of years using techniques which included the spreading of refuse followed by the planting of alien invasive plants from 1883 to 1897 (Lord *et al.*, 1985 cited by McLachlan *et al.*, 1994). The Noordhoek Dunefield was stabilised between 1960 and 1970, to allow for the development of sewage works and maturation ponds.

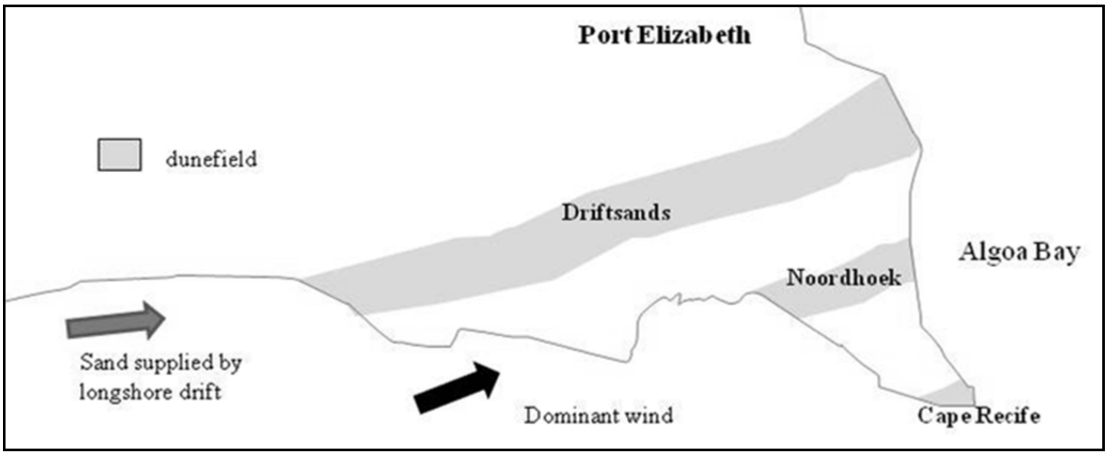


Figure 3-5: Diagram showing the location and layout of the Cape Recife HBD system (diagram not drawn to scale).

Source of figure: Adapted from McLachan *et al.* (1994).

Today, only the smallest dune system located at the Cape Recife point itself is still operating (Figure 3-6). However this system was an insufficient source of littoral and aeolian sand for the Algoa Bay beaches, which were experiencing a severe net reduction in sand supply up until the development of the harbour's breakwater in 1930. This breakwater resulted in the trapping of sand from longshore sand transport, estimated at 150 000 $m^3.a^{-1}$ (1931 – 1985), leading to the 800 m seaward growth of the beach preceding the wall (McLachlan *et al.*, 1994). Without this breakwater wall, erosion rates similar to that observed at St. Francis Bay, may have continued.

Figure 3-6: Current view of Noordhoek and Cape Recife HBD systems.

Source of imagery: Google Earth (2012)

3.3.2 National Situation

The Agulhus Headland / Struis Baai / Waenhuiskrans dunefield system is not typical of the description used by Tinley (1985) when categorising HBD systems. However, there are many aspects which apply to the functioning of this system and to other HBD systems. The 'HBD' part of this complex dunefield system used to pass across the Agulhas Headland into the downwind bay of Struis Baai (where the town of Struis Baai is located) – the past outline of the dunefield can be seen in Figure 3-7. The dunefield was approximately three to four kilometres wide (north south) and 15 kms long when active, supplying sand to Struis Baai. This HBD system formed part of a more complex dunefield system which together extended across Struis Baai into the next bay, Marcus Bay, located just south of the town of Waenhuiskrans.

Figure 3-7: The Agulhus Headland / Struis Baai / Waenhuiskrans dunefield system.

Source of imagery: Google Earth (2012).

This system has not always been active. In the 1960s, the headland was stabilised and as a result, severe erosion was experienced along the beach below Waenhuiskrans due to a deficit in the littoral sediment budget (McLachlan & Burns, 1992). Unlike the case of St. Francis Bay, it was realised that the cost of re-establishing the eroded beaches was excessive and therefore in the 1980s a pilot project was carried out to consider the possibility of re-activating the eastern part of the dunefield system (McLachlan *et al.*, 1994). Initial attempts failed as the coppicing rates after the burning of shrubs was very high. However a successful subsequent burn carried out in 1988 led to the re-activation of the dunefield and an increase in the sediment supply to previously eroding beaches (McLachlan *et al.*, 1994). As of 1994, the results from beach monitoring programmes have shown that the recovery process was already working, albeit slowly. Today, as seen from aerial photos, the western 'HBD' system is stabilised.

In another study at the Goukamma / Buffelsbaai dunefield system, Burkinshaw (1998) used aerial photography to show the occurrence of a HBD system operating between the Goukamma river mouth (in the west) and Buffelsbaai (eastern, downwind beach). The northern dune was initially stabilised around the 1930s and was almost completely vegetated by 1974. Again, in a similar way to the HBD systems operating across the Cape St.

Francis and Cape Recife headlands, this system was host to three sets of dunes. All of these dune systems have now been stabilised to a greater or lesser degree. As a result, the Buffelsbaai beach has been eroding, which may be increased in part by the apparent weaker wind strength and conditions of depleted sand supplies (Hunter, 1987 cited by Burkinshaw, 1998).

All of the above systems fall within the defined Cape South Coast system. These systems lend themselves well to being comparative examples of how active management of dunefield systems can effect, destroy and / or restore complex dunefield systems along the coast of South Africa. An increased understanding of how these systems operate could potentially allow for comparison of dunefield functionality in terms of explaining processes or key drivers.

3.3.3 International Situation

In south eastern Brazil, Boeyinga *et al.* (2010) have presented findings on research conducted on a headland bay beach (the downwind bay) subject to persistent erosion (Figure 3-8). In this area, the town Ingleses is being threatened from two ends: the migration and encroaching onto houses of the HBD system from the south and the erosion of the beach from the north-east (Boeyinga *et al.*, 2010). Similar to the systems present across the Cape St. Francis headland, there is a second dunefield which is still currently supplying sediment to the downwind bay at a rate of approximately 10 000 $m^3.a^{-1}$. This system lends itself well to showing the implications that various management approaches can have on the immediate surrounding areas of HBD systems and their downwind bays. Unlike the Oyster Bay HBD which is completely vegetated in the eastern extreme, therefore limiting the migration of dunes beyond a certain point, the Mocambique dunefield is not vegetated and continues to act as a threat to the town to the north.

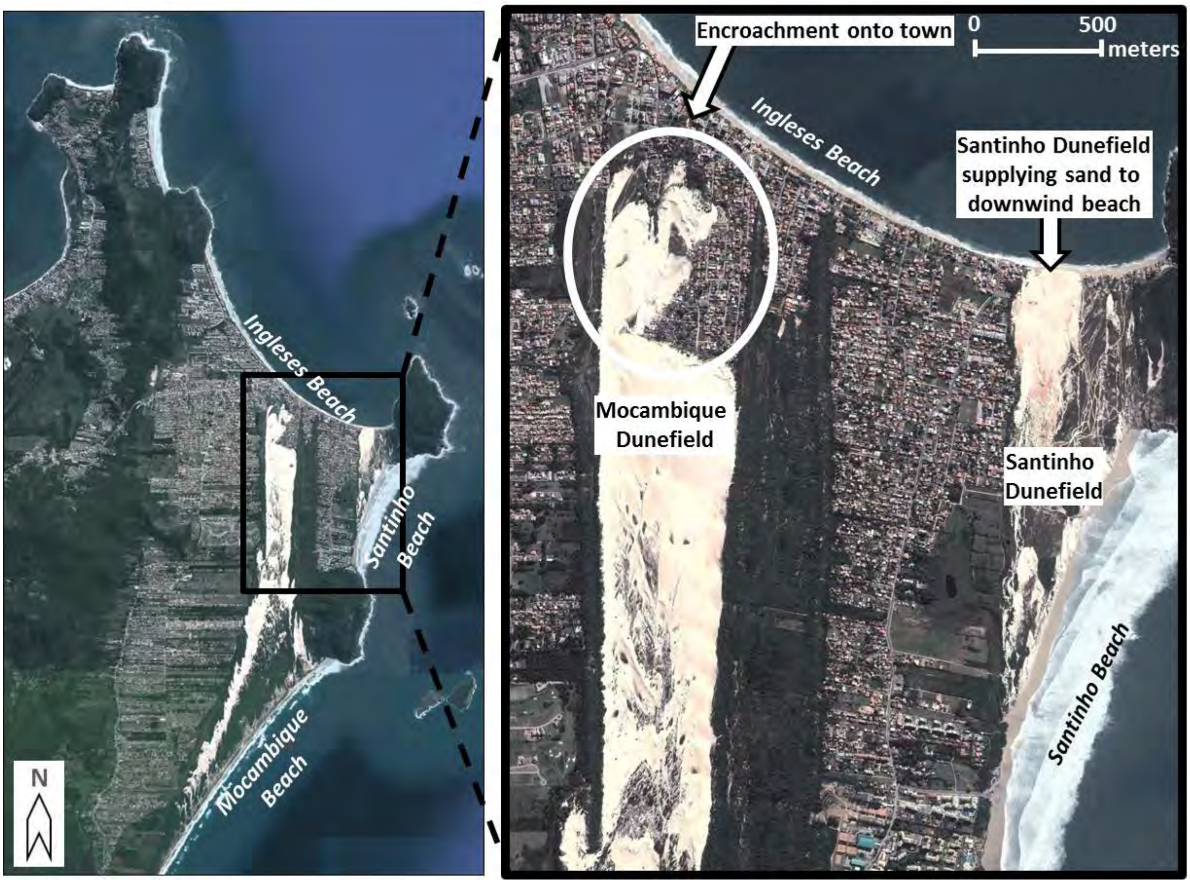


Figure 3-8: The town of Ingleses in the north being encroached upon by the Mocambique dunefield. To the east the Santinho dunefield continues to supply sand to Ingleses Beach. **Source of figure and imagery:** Adapted from Boeyengi *et al*. (2010: 153) and Google Earth (2012).

Da Silva & Hesp (2010) have also conducted research on the same system, but their research focused on the behaviour of the foredune in relation to the beach orientation, and the dynamics of sediment transport in relation to wind variation. Their study lends itself well to analysing the key drivers and related processes occurring within the Oyster Bay HBD system, providing insight into the relationship between wind dynamics, the orientation of bays and consequently, sediment movement. The results of this research show the effect that the wind opposite to the dominant wind direction has on the accretion and steeping of dunes and the impact that the dominant wind can have on the resultant dune type (small parabolic dunes verse an extensive transgressive dunefield) that forms over the headland due to varying wind speeds and direction over time (da Silva & Hesp, 2010: 275). This can be compared to results found by Burkinshaw (1998) within the Oyster Bay HBD.

In north eastern to central eastern Brazil, Castro (2005) presented findings on the migration of a dunefield system and the consequent burying processes of the city of Paracuru by a mobile transverse dunefield (Figure 3-9). In this system, similar to those occurring across the Cape St. Francis headland, the transverse dunes have ridges that are perpendicular to the dominant wind direction and shift with the uni-directional wind pattern which predominantly blows from the east . The heights of the dunes range from 13 to 25 m with wavelengths varying from 100 – 250 m (Castro, 2005). The morphology of the coastline and the predominantly uni-directional system of aeolian transportation allows this system to be classified as a headland bypass dunefield (Castro, 2005). Sediment is transported from the upwind bay's beach, traversing inland and across the headland, partially returning to the downwind bay's beach either through a localised drainage network or the dunes that constitute the deflation plane.

In the research done by Castro (2005), overlapping aerial photographs from different flights were used as a reference from which changes in the morphology and movement of the dunefield system could be shown. Both changes in the total area that the dunefield covered and migration rates were examined using aerial photographs over a period from 1958 to 1999. Changes in the morphology of the dunefield were then related back to rainfall records to determine what relationship exists between rainfall and dune movement.

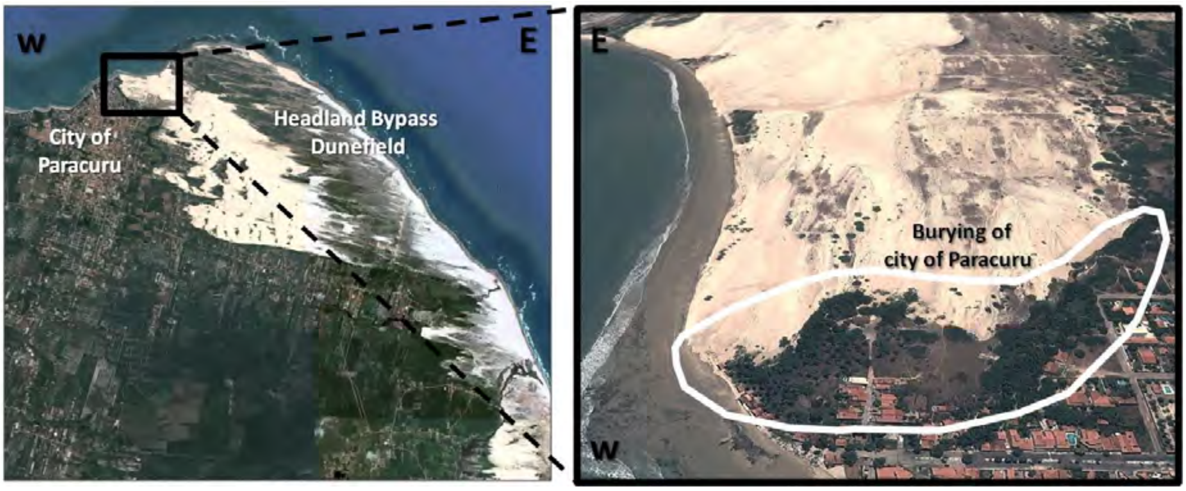


Figure 3-9: The burying of the city of Paracuru by an HBD system.

Source of figure and imagery: Adapted from Castro (2005) and Google Earth (2012).

In another study, Parteli *et al*. (2006) looked at one of the largest coastal dunefields on the tropical north eastern coast of Brazil; which extends over several kilometres and is known as the Lençóis Maranhenses Dunefield. The type of dunefield is a transgressive system resulting from high energy beaches that experience high littoral drift. This dunefield system is more extensive in size and complex than that of the relatively smaller HBD systems occurring across the Cape St. Francis Headland. The Lençóis Dunefields and more specifically the research conducted by Parteli *et al*. (2006) do however lend themselves well to providing examples of the occurrence, development and functioning of dunefields, and the relationship between transverse and barchanoid dunes within one system. This dunefield system will also add to our understanding of dune morphodynamics in the presence of a varying groundwater table through the research conducted by Luna *et al*. (2012).

The Cresmina Dune forms part of a HBD system, classified according to Tinley (1985), known as the Guincho-Oitavos Dunefield which is located on the west coast of Portugal (Rebêlo *et al*., 2002). The aim of this research was to, '…quantify the advance rate and the resultant aeolian sand transport of the dune' (Rebêlo *et al*., 2002: 591). GIS and GPSs were used in topographic surveys which were undertaken in two consecutive years to monitor change in the dune system. This research is very relevant to the research undertaken for this dissertation, despite the different methods used, the intended outcome of analysing the extent of an HBD system is similar.

To a large degree, these systems elsewhere in the world are useful for comparison with the functioning of the HBDs occurring along the south coast of South Africa. These examples show the uniqueness of each HBD system, emphasising the necessity to continue studying these dunefield systems as distinctive systems in their own right, in order that they might be appropriately managed in the future. Simultaneously, these examples show the main factors that contribute to the formation of HBD systems, such as predominantly uni-directional wind conditions and an abundant sediment supply, as well as the resultant types of dunes that may occur within these systems, such as transverse or barchan dunes. The various methods mentioned and used within these studies lend themselves well to being adapted to the research undertaken within other similar systems, including the Oyster Bay HBD system, making results comparable. Lastly, the discussions, conclusions and the lessons learnt from the various studies reviewed can be drawn upon for this research.

3.4 HISTORY OF STABILISATION AND DEVELOPMENT OF DUNEFIELDS ALONG THE SOUTH COAST

The review now looks at the history of management and development along the south coast of South Africa, with a particular focus on the area between Oyster Bay and St. Francis Bay. According to Tinley (1985), HBD's along the southern coast of South Africa have been poorly managed. As mentioned previously, it is vital to maintain the long-term downwind flow of sand supply in a HBD system in order to ensure that the sand supply to the downwind bay is sustained. If sections of a HBD system are stabilised, resulting in a reduction in sediment flux through the system, net erosion of the downwind beaches will occur; as has been described for many of the HBD systems mentioned previously. Disruption of sand transport across the HBD's through human activities is a recognised problem on high energy coasts (Komar, 1983).

Dune stabilisation or reclamation is defined by Avis (1989: 56) as "the process of limiting or preventing the movement of shifting sands by covering the surface with artificial material or by establishing a vegetation cover". Stabilisation of dunefields along the south coast of South Africa dates back to 1845 (Avis, 1989). From the outset, *Acacia* species such as Port Jackson or Rooikrans were used, as they were regarded as the most suitable plants for this purpose. In 1875, stabilisation methods were modified to the spreading of city refuse over bare sand to temporarily stabilise the sands, before using alien plants. At this time the Cape Forestry Department had the onus of stabilising drift sand areas. Their policy was to use tree plantations that could in turn be harvested, making this an economically viable method (Avis, 1989). In 1888 this method was introduced to the Eastern Cape for the stabilisation of the drift sands around Cape Recife. In 1892, Marram Grass was introduced as a means to stabilising drift sands. This method differed from measures that simply covered the dunefields and therefore stabilised them, to target the source of sand supply. The success of this method saw a decrease in the use of city refuse for stabilisation. Methods involving the use of vegetation to stabilise driftsands were used up until about 1970.

The threat of alien vegetation (specifically Rooikrans) was first raised in the mid-1930's (Keet, 1936 cited by Avis, 1989). However, it was not until 1974 that it was decided that the use of invasive alien plant species should in fact be phased out to be replaced either by indigenous species or non-invasive alien species (Avis, 1989). Ultimately in 1980 it was decided by the Directory of Forestry that drift sands should be considered as natural areas and should thus be preserved as such (Cobby, 1988). The only exception was that if farm lands or settlements were deemed threatened by drift sands, then stabilisation, with indigenous species only, would be considered. If this policy had been introduced in the 19th century it is likely that many drift sands, including transgressive dunefields and HBD systems would still be functioning to their full extent today (Burns & Reyneke, 1983). A complicating factor has been human development and provision of infrastructure.

3.4.1 Dune stabilisation between Oyster Bay and St. Francis Bay

Before 1960 there was little recreational use of the headland at Cape St. Francis (La Cock & Burkinshaw, 1996). Due to the extensive dunefield systems, this area was largely inaccessible, with the exception of a sandy track through the dunes (Bulpin, 1980). This track was used by the people who lived in the few holiday cottages south of the Krom River. It was only between 1917 and 1924 that stabilisation of drift sands was initiated in the area, when approximately 100 hectares of drift sand were stabilised at the western end of the Oyster Bay HBD (La Cock & Burkinshaw, 1996). The invasive species, *Acacia cyclops*, was used supposedly in the interest of the farming community whose land was being encroached by drifting sands (Avis, 1989). Between 1970 and 1980, despite warnings by ecologists not to interfere with the functioning of the bypass dunes (McLachlan & Burns, 1992), the Santareme Dune system was stabilised to allow for the development of a holiday resort.

It has been estimated that the Oyster Bay HBD used to discharge approximately 70 000 m^3 of sand per year into the downwind beach of St. Francis Bay (McLachlan & Burns, 1992). In contrast, the Santareme Dunefield, which reached the eastern bay, up until about 1990, discharged between 91 000 m^3 and 150 000 m^3 of sand per year to the beach at St. Francis Bay (Illenberger & Burkinshaw, 2008). It is therefore only in the last two decades or so that the importance of the systems has been realised as a deficit in the sediment budget has been observed. As a result, the beach at St. Francis Bay has been severely eroding with retraction measurements of up to nine metres recorded between 1975 and 1982 (Lubke, 1985).

It is unfortunate from environmental, economical and recreational perspectives that the proper functioning of these HBD systems has been poorly conserved. When decisions to stabilise the dunes in the vicinity of St Francis bay were being made, the value of real estate was so high that "ecological issues enjoy(ed) low status roles" (McLachlan & Burns, 1992: 201). Development in the area has now decreased but has probably eliminated the possibility of re-activating the HBD systems across the headland.

3.4.2 Vegetation within dunefield systems

Vegetation is responsible for a deceleration of wind near the dunefield surface (Sarre, 1989 cited by Judd, 2008). This is significant when studying and wanting to understand the movement of sand within a dunefield system, as when wind decelerates due to the presence of vegetation, entrainment of sediment is difficult but deposition of sand can occur (Judd, 2008). The amount of vegetation cover needed to affect sand movement is debated in the literature (Buckley, 1987 and Walker *et al*., 2006). However the fact that vegetation cover reduces the movement of sand through the deceleration of wind is well known.

Luna *et al*. (2009) have acknowledged that despite large quantities of research on various aspects of transverse dunes, there is a gap in the literature relating to the shape and dynamics of transverse dunes in the presence of vegetation. The complex process of the competition between sand dunes and vegetation is not completely understood (Luna *et al*., 2009). It is however known that vegetation plays a key role in trapping sand that would otherwise most likely be blown in the direction of the dominant winds. Luna *et al*. (2009: 32) conclude from their research that, “the higher the vegetation growth rate, the larger the stabilised sand hill and the smaller the volume of sand that escapes stabilisation”.

In other research, the succession and dynamics of coastal vegetation along the Eastern Cape coastline within various dunefield formations has been investigated (Avis & Lubke, 1996). Avis & Lubke (1996) acknowledged that there were a few controlling environmental drivers and factors that affected the growth of vegetation within dunefield systems, namely soil moisture, rainfall and wind. Wind is responsible for the reduction in growth of the vegetation due to the burial of seedling and plants by sand as well as the damage to plants by salt spray (Avis & Lubke, 1996). This together with low and variable rainfall is responsible for the ‘paucity of vegetation and maintenance of mobile dune systems along this coastline” (Avis & Lubke, 1996: 251).

Looking further afield, at research conducted on South Padre Island, Texas (Judd *et al*., 2008), one can see the similarities of the environmental factors which control the growth, the type, and the dynamics of vegetation within dunefields to those mentioned by Avis & Lubke (1996). Judd *et al*. (2008: 992) acknowledged that the environmental factors which controlled the vegetation patterns included prevailing winds laden with salt spray, periodic tropical storms, low annual precipitation, nature of the soil and its water and salt content, as well as the water table relative to the root zone.

In a study of dune mobility conducted by Jiminez *et al*. (1999) on the Ceará coast of north eastern Brazil a method for monitoring dune movement was developed. Their method included the use of a natural marker, vegetation. Jiminez *et al*. (1999: 694) observed in the field that during the dry seasons, cuspate vegetation marks could be observed, indicating the position of the dune during the previous wet season each year; hence acting ‘as a time datum indicating the annual dune migration’. The theory behind this method is that during the wet season, vegetation growth is optimal and sand movement is reduced due to increased moisture. Wind intensity drops due to vegetation establishment and sand becomes trapped by vegetation, thus resulting in a temporary ‘fixing’ of the dune. However, in the dry season the opposite effect is observed. With a decrease in rainfall and sand moisture content, and an increase in wind intensity, dune movement is reactivated. However, the area of sand that was fixed by the vegetation remains in place as a result of the stabilising effect of plants (Jiminez *et al*., 1999). The stabilised region, when exposed, is the cuspate vegetation markings which are used to show the position of the dune in the previous wet season. In this region, there are distinct wet and dry periods thus allowing for the assumption that the vegetation cuspates correspond to the previous season. Of significance to this dissertation is that, in dunefields, the presence of vegetation indicates that water must be at or close to the land surface or the sand must be partially saturated, thus allowing for vegetation establishment.

The above literature shows that vegetation has a controlling influence over the movement of sand within a dunefield system. In addition there are key environmental factors that in turn control for the presence, succession and dynamics of vegetation within these dunefield systems, including: wind, rainfall, groundwater and wind. The following section will examine some of these controlling, natural factors and their relationship with each other.

3.5 DRIVERS OF AND PROCESSES OCCURING WITHIN COASTAL SYSTEMS

3.5.1 Aeolian sand and its relationship with wind and water

Coastal sand dunes are sedimentary deposits (e.g. a sink zone) formed as a result of wind blowing sediment inland from beaches (Davidson-Arnott, 2010). A general understanding of the nature of processes associated with wind and the movement of sediment by wind is necessary to understand the development of dunes over time (Davidson-Arnott, 2010: 235). Sand is moved via longshore drift, resulting from wind and wave currents, ultimately ending up on a beach somewhere. The location of the beach and its orientation in relation to the predominant winds and currents ultimately determines the amount of sediment that can potentially move on shore, and therefore influences the type of system that consequently develops. Figure 3-10, taken from Tinley (1985: 215), helps to show the variation in refraction patterns and longshore currents due largely to opposing predominant winds in half-heart bays. This figure helps to emphasise the role that sea currents and wind play in conjunction with beach orientation in the formation and progression of dunefield systems.

The figure emphasises the locations at which deposition or removing of sediment would occur. Therefore, with regards to the Oyster Bay HBD where the volume of sediment crossing the headland has been greatly reduced, the right hand drawing helps to further depict why erosion is occurring in the downwind bay. In the right hand drawing, the dominant wind is south-westerly (such as that in the region of the study area), resulting in diverging currents and sand being removed from the downwind bay.

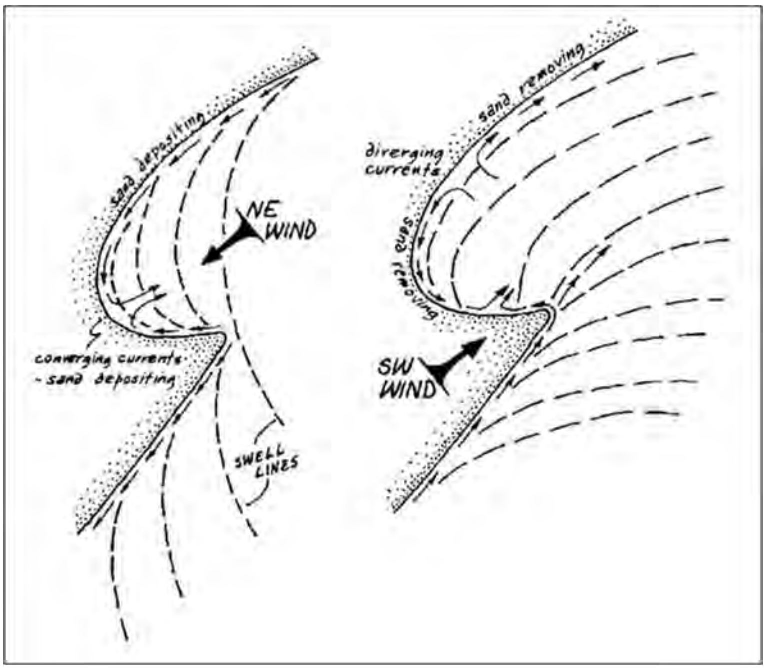


Figure 3-10: Diagram showing the contrasting refraction patterns and longshore currents generated by the opposing predominant winds in half-heart bays.
Source of figure: Tinley (1985: 215).

Knowing the type and or size of sediment that occurs within a system is also of significance in dunefield systems. The particle size and sorting characteristics of the surface sands of aeolian dunes have been studied and reviewed by numerous authors (Bagnold, 1941; Owen, 1964; Pye, 1982; Burkinshaw, 1998 (Oyster Bay HBD); Arens, 2002; Lancaster *et al*., 2002; Almeida *et al*., 2007 and Li *et al*., 2008). In some of these studies an explanation of the movement of sand grains by various motions is given. Similar to water, there are three possible types of aeolian sediment transport by wind: suspension, saltation and creep (Bagnold, 1941: 37, Figure 3-11). The transport of sand by air or water differs due to the individual properties of water and air, specifically in terms of differences in their density and viscosity (Davidson-Arnott, 2010: 236). Water is denser than air and therefore sand is more buoyant in water than in the air. As a result, less force is needed in water to move sand as opposed to wind, where relatively high wind speeds are needed.

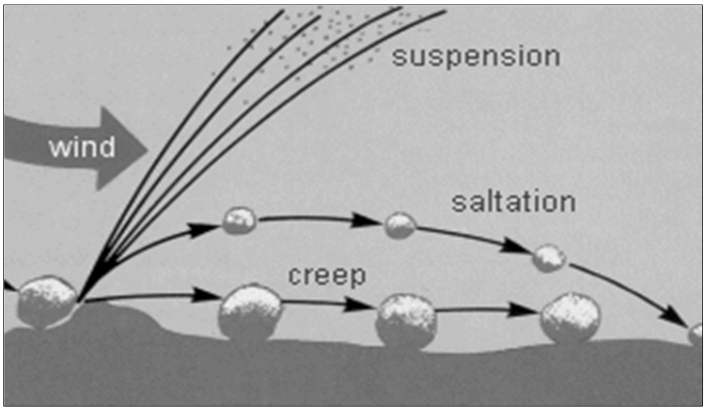


Figure 3-11: The three types of aeolian sediment transport by wind.
Source of figure: WERU (2012).

Unlike silt and clay particles, sand grains are generally too large to be moved large distances in suspension. However in strong winds the finer sand grains may approach suspension, "…in that the upward wind eddies may check the descent of grain and so cause it to remain in the air longer and to travel further before it again strikes the ground" (Bagnold, 1941: 37). In surface creep, typically larger grains receive their forward motion from the impact of other grains; they travel slower than finer particles and remain on the ground (Lancaster *et al.*, 2002). The poorly sorted, coarse sand grains have been found to remain in lower slope positions, in contrast to finer, better sorted sand grains found in the upper areas and crests of slopes (Lancaster *et al.*, 2002). Saltation is the only motion which opposes the wind, reducing momentum, in that it creates a resistance to the wind through alternate contact with the air and the ground (Bagnold, 1941). In the case of saltation, grains are initially lifted by the wind and after some distance they land back onto the ground, in so doing the impact ejects additional grains back into the air and so forth, until momentum is lost due to a lack of wind (Herrmann *et al.*, 2008). As much as 75% of sand transport by wind occurs in saltation (Bagnold, 1941).

Coastal dune sands are normally medium to fine grained and well-sorted to very well-sorted (Pye, 1983: 544). Coastal dunes have a very small amount of sediment less than 0.15 mm in size due to the fact that fine sediments are generally scarce in active sandy beaches (Davidson-Arnott, 2010: 229). Similarly, due to the inability of the wind to suspend particles that are greater than 1 mm in size, this size class is generally left on the beach during deflation (Davidson–Arnott, 2010).

Several authors have argued that wind should typically remove finer, lighter grains from the beach and that aeolian sediments may therefore be expected to show positive skewness away from the source (Pye, 1983). However, other studies have shown that in instances where the beach sand is already fine grained, aeolian transport is not necessarily selective and that differences in the mean size, sorting and skewness of beach and dune sands need not be expected (Bigarella *et al.*, 1969 cited by Pye, 1983: 544 and Burkinshaw, 1998). Furthermore, for parabolic dunes, negative skewness is typical (Pye, 1982). Negative skewness in parabolic dunes is thought to be a result of a 'winnowing of fines' at dune crests by persistently strong unidirectional winds, together with grain size sorting during slumping on the lee slip faces (Pye, 1982: 263).

In addition to the above, the movement of sand by wind from surfaces that are wet verses those that are dry must also be explored. Moisture content, of a beach surface, is acknowledged in much literature as an important factor controlling the release of sediment (Bauer *et al.*, 2009). Without considering any other factors, the simple rate of sediment transport over a dry surface is greater than that over a wet surface (Bauer *et al.*, 2009). The effect of moisture has been shown to have two important influences on the movement of sand (Bauer *et al.*, 2009):

i) on a temporal scale – the rate of sediment transport by wind generally decreases with increased rainfall and increases with surface drying; and
ii) on a spatio-temporal scale – nearshore processes such as wave run-up, have an effect of constraining the fetch-geometry of the beach.

All of this is of significance to the HBD systems occurring across the Cape St. Francis headland, as high rainfall events have occurred in the past and they were likely to have affected sediment flux.

3.5.2 The channelling / tunnelling effect of wind by beach ridges

In most sandy coastal systems, aeolian processes play an important role in the morphodynamics and sediment budgets (Hesp *et al.*, 2005: 71). The airflow over dunes is critical to dune formation and evolution (Schatz & Herrmann, 2006). Wind flow direction and speed are affected by the topography of the beach and dune (Davidson-Arnott, 2010). For example in a foreshore setting, gentle-sloped beaches hardly affect the wind's motions, but in areas where there are steep foreshores and berm crests, wind speed is accelerated over the top of the foreshore and crest (Davidson-Arnott, 2010). In addition to this, steep crests or ridges can affect the sediment properties of dune sand that is blown in from the beach.

3.5.3 The role of groundwater and rainfall in coastal dunefields

During periods of high rainfall, water collects in pools within the Oyster Bay HBD system. Some of these pools or wetlands are more permanent and / or successionally advanced than others. In addition to these wetlands, during periods of high rainfall, the Sand River system drains the north eastern region of the Oyster Bay HBD into the Krom River. As mentioned in the introductory chapter, on a few occasions the volume of water within the system has been so substantial that episodic flooding events have occurred, resulting in massive amounts of sediment being washed down and out of the Sand River and Oyster Bay HBD systems in the form of debris flows, covering surfaces and obstacles in the pathway of the flow. Such events have shown that sediment flux through the Oyster Bay HBD and Sand River systems is not simply a function of wind and sand, but rather that water (both rain and ground-fed) is also a factor influencing processes occurring within this system.

Luna *et al*. (2012) emphasized the role that groundwater can play in sediment transport within coastal and desert systems, noting that the groundwater table is largely seasonally connected with variations in rainfall and climate, as was shown by other research (Levin *et al*., 2009). Luna *et al*. (2012) acknowledge that this relationship between groundwater and seasonal variance in rainfall has been sufficiently modeled but that in terms of quantitative research, very little is known about the morphodynamics of dunefields in the presence of a varying groundwater level. The Lençóis Maranhenses forms the basis of this research.

Of significance to this section is the theory of geomorphic thresholds as presented by Schumm (1979). The first threshold presented in his work is the extrinsic threshold, that which exists within the system, “but will not be crossed and change will not occur without the influence of an external variable” (Schumm, 1979: 487). The second type of threshold is that which is intrinsic, with changes occurring within the system without a change in an external variable. Of significance to this research regarding the geomorphic threshold, ‘which involves landform change without a change in external controls’, is that ‘abrupt erosional changes can be inherent in the normal development of a landscape’ (Schumm, 1979: 487). These inherent processes occur as a response to the continual need for a specific system to find equilibrium in response to progressively altering conditions. In this sense, an external variable is not always required for a geomorphic threshold to be crossed or an abrupt erosional event to occur.

This principle is captured in the theory on geomorphic thresholds, where it is stated that, ‘…the fluvial system must hunt for a new equilibrium (complex response), and when the change is major it is overwhelmed by the quantity of sediment that requires movement and the results are episodes of erosion and deposition (episodic response)’ (Schumm, 1979: 497). With regards to the Oyster Bay HBD system, the dunes are continually shifting across the dunefield and are constantly trying to find equilibrium at the mircro- and macro-scales. Processes such as slumping of individual dunes are progressive and are the result of intrinsic thresholds being crossed. The north eastern region is also constantly trying to remain in equilibrium. However in this part of the system, extreme rainfall events have a large effect, resulting in the over saturation of sediment which ultimately result in debris flows occurring. This can therefore be seen as an extrinsic threshold being crossed as a result of an external variable, in this case excessive rainfall. In the case of fluvial systems, based on the above theory, the catastrophic event that results from sedimentation in localised zones in the landscape is a channel avulsion (Ellery *et al.*, 2003a and Ellery *et al.*, 2009).

3.5.3.1 Debris flows

The occurrence of debris flows is dependent on numerous factors (Bonte *et al.*, 2000):

i) a significant input of water,
ii) unvegetated land surface where vegetation does not provide cohesion to soils or sediment,
iii) the availability of loose removable sediment and
iv) an incline that is sufficiently steep, typically greater than 15%.

Debris flows usually also have a diversity of substances involved, including water, sediment of variable grain size dispersions and mixtures of particles of various types such as wood, granular substances or even boulders (Hungr, 2000). Debris flows typically have a steep front with the densest mixture of particles and the greatest depth, followed by a progressively less dense tail that is less deep (Hungr, 2000). In a fine-grained debris flow, the saturated debris behind the surge front is almost liquefied by high pore pressure, largely due to the ‘great compressibility and moderate permeability’ of the debris (Iverson, 1997: 245).

Debris flows, which depend on a sufficiently steep incline to occur, can continue flowing on low gradient slopes of 1° or more (Illenberger & Associates, 2010). To initiate a debris flow, Illenberger & Associates (2010: 5) have suggested that an incline of at least 15° is needed; stating that gravity if the driving force creating the flows, not the entrainment of sediment by water. The high peak discharge of debris flow surges is the main cause of destruction (Hungr, 2000). This characteristic is also used to distinguish a debris flow from a debris flood – the latter requiring the ‘tractive forces’ of moving / flowing water (Hungr, 2000: 486).

3.5.3.2 Water quality

The term water quality is used to describe in a general way the concentration of dissolved solutes and particulate (clastic) sediment. It is recognized from the outset that the nature and level of solutes found in wetlands varies considerably from one wetland area to the next. Variation over time within a given wetland area may also be considerable, particularly in areas subject to seasonal climatic variation.

The electrical conductivity (EC) of water estimates the concentration of dissolved salts (Wetzel, 1983). Electrical conductivity is influenced by many external factors including the geology of the surrounding area (e.g. increased limestone raises EC levels), the size of the watershed (e.g. a bigger catchment might increase the amount of water flowing into a river), the length of time that water is present in the ground, the ratio of rainfall to evaporation, or even salt spray from the ocean. The influence of ocean water is implicit in the wetland regions within the Oyster Bay HBD, where the salinity of dry aerosol and wet precipitation may be factors increasing the electrical conductivity of water in the wetlands. In addition to this, the wetlands within the Oyster Bay HBD are relatively shallow and therefore evapotranspiration of water from the surface of the wetland may result in a higher concentration of salts thus increasing EC (Ellery *et al.*, 2009). Electrical conductivity tests will therefore be useful to examine the potential source of water and its fate in the dunefield, which will increase our understanding of groundwater dynamics within the dune system.

The pH of the water is also important to understanding the functioning of the wetlands within the bigger environmental setting. The pH of water is a measurement of the concentration of hydrogen ions; the higher the pH the less available hydrogen ions become and the more basic the sample is. In addition, a change in pH by one unit reflects a tenfold change in the concentrations of the hydrogen ion (Water on the Web, 2004). It is therefore important to use a pH metre which measures to at least one decimal place so as to increase the meaning and accuracy of the recordings. The importance of pH reflects onto biotic life as it determines the solubility of water and therefore the biological availability of chemical constituents such as nutrients (Water on the Web, 2004). The use of carbon dioxide by plants by photosynthesis is therefore another aspect to be considered. In water, the removal of carbon dioxide essentially reduces the acidity of the water and thus increases the pH level. At the same time, respiration of organic matter produces carbon dioxide which, in contrast to plants, decreases the pH level.

All of the above theory must be considered when interpreting water sample results. This theory must also be considered in the context of the system as a whole and not as just the isolated samples that were collected on a monthly basis.

3.6 GEOGRAPHIC INFORMATION SYSTEMS (GIS)

Using Geographic Information Systems (GIS) as a tool to establish the relationship between morphology, pattern and process in the Oyster Bay HBD system was a significant aspect of this research. The GIS provided the framework for the research, allowing for the gathering and organising of spatial data and related attribute information so that it could be displayed and analysed (DeMers, 1997). Furthermore, understanding processes and relationships within the system could possibly be used to predict how the system will develop in the future. Such understanding could have implications for the management of the system in the future. GIS was therefore considered an appropriate tool for this research, aiding the integration of data collected in the field as well as data utilised from secondary sources. The material presented here explains some of the theory behind GIS and describes related terminology, as well as providing an overview of similar applications of GIS use in other environmental research.

3.6.1 Theory of GIS

Geographical information is information about a geographical feature that is in some way associated with a specific spatial location on the earth’s surface. According to Longley *et al*. (2005), there is something ‘special about spatial’ data; not only allowing us to keep track of features, events or processes, but also the change in geographical location of such features events or processes over time. Longley *et al*. (2005) described this information as having ‘an atomic element’ of location, attribute(s), and an optional time reference. These aspects of spatial features are imperative within the field of geography, and GIS and can be further explained as the ‘where’ – the absolute and relative locations of spatial features; and the ‘what’ – the associated attributes and properties of those features (Bolstad, 2008: 1).

Dueker & Kjerne (1989: 7-8) defined a GIS in a very comprehensive way, stating that a GIS is, “…a system of hardware, software, data, people, organizations and institutional arrangements for collecting, storing, analysing and dissembling information about areas of the earth” (cited by Chrisman, 1997).

In the past, there was a strong reliance on hard copy map products which were different from each other in various ways, including scales, level of detail, and size. Ultimately, the end product was a function of the desired level of detail that was required by the end user (Cherinin & LeRoux, 2005). However, due to the user-friendly nature of software today, the ‘special’ has become partially invisible and the necessity to theoretically understand the data, the analyses being conducted on the data, and how the data are ultimately available to be viewed, is lost to some degree (Longley *et al*., 2005). For the purpose of this research however, it is important to ensure that a certain level of theory is discussed to ensure that the functioning of the GIS and certain processes that were conducted in this research are understood.

3.6.1.1 Projections

Of great importance to a GIS is its ability to take data from a spherical surface (earth) or 3D environment, and accurately present the same data on a flattened surface in two dimensions; a process known as projecting data. A map projection is a mathematical model that allows for the three dimensional network of angular meridians and parallels of the earth to be shown in two dimensions (Dickinson, 1979). The important aspect of projections is that they can only retain or preserve certain properties – such as distance, direction, area and shape – at any one time. It should be noted that maintaining one property will result in the distortion of other properties (Dickinson, 1979). In conclusion, for the map to be useful it needs to provide the most representative display of the world on a two dimensional surface (CDSM, 2003). Therefore the application and / or intended use of the data will be important in informing the choice of projection used (Dickinson, 1979).

For this research, a Universal Transverse Mercator (UTM) projection was used. This projection is based on the Mercator Projection, but in transverse aspect. Therefore a cylinder is wrapped around the meridian (poles) rather than the equator. Its co-ordinates are in meters, which therefore makes it easy to make accurate calculation of short distances between points. The Gauss-conform projection was specifically used and is based on the UTM projection. The Gauss-conform projection retains the shape of small areas, therefore ensuring accuracy for the measurement of distance between points of interest and for calculating areas. It is based on two degree zones of longitude in the system with each zone being based on a central odd meridian that is located closest to the centre of the region of interest. The central meridian used is known as the Longitude of Origin (Lo) and this line is the only straight line of longitude in the projected map while the equator is the only straight line of latitude (Carter, 1997). In this projection, the zone surrounding the central Lo is flattened. For example, for the central Lo of 25, the area between 24 and 26 degrees east will be flattened. In South Africa, this projection is the most commonly used (CDSM, 2003).

3.6.1.2 Aerial photographs

Aerial photographs were used throughout this research. They are useful as they provide a broad overview of a general area at a given time. They are also useful due to the fact that other data can be captured against them, for example, vegetation change over the past 40 years was mapped using the available aerial photographs as base images. In order for the aerial photographs to be used within a GIS however, they need to be accurately located in space. To achieve this, one of two processes needs to be undertaken within a GIS: orthorectification or geo-referencing.

Orthorectification deals with fixing the inherent distortion that occur during the capturing of aerial photographs. In short, for example, when an aerial photograph is captured, the centre of the photograph is the most accurate reflection of the earth with features becoming displaced or distorted towards the edge of the photograph (Dickinson, 1979). To fix this, the displaced or distorted features need to be rectified to ensure that the flattened photograph is a true representation of the area on the ground across the entire area of the photograph. This process is known as orthorectification.

Orthorectification is an extremely expensive and time-consuming process and geo-referencing images is a simpler, less expensive process that allows for sufficient accuracy of representation of the earth for many applications. Geo-referencing is the process by which non-spatially defined data, such as scanned maps, aerial photographs or raw satellite imagery, are linked to spatially defined map coordinates manually. Geo-referencing does not remove any of the inherent errors associated with map projections. For example, in this research, aerial photographs were geo-referenced to the roads vector layer from the 1:50 000 topographic series, which included sheets: 3424BA and 3424BB. The process involves identifying the same location on the aerial photograph to that which occurs on the roads vector layer. Geo-referenced locations need to be *unique* so that there is no confusion about the point referenced and in addition, the location needs to be *persistent through time* (Longley *et al*., 2005). For example, it is not wise to use a river bend, which changes location with time as a point against which to geo-reference an aerial photograph – especially if the dates of the aerial photographs are different to the date of the river vector data from a topographic 1:50 000 series. Instead, one should use features which are known to not have changed spatial location over time, for example road intersections.

3.6.2 GIS applications

There are many similar GIS applications to that used in this research. Studies that have used GIS in similar ways will be outlined briefly below.

3.6.2.1 Monitoring dune movement

Rebêlo *et al*. (2002) monitored the advancement of a transgressive dune within a HBD system located on the west coast of Portugal. Their study included topographic surveys conducted using a Trimble differential GPS with an accuracy of 1.5 cm in the x- / y-axis and 2.5 cm in the z-axis (Rebêlo *et al.*, 2002: 594). The level of accuracy in monitoring the morphology of a dunefield is a significant aspect to research conducted in this regard; as not being able to achieve this level of accuracy would result in an false representation of the dune / dunefield system concerned. For example, to ensure an accurate representation of dune morphology, Rebêlo *et al*. (2002) surveyed smooth, flat surfaces at 10 m spaced measurements but in rough, undulating topography 0.15 m spaced measurements were used. In this research, the field work was repeated over the same area for two consecutive years, thus allowing for a comparison between the data obtained in the surveys, which ultimately showed areas of change – the relative accumulation or deflation of sand.

In another study using topographic surveys in the field, Andrews *et al*. (2002) used a total station and prism rods to survey a section of dune measuring approximately 150m by 40m in North Carolina, USA. In their study, in which field work was conducted over a period of one year, various methods and factors were reviewed and considered in order to determine the best procedure for acquiring spatial data – some of which were insightful and relevant to our research, including (Andrews *et al*., 2002):

- the spatial and temporal scales of the research question (290);
- the general morphological features that needed to be surveyed (296);
- the transect approach and grid based methodologies (291);
- the use of aerial photographs in conjunction with ground surveys (290);
- the correct use of interpolation options within the GIS (291); and
- the precision of the entire data acquisition phase (296).

3.6.2.2 Use of aerial photographs

In another study, Jiminez *et al*. (1999) monitored the movement of aeolian dunes (barchans and sand sheets) located along the Ceará coast in the north eastern region of Brazil. However the approach differed from that used by the studies previously mentioned. In the study by Jiminez *et al*. (1999), aerial photographs from different years (1958 and 1988) were used. Individual dunes were identified in the two sets of photographs and displacements were measured at numerous points along the dune to obtain an overall average displacement for each dune (Jiminez *et al*., 1999: 693).

The study conducted by Castro (2005), already mentioned previously in this chapter, is also relevant in that it examined a headland bypass dunefield in north eastern Portugal and used overlapping aerial photographs to access changes in morphology and dune movement. Specifically, the total dune area and the migration rates were examined. As mentioned by Castro (2005), many researchers in the past have used aerial photographs in the analysis of change within coastal zones (McKee 1979 cited by Castro 2005).

The use of aerial photographs for monitoring changes in the morphology of the earth's surface can be found in much literature: Dolan *et al*. (1978); DeKimpe *et al*. (1991); Bailey & Bistrow (2004); Castro (2005); Muñoz-Perez *et al*. (2009); Ewing & Kocurek (2010); Harris *et al*. (2011); and Wolfe *et al*. (2011). The above mentioned research applications, as well as others, were constantly referred to during all stages of the research as the methodologies and applications within a dunefield system specifically were transferable, and the results comparable, to data acquired an in this study.

From the above studies it can be seen that GIS is a highly valuable tool, allowing for the collection, analysis, interpretation and viewing of spatial data collected during research. The accurate use of GIS for this research will be vital to the overall outcome of the study. Current GIS and mapping software allow for numerous analysis and manipulation options, with the choice of software often being limited by budget or types of data needed to be analysed (Andrews *et al*., 2002). It has been shown that aerial photographs are a common source of data for the assessment of land cover changes over time. The literature reviewed here will be used within the methods and other sections of this research. Using GIS will help to establish spatial relationships between components of and processes that are occurring within the Oyster Bay HBD system.

3.7 CONCLUDING REMARKS

Burkinshaw (1998), whose PhD thesis is based on the same Oyster Bay HBD system, was continuously referred to throughout the course of this research. Starting from the literature, through to the methods, the results and her discussion, her interpretation and understanding of the functioning of the system was always at the forefront of this research and played a significant role in developing a greater understanding of the system (Burkinshaw *et al*., 1993; La Cock & Burkinshaw, 1996; Burkinshaw, 1998 and Illenberger & Burkinshaw, 2008). As with Burkinshaw (1998), the morphodynamic approach to studying coastal depositional landforms, first introduced by Wright & Thom (1977), was also used in our research. Their approach is based on the understanding that dunefields are process-response systems (Chorley & Kennedy, 1971), and that understanding the relationship between key drivers and their relative responses is key to the understanding of dunefield functioning.

Despite all the information covered in this literature review, there still appears to be a gap in the literature pertaining to the relationship between sand, wind and water (rain-fed and ground-fed) as dominant drivers within a HBD system (specifically the Oyster Bay HBD). The present research attempts to address this gap.

CHAPTER 4: OVERVIEW OF RESEARCH STRATEGY

4.1 INTRODUCTION

This chapter provides a description of the methods used to increase the understanding of the dunefield. Figure 4-1 shows a broad overview of the research methodology followed during the course of the research; indicating where certain processes fitted in and what needed to be considered and / or adapted within the various research stages. For each research stage the associated processes were carried out with numerous factors constantly being considered and adapted before moving onto the next research stage.

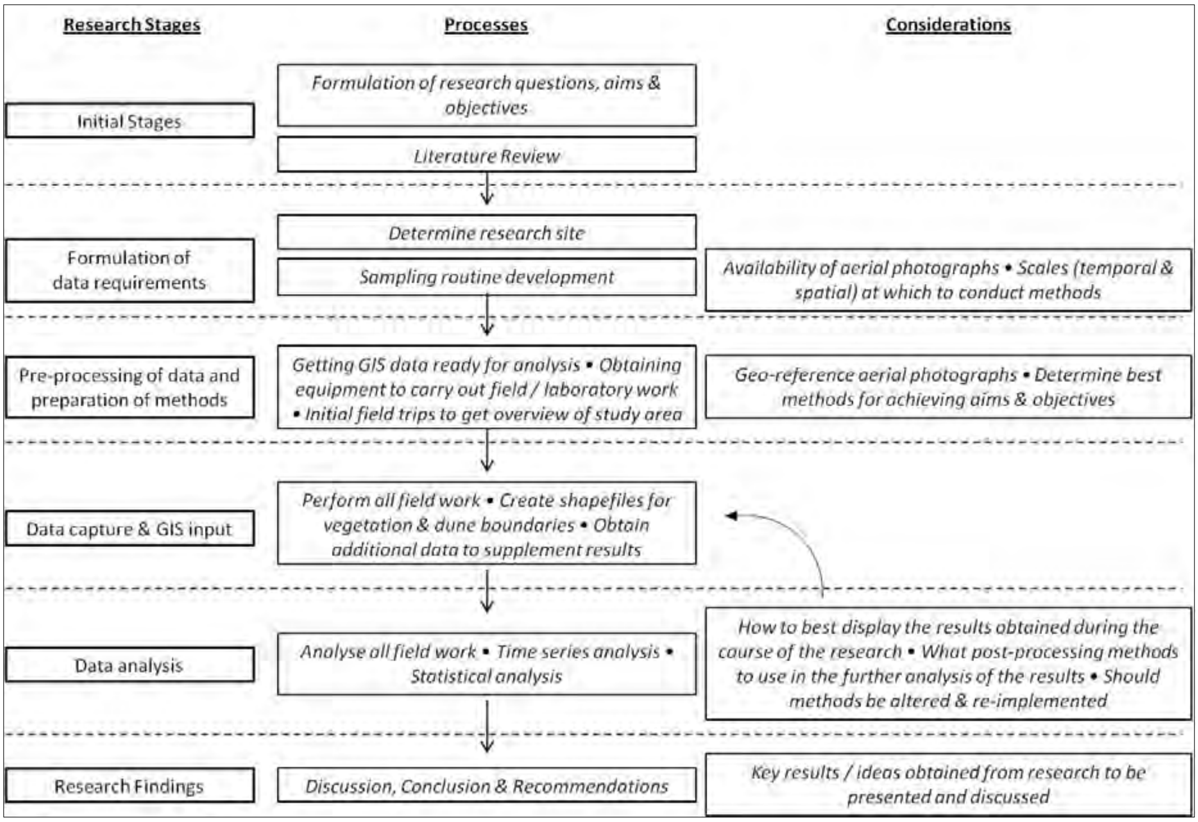


Figure 4-1: Overview of research methods

4.2 SAMPLING ROUTINE DEVELOPMENT

During the first few visits to the Oyster Bay HBD a very broad understanding of the system was achieved and resulted in numerous discussions and sessions to devise plans for monitoring various components of and processes occurring within the dunefield. It was decided that certain components within the dunefield should be monitored in order to achieve the desired outcomes, which included:

- water – groundwater level and chemistry (electrical conductivity and pH);
- vegetation – an analysis of the spatial distribution of vegetation structural types ;
- dune sand – particle size analysis;
- dune movement – change at macro- and micro-scales;
- dune extent – changes occurring over time; and
- dune morphology – overall shape (profiles) of the dunefield system.

An important factor to consider was the area that would be investigated. Due to the extensive size of the Oyster Bay HBD and the fact that debris flows are confined to the eastern region of the dunefield, it was decided that only the central and eastern part of the dunefield would be investigated. The area selected was approximately two kilometres wide from north to south and approximately six kilometres long.

4.3 OBTAINING AND PREPARING PRIMARY AND SECONDARY DATA SOURCES

For this research the Gauss-conform projection was used as it retains the shape of features on the earth in the map (Chrisman, 1997). Through the retention of shape, area is also preserved to a large degree, together with the fact that this aligns with the SA standard for large scale mapping, therefore making this projection the most suitable to this research. For this projection, odd lines of longitude are used as central meridians of reference and are referred to as the “Longitude of origin” – Lo (Carter, 1997). An Lo is chosen that best corresponds to the area of reference, in this case Lo 25 was used, referenced to the WGS84 datum (Figure 4-2).

Time series aerial photographs were geo-referenced to the projected roads vector layer from the 1:50 000 topographical series for South Africa.

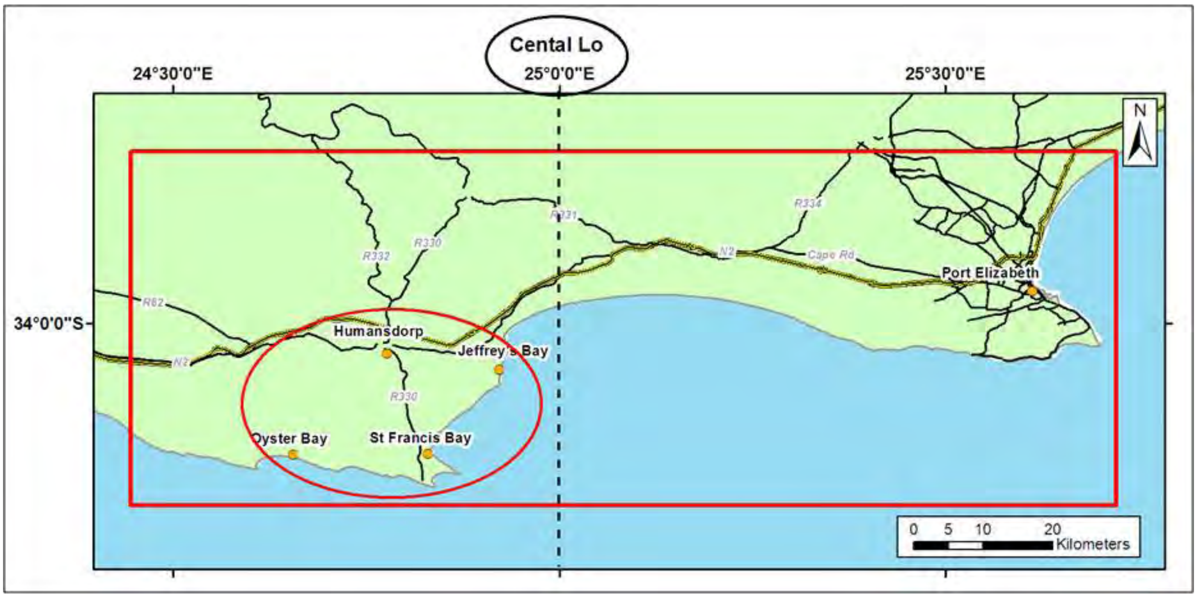


Figure 4-2: The location of the study site (oval) showing the central Lo of 25 degrees east.

4.4 THE PIEZOMETERS AND DELINEATING DUNEFIELD ZONES

4.4.1 The piezometers

A number of piezometers were set up within the dunefield. These piezometers were used as fixed spatial features / control points within the system against which change was measured. They were placed relatively evenly within the study area. A total of 21 piezometers were placed relatively evenly across the study area (Figure 4-3), from which groundwater elevation, electrical conductivity and pH were measured on a monthly basis for a period of one year.

The x-y co-ordinates of these piezometers were recorded using a GPS, while the elevation (z-value) of these piezometers was more accurately determined using available LiDAR data. The height of the piezometers in relation to the surrounding landscape was a key aspect of this research, due to the fact that much of the data collected related back to these fixed points.

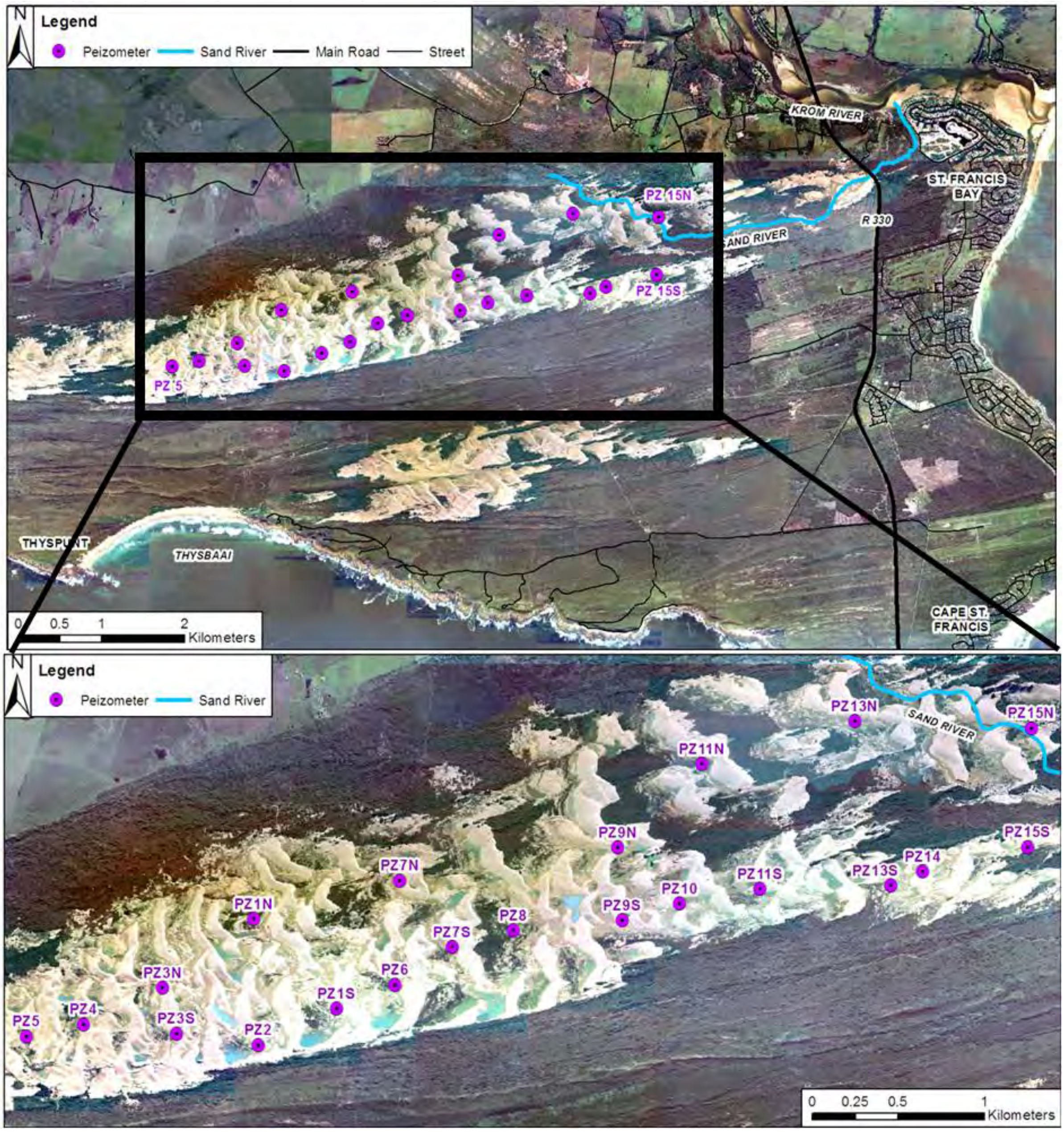


Figure 4-3: Piezometers within the context of the Oyster Bay Dunefield System

4.4.2 Delineating dunefield zones

Figure 4-4 shows the cumulative distance of the piezometers from PZ 5 in the west to PZ 15 in the east in the context of the delineated dunefield zones. The zones were based on the land surface topography of the Oyster Bay HBD, with the western zone being in the zone of the dunefield sloping down towards the west. The central zone was roughly flat and the north eastern zone sloped towards the east. The piezometers and the delineated zones formed a spatial framework for the presentation of the results and help contextualise the discussion of the results in Chapter 6.

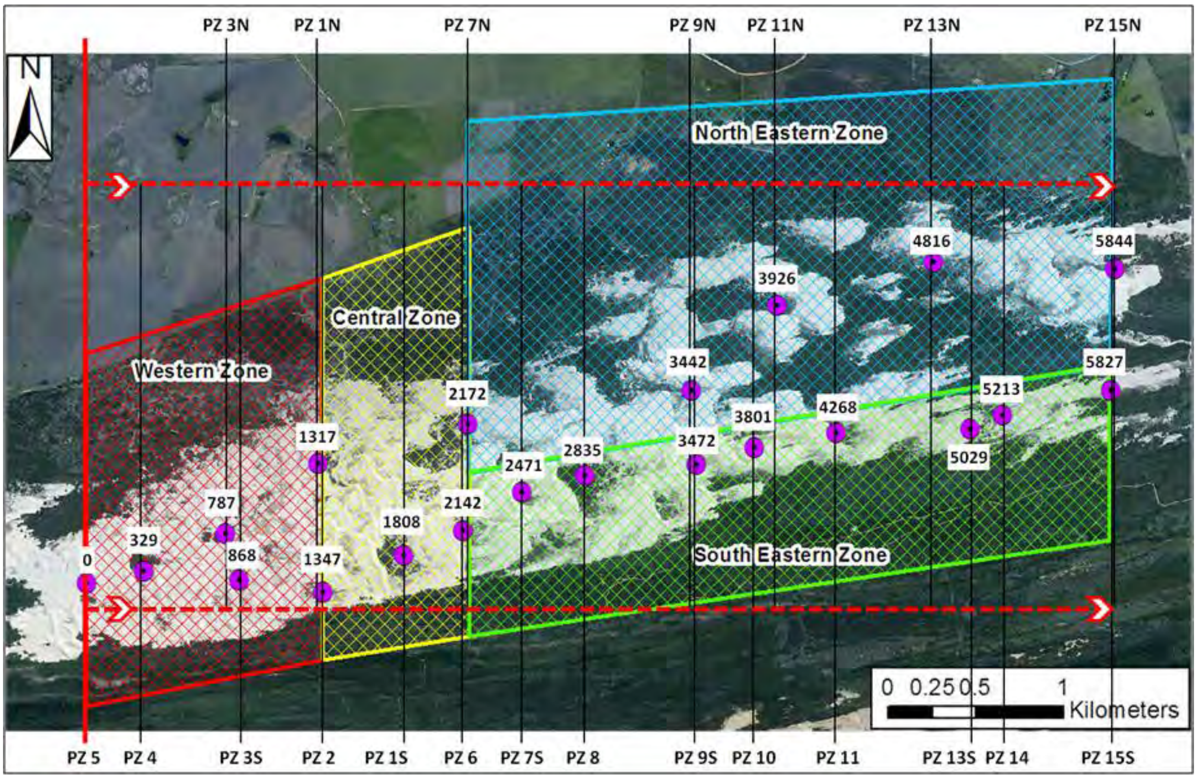


Figure 4-4: Spatial representation and cumulative distance in meters of the piezometers and their location in relation to the self-delineated dunefield zones.

4.5 DATA USED TO SUPPLEMENT THE FIELD RESEARCH

Rainfall data was collected from stations indicated on the map (Figure 4-5).Of the stations where weather was recorded daily, all had complete rainfall recordings for the 12 years preceding this research (1997 – 2009), while three of the stations (South African Weather Services (SAWS) stations) had recordings dating as far back as 1960: Cape St. Francis (the lighthouse), Humansdorp, and Jeffrey's Bay.

For the SAWS stations monthly mean rainfall values were measured and variation within the study area overall were investigated. In addition to this, more detailed analyses were undertaken of the rainfall patterns for the years 2008 and 2009, during which the main field work component of this study was undertaken.

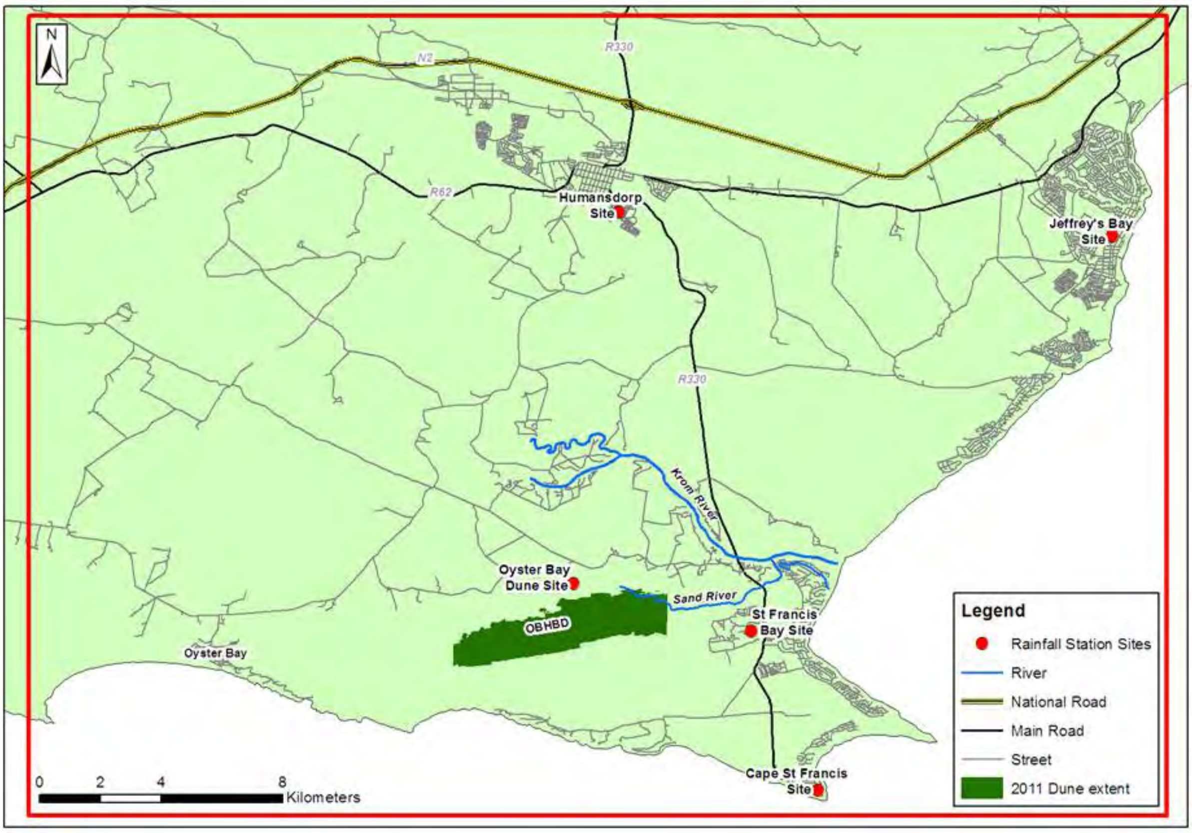


Figure 4-5: The spatial location of the five stations for which MAP data was obtained.

Wind data was also obtained from SAWS. The data were obtained in the form of wind roses recorded at Cape St. Francis. The wind roses showed the average wind speed and frequency on a monthly and annual basis recorded during the period of 2004 – 2009.

4.6 OBJECTIVE 1 – MAPPING THE MORPHOLOGY AND EXTENT OF THE OYSTER BAY HBD

4.6.1 Mapping the extent of the dunefield

This part of objective one was undertaken using the aerial photographs that were obtained in the 'pre-processing of data' phase of this research (Figure 4-1). All of the available aerial photographs were used in this analysis as the quality was deemed suitable to the outcome that was desired.

The process of manually mapping features from various data sources is known as ‘heads-up digitising’ and is conducted within a GIS (ArcView 9.3). The boundary line was determined by the contrast of the main body of sand and the bordering vegetation. The scale at which the boundaries were captured was dependent on the quality of the aerial photograph. For the poorer quality aerial photographs, for example those for 1994 and 1986, dune boundary polygon features were captured at scales of between 1:5 000 and 1:10 000, whereas for the remaining better quality aerial photographs, dune boundary polygon features were captured at scales of between 1:1000 and 1:5000. For this objective, the use of the poorer quality aerial photographs was deemed satisfactory as the objective was to understand the overall change in the extent of the dunefield over time and very detailed measurements were not necessary.

Change in dune extent was a measurement of areas of bare sand / mobile dunes to vegetated / stabilised dune areas.

4.6.2 Mapping the overall morphology of the dunefield

Dune profiles were created using 2011 LiDAR contour data (ESKOM, 2011). Four profiles in the west to east direction were created and ten in the north south direction. All of the profiles were limited to the region approximately 500m west of PZ 5 and east of PZ 15.

Line features were created in ArcGIS which represented the contour profiles that were plotted (Figure 4-6). Figure 4-6 (a & b) shows the location of the profiles that were created. The west to east profile lines consisted of, from north to south, the northern boundary profile (NBP); the northern dunefield profile (NDP); the southern dunefield profile (SDP) and the southern boundary profile (SBP) (Figure 4-6b). Whereas the north to south profile lines consisted of numerically ordered lines from Profile 1 (P1) – Profile 10 (P10) (Figure 4-6a).

For each of the profiles the overall slope of the land surface was calculated. For the north to south oriented profiles, the general slopes of the land surface were measured from north to south and recorded. Linear regression models of the best fit (shown by ‘r^2’ on the respective graphs) over the relevant profile sections were used. The equations describing the lines of best fit were then translated to slopes (indicated by ‘m’ on the respective graphs) by multiplying by 100. For the west to east profiles, the change in the slope was measured across the entire profile, analysing the obvious changes in slopes in the land surface.

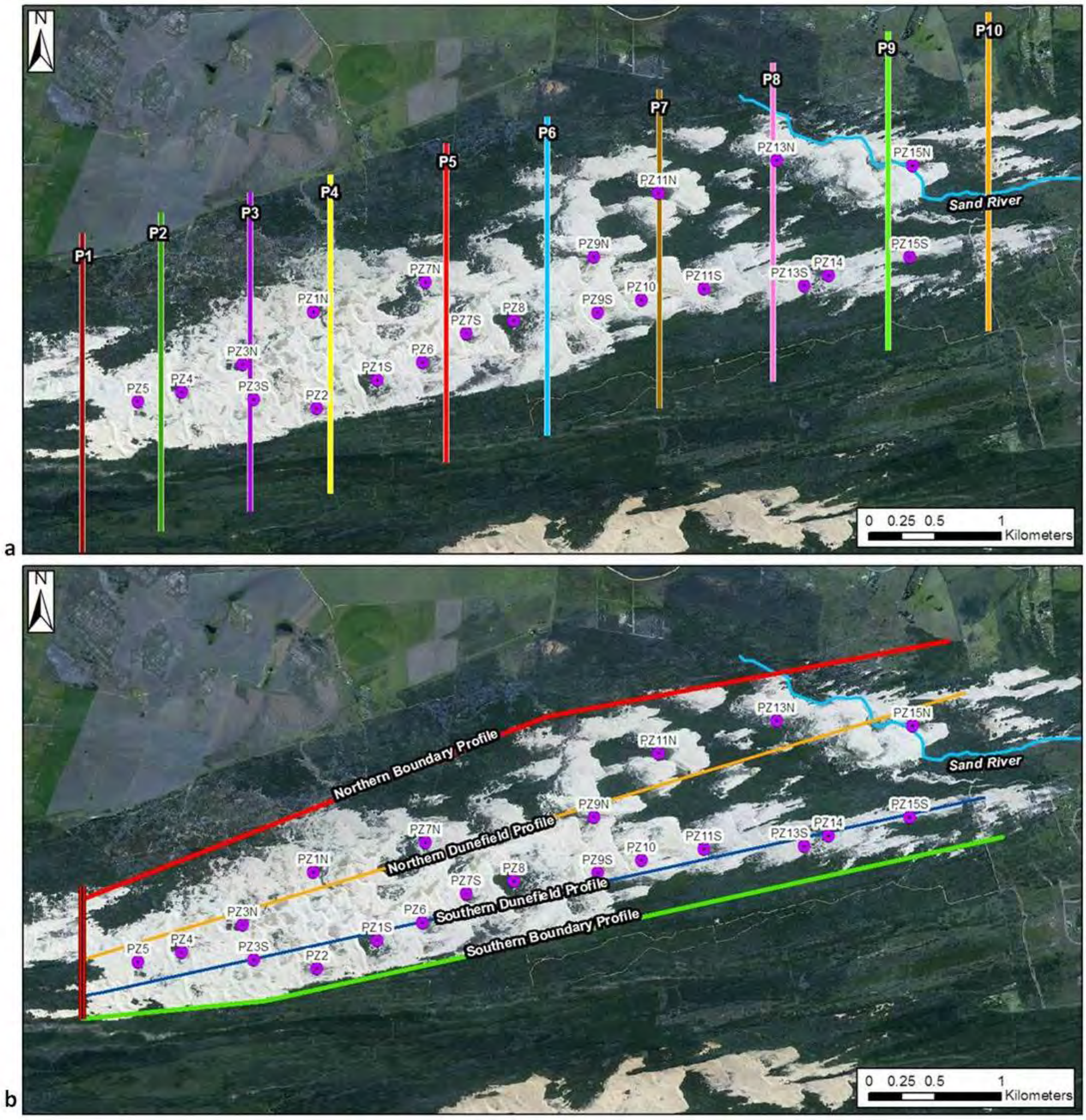


Figure 4-6 (a & b): The spatial location of all the generated topographic profiles. **a:** the four west to east topographic profiles, and **b:** the ten north to south topographic profiles.

4.6.3 Field GPS exercise conducted but not included in this research

As part of this research, an extensive GPS exercise was carried out in an attempt to map the morphology of the dunefield. This exercise was conducted using 11 people each walking with hand-held GPSs. The idea was to walk transects in a grid-like process with people spread evenly across the dunefield with the GPS set to record their paths. The entire process was conducted over a five day period, with specific days focused on capturing the various aspects of the Oyster Bay HBD, including: the overall change in morphology in the west to east direction and north to south direction, the change in the height and length of specific dunes in the various zones of the dunefield, and the extremities of the dunefield.

After careful examination of the data it became apparent that the inaccuracies within the data set, specifically related to changes in the z-axis were too large and that this data would not be able to give an accurate reflection of the morphology of the system. These inaccuracies were the result of the only available bottom of the range hardware (GPSs) used for this research and not as a result of the method used. During the course of the research, the LiDAR data became available and the original data sets were therefore disregarded.

4.7 OBJECTIVE 2 – MEASUREMENT OF THE RATES OF DUNE MOVEMENT AS A SURROGATE MEASURE OF SEDIMENT FLUX

4.7.1 Background

This objective was approached using the aerial photographs that were obtained in the ‘pre-processing of data phase’ of this research. In order to examine the rate at which the individual dunes were moving within the Oyster Bay HBD good quality aerial photographs were needed. It was therefore decided that only the colour aerial photographs for the years 2000, 2007 and 2011 would be used. Aerial photographs have been used by many researchers since the 1960s to measure changes in dune movement (Simons *et al.*, 1965; Illenberger & Rust, 1988; Burkinshaw, 1998 and Castro, 2005).

In order to ensure that dune movement was being accurately measured, it was necessary to ensure that sufficient data of high resolution was available to show what was occurring at specific locations between PZ5 and PZ 15 for the period between 2000 and 2011. It was also necessary to ensure that a spatially significant extent of the Oyster Bay HBD was covered in order to quantify variation in dune movement from east to west within the dunefield. This meant including dune movement occurring within each designated zone of the dunefield, and within both the northern and southern parts of the Oyster Bay HBD. As with most landforms, such monitoring involved balancing the desire for detail against the need for gathering information over a fairly large geographic area.

4.7.2 Measurement of dune movement from aerial photographs using GIS

Average dune movement of the base of individual slipfaces was calculated along 3 east-west oriented lines at a number of piezometers where dune movement was measured (western zone = PZ 5, PZ 3N AND PZ3S; central zone = PZ 1N, PZ 1S, PZ 7N, PZ 7S; eastern zone = PZ 9N, PZ 9S, PZ 11N, PZ 11S, PZ 15N AND PZ 15S). The set of 3 east-west lines was placed such that the central line was centred on the piezometer, with another line 150 m to the north and another 150 m to the south. Line features were then created depicting a dune base for each set of aerial photographs based on mapping at a scale of about 1:1000. The average distance was calculated for the 3 east-west trending lines, giving one value for the interval 2000 to 2007 and another for the interval 2007 to 2011. Figure 4-7 illustrates this method for two east-west lines in a single study site over the period of photography.

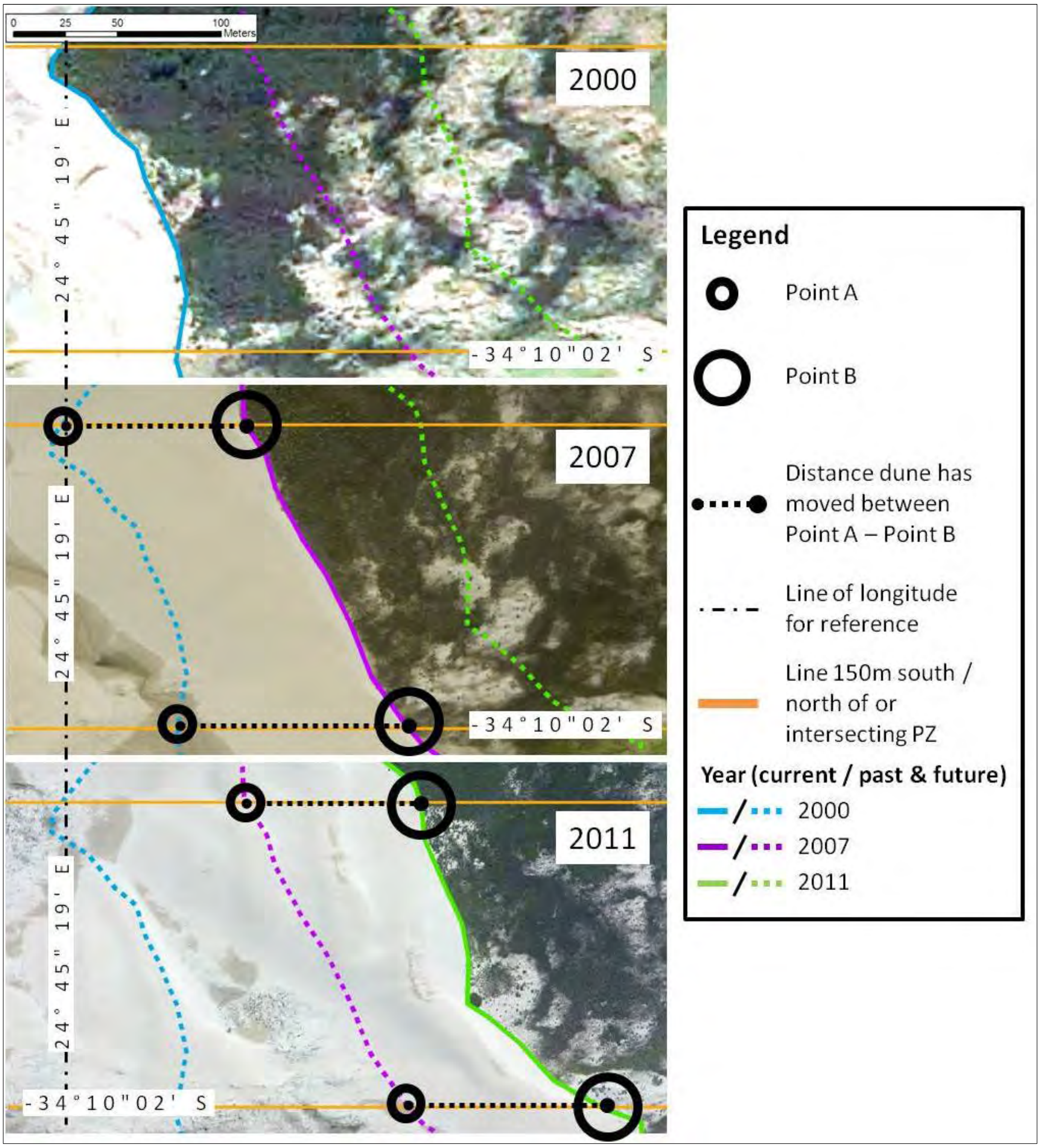


Figure 4-7: The method by which dune movement was analysed and measured along two east-west lines for a single site in the dunefield.

4.7.3 Sediment flux within the Oyster Bay HBD system

According to Illenberger & Rust (1988), dune migration rates measured off aerial photographs can be converted to sand transport rates using a pre-defined equation (Equation 1 below), provided that the heights of specific dunes can be estimated to a reasonable level of accuracy. The equation for sand transport rate represented by bedform migration, q_b, is as follows (Simons *et al*., 1965):

$$\mathbf{q_b = kHV} \qquad \text{............ (1).}$$

In this equation k is a non-dimensional bedform factor, H is the dune height, and V is migration speed measured normal to the dune axis (Simons *et al*., 1965). The bedform factor, k, is equal to A / LH, where A is the cross-sectional area of the dune, and L is the dune spacing. Dune migration rates were therefore calculated for each zone. Average dune height and spacing were determined from one meter contours generated from available LiDAR data. Therefore overall dune movement rates, using Equation 1, were calculated for the western central and eastern delineated zones. The value of q_b is independent of dune size (Illenberger & Rust, 1988: 515), a small dune would move faster than a larger dune for a given value of q_b.

4.8 OBJECTIVE 3 – INVESTIGATION OF BIOPHYSICAL ATTRIBUTES AS INDICES OF NATURAL PROCESSES (VEGETATION, WATER AND SAND)

4.8.1 Vegetation

4.8.1.1 Vegetation functional classification and sampling method

During December 2009, a vegetation survey was undertaken. The aim of the survey was to show variation in the distribution of vegetation type and cover between the western, central and eastern delineated zones of the Oyster Bay HBD. The intention was to differentiate vegetation successional stage based on functional characteristics of plants in the study area. The method was based on the suggestion by R.M. Cowling (pers. comm., 2010) based on the notion that herbaceous species would colonise recently disturbed sites before woody species. Furthermore, plants with a clonal growth form would colonise areas before tufted forms in a dynamic environment such as this. Figure 4-8 outlines the basic classification system used.

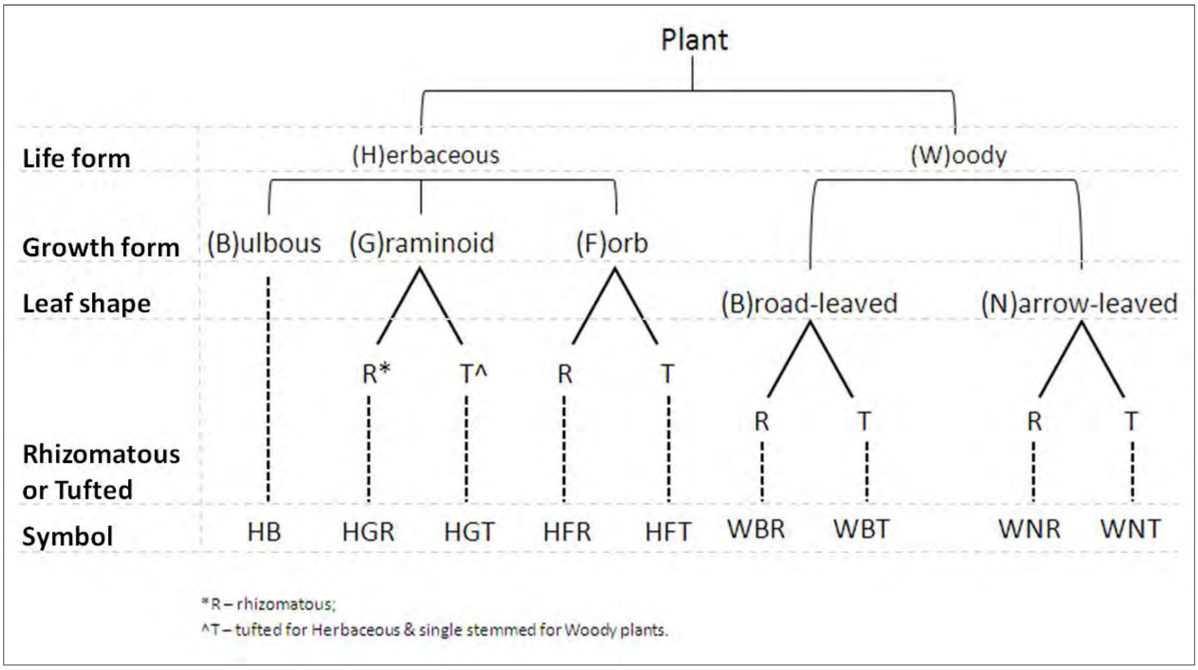


Figure 4-8: The classification system used to determine the type and cover of vegetation within the Oyster Bay HBD

Samples comprised an estimation of the cover of individual plant functional types within a two metre radius around the piezometer. Percentage cover was estimated to the nearest 1% between 0 and 5%, and then to the nearest 5% between 5 and 100%. In addition to percentage cover of each of the types of vegetation mentioned, the total percentage cover of plant litter was determined as well as the average height of the vegetation per sample site.

Vegetation sampling was confined to the piezometer sites which were deliberately located in wetland areas in the dunefield. Vegetation surveys were expected to reflect typical wetland species composition. The broader vegetation patterns were therefore obtained from the aerial photo mapping which included an analysis of overall change in total vegetation (cover) as a percentage of the total dune area and for each delineated zone. This was all achieved within ArcGIS.

4.8.1.2 Time series: GIS analysis

Aerial photographs were used to map the total vegetation cover within the delineated zones of the dunefield. Using ArcGIS, an investigation into vegetation change – in total cover and spatial distribution – was investigated.

The years that were used in this analysis were dependent on the availability and quality of aerial photographs for the area. Table 4-1 shows a breakdown of aerial photographs that were used.

Table 4-1: The aerial photographs that were used in the vegetation analysis

Year	Aerial Photograph	Dunefield Boundary (from Objective 1)	Vegetation analysis and the scale at which the analysis was conducted
2011	Colour	Yes	1:1000
2007	Colour	Yes	1:1000
2000	Colour	Yes	1:1000
1994	Black and white	Yes	Overall veg. analysis only – 1:5000
1986	Black and white	Yes	Overall veg. analysis only – 1:5000
1980	Black and white	Yes	1:3500
1975	Black and white	Yes	1:3500
1961	Black and white	Yes	Overall veg. analysis only – 1:5000

The geo-referenced aerial photographs were used in the vegetation analysis as the base images from which to map the changes that have occurred in the dunefield system from as early as 1961 to 2011. The results are presented as a series of images showing the change over time in the abundance and spatial distribution of vegetation within the Oyster Bay HBD delineated dune boundary.

4.8.2 Water - determining the level of the groundwater table

On each monthly field trip water samples were collected at each piezometer. To begin, an auger was used to dig a hole that was always within a metre from the location of the piezometer pipe. The depth of the hole was dependent on the groundwater level at the time of the sampling. As and when water was observed, augering would stop and the depth to the water level would be measured and related to the height of the original piezometer.

Following this, if water was present, a 250 ml water sample was collected and this was taken back to the laboratory for further analysis. The tests that were conducted on each of the water samples included tests for electrical conductivity (EC) and pH. On occasions the water depth was greater than could be measured using the available soil auger (one metre).

4.8.3 Sand - particle size analysis

A series of sand samples were collected at all of the piezometers in order to get a better understanding of the change in the particle size of the sand between the western and eastern regions of the dunefield. In total, 61 samples were collected at intervals of approximately 500 to 1000 metres apart. The samples were collected at various positions within the dunefield; alternating between inter-dune slacks, the crests of dune ridges and within the wetlands. Figure 4-9 shows the location of the sand samples collected in the Oyster Bay HBD.

The size of sediment particles is one of the fundamental properties of geological materials and the most widely used method for determining this property is sieving (Gale & Hoare, 1991). This method provides a geometric size for individual particles (Fieller *et al*., 1992) and it is most suited to particles which are smaller than cobble size but larger than silt grades smaller than 63µm (Gale & Hoare, 1991: 81). The samples were dried in an oven at 100° C and then sieved. The sieving procedure involved passing sediment through an ordered sequence of sieves with progressively finer mesh sizes as described by Gale & Hoare (1991: 86). Ultimately, relative proportions by mass were determined, resulting in weight size distribution of the total sample for each of the sieve sizes used.

The sieve rack selection for this research consisted of 11 sieve sizes plus the bottom tray, in descending order: 2000 µm; 1400 µm; 1000 µm; 710 µm; 500 µm; 355 µm; 250 µm; 180 µm; 125 µm; 90 µm; 63 µm and grains under 63 µm in size (the bottom tray). These sizes are in approximate geometric progression with ration √2 – a standard set in such applications. This contained one extra sieve than often used in sediment particle size analysis.

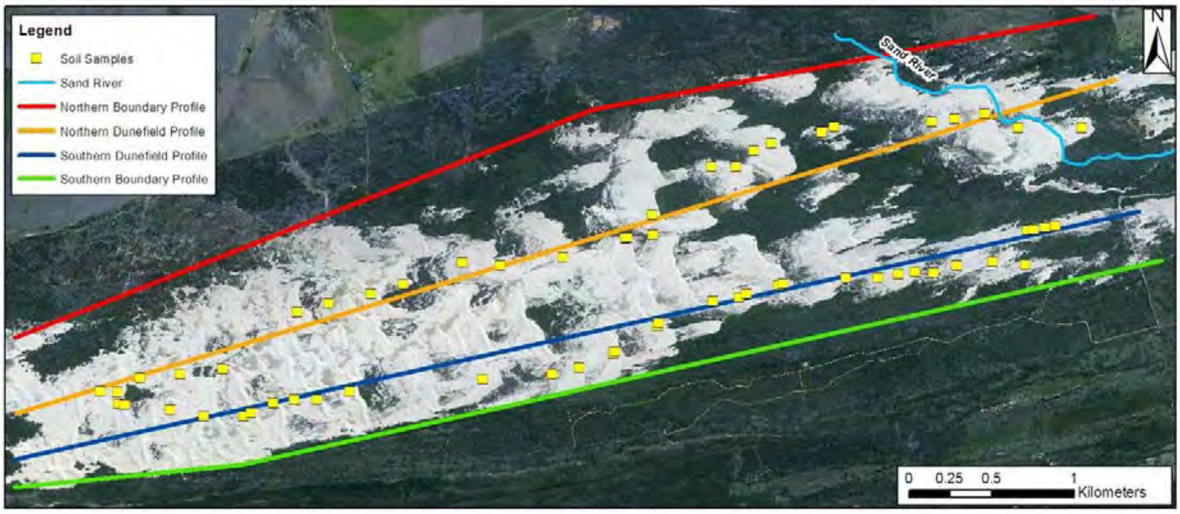


Figure 4-9: Location of the sediment samples in relation to the W-E generated profile lines within the Oyster Bay HBD.

4.9 OBJECTIVE 4 – DEVELOPMENT OF SUMMARY DIAGRAMS AND TABLES AND A CONCEPTUAL DIAGRAM OF DUNEFIELD STRUCTURE AND FUNCTION

This objective aims to present a series of summary diagrams and tables that relate to the results presented in each objective. They will factor in the issue of scale, changes over time (e.g. 1961 – 2011 or the period of one year) and space (e.g. delineated zones or dune spacing). Ultimately, the summary diagrams will aim to integrate the processes within the system, including the main factors affecting / driving its structure and function.

The basic summary diagram will be based on Figure 4-10, which shows the zones, location of the piezometers as well as a scale bar for reference. For each objective, the structure of the diagram will remain constant while the various results will change.

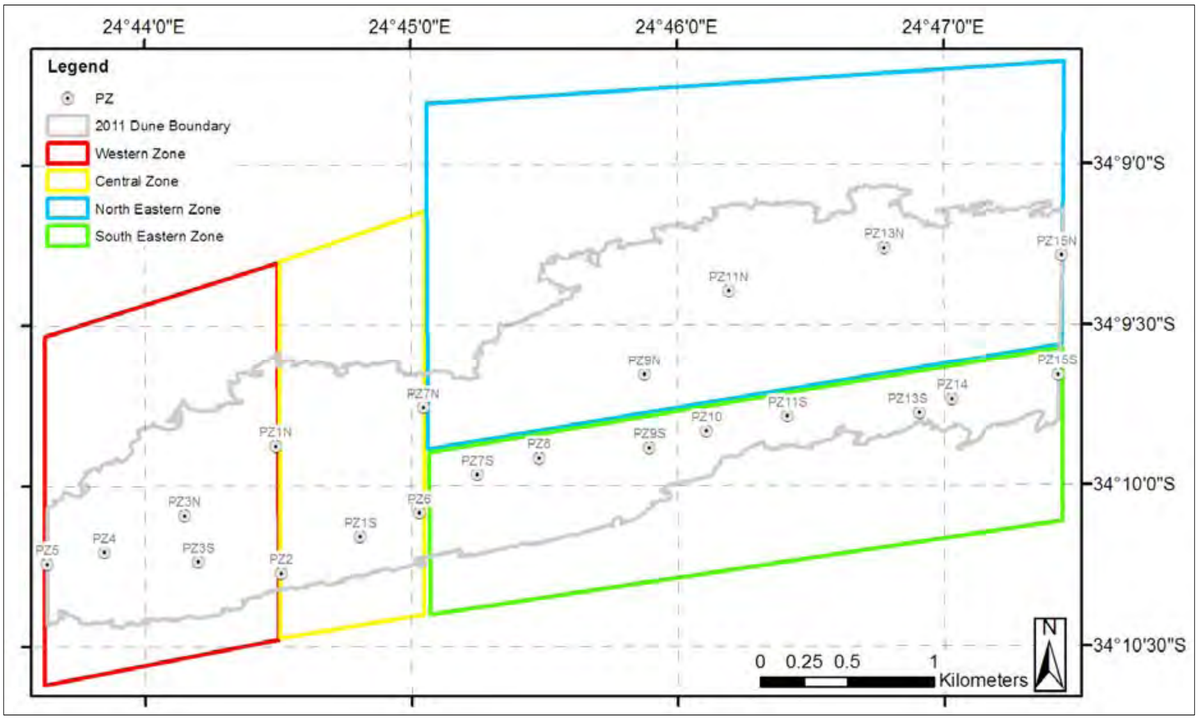


Figure 4-10: Base summary diagram from which all main results for each objective will be discussed.

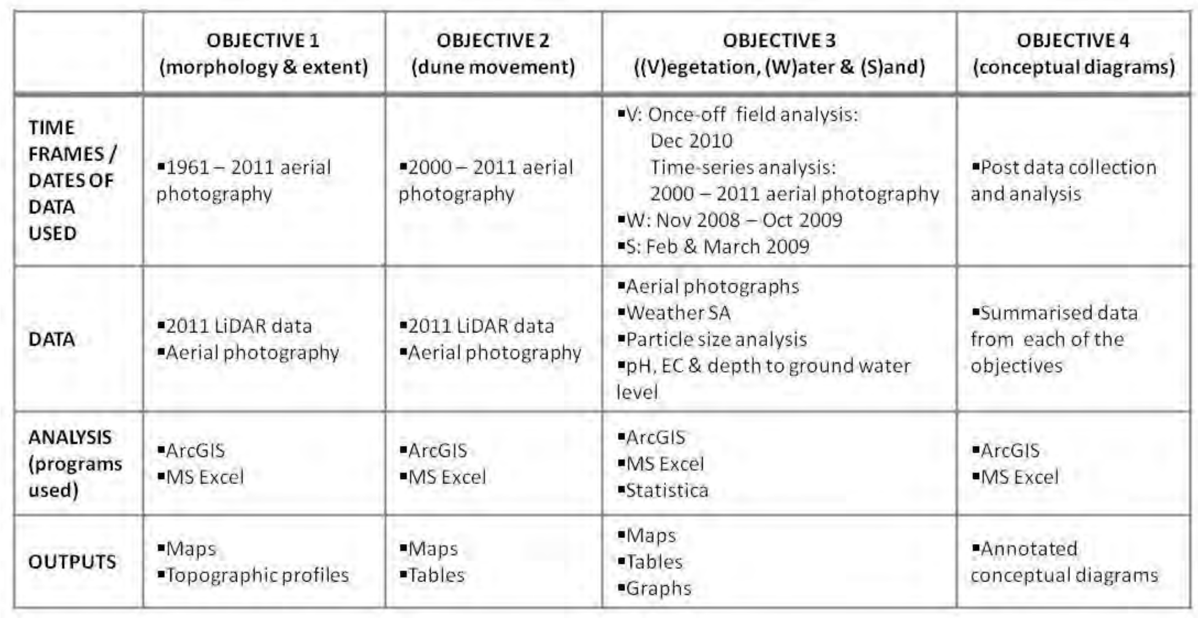
To complete Objective 4, a conceptual model will be presented which highlights the significant drivers of change, features and / or components, and processes occurring within the Oyster Bay HBD.

CHAPTER 5: RESULTS

5.1 INTRODUCTION

Table 5-1 presents the information sources and programs that were necessary to obtain the results. A summarised annotated conceptual diagram will be presented at the end of each section related to each objective, therefore fulfilling Objective 4 of this research.

Table 5-1: Fundamental information and programs used to achieve results.



	OBJECTIVE 1 (morphology & extent)	**OBJECTIVE 2 (dune movement)**	**OBJECTIVE 3 ((V)egetation, (W)ater & (S)and)**	**OBJECTIVE 4 (conceptual diagrams)**
TIME FRAMES / DATES OF DATA USED	▪1961 – 2011 aerial photography	▪2000 – 2011 aerial photography	▪V: Once-off field analysis: Dec 2010 Time-series analysis: 2000 – 2011 aerial photography ▪W: Nov 2008 – Oct 2009 ▪S: Feb & March 2009	▪Post data collection and analysis
DATA	▪2011 LiDAR data ▪Aerial photography	▪2011 LiDAR data ▪Aerial photography	▪Aerial photographs ▪Weather SA ▪Particle size analysis ▪pH, EC & depth to ground water level	▪Summarised data from each of the objectives
ANALYSIS (programs used)	▪ArcGIS ▪MS Excel	▪ArcGIS ▪MS Excel	▪ArcGIS ▪MS Excel ▪Statistica	▪ArcGIS ▪MS Excel
OUTPUTS	▪Maps ▪Topographic profiles	▪Maps ▪Tables	▪Maps ▪Tables ▪Graphs	▪Annotated conceptual diagrams

5.2 RAINFALL AND WIND – SPATIAL AND TEMPORAL TRENDS

5.2.1 Rainfall trends

Oyster Bay (the most western site) typically experienced higher rainfall than the other weather stations, while Jeffrey’s Bay (the most eastern site) typically experienced the lowest (Table 5-2). The data also showed that generally as one moves from west to east there was an overall decrease in the mean, maximum and minimum rainfall for all stations, with the exception of Humansdorp which was the far northern station (see Figure 4-5 for spatial location of rainfall stations).

Table 5-2: Descriptive rainfall statistics for weather stations in the study area for the period 1997 – 2009.

	Oyster Bay	Humansdorp	St. Francis Bay	Cape St. Francis	Jeffrey's Bay
Mean	828	574	749	599	541
Max	1241	1031	1239	765	756
Min	544	390	533	411	343
Std. Deviation	219	160	189	112	136

For the five stations for which data were available, years of high and low rainfall largely coincided (Figure 5-1). Mean annual rainfall was calculated for the Humansdorp, Cape St. Francis and Jeffrey's Bay weather stations. Figure 5-1 shows that the five stations followed similar inter-annual trends with related peak and low rainfall years. Clear peaks can be observed such that a mean value of 800 mm or more was recorded at two or more stations in 1971, 1976, 1981, 1992, 1993, 1996, 2002, 2006 and 2007. Years of low rainfall of 450 mm or less were recorded at two or more stations in 1967, 1969, 1972, 1984, 1988, 1991, 1999, 2005, 2008 and 2009.

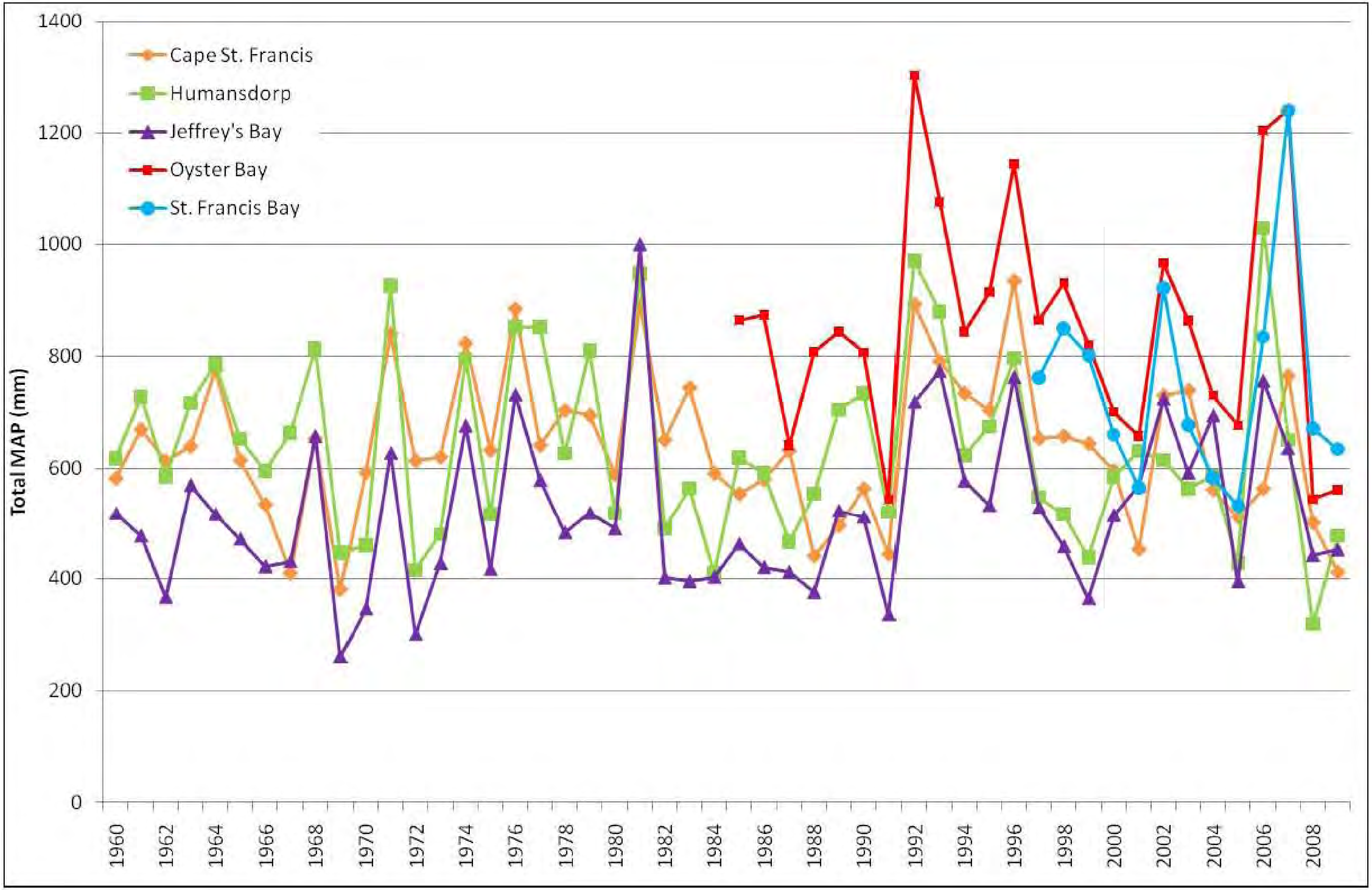


Figure 5-1: Mean annual precipitation at five weather stations in the study area.

In addition to spatial trends, seasonal trends were also examined (Table 5-3). For Oyster Bay, St Francis Bay and Cape St. Francis, the highest rainfall occurred in winter. For Humansdorp the highest rainfall was in autumn, while for Jeffrey's Bay, high rainfall occurred in autumn and winter. The lowest rainfall was in summer for all stations except Humansdorp, which experienced its lowest rainfall in spring.

Table 5-3: Average seasonal rainfall for weather stations over the period 1997 – 2009.

	Oyster Bay		**Humansdorp**		**St. Francis Bay**		**Cape St. Francis**		**Jeffrey's Bay**	
	Rainfall (mm) / Rank									
Spring	211	2	116	4	179	3	139	3	118	3
Summer	160	4	143	3	142	4	98	4	112	4
Autumn	201	3	166	1	182	2	151	2	158	1
Winter	257	1	149	2	245	1	210	1	153	2
Year Total	**828**		**574**		**749**		**599**		**541**	

In addition to the above, a long term analysis of the seasonal trends of Humansdorp, Cape St. Francis and Jeffrey's Bay was undertaken for the period 1960 – 2009 (Figure 5-2). The results from the graph differed slightly from the data summarised in Table 5-3, in that from 1960 - 2009 most rain fell in winter and the least in summer for all three locations. Rainfall patterns for Humansdorp and Jeffrey's Bay over the last decade have changed slightly, with higher volumes of rainfall recorded in autumn, rather than typically in winter.

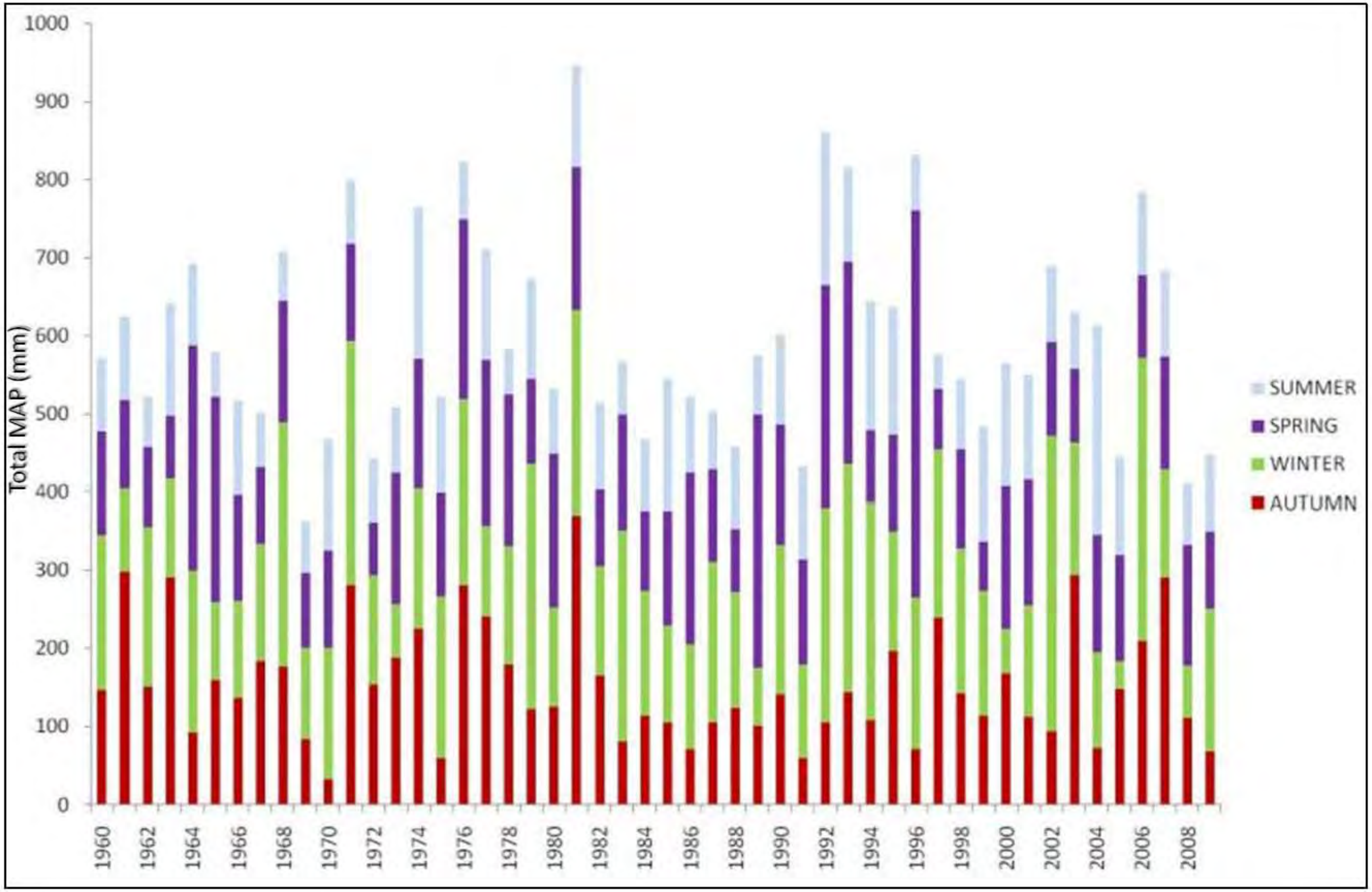


Figure 5-2: Regional mean annual rainfall (with seasonal breakdown), for Humansdorp, Jeffrey's Bay and Cape St. Francis for the period 1960 to 2009.

5.2.2 Wind direction and strength

Average wind direction and speed have been plotted as an average annual rose for the period between 2004 and 2009 (Figure 5-3) together with average wind roses for each month over the same period (Figure 5-4).

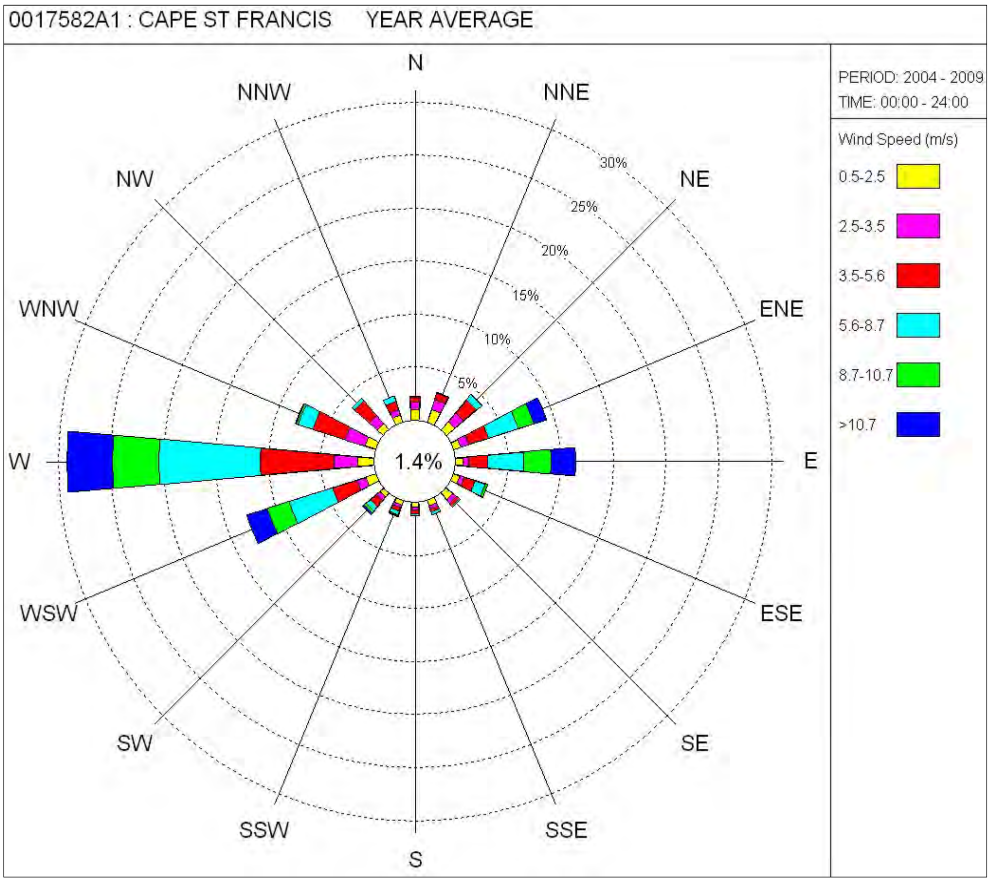


Figure 5-3: The annual average wind direction and speed for the period 2004 – 2009.

Source of figure: SAWS (2010)

The strongest and most frequent winds are westerly winds, with strong winds (> 10.7 m/s) having occurred more than 5% of the time during the months of May to October. The frequency (>15%) and strength of easterly winds increased during the months of October to February.

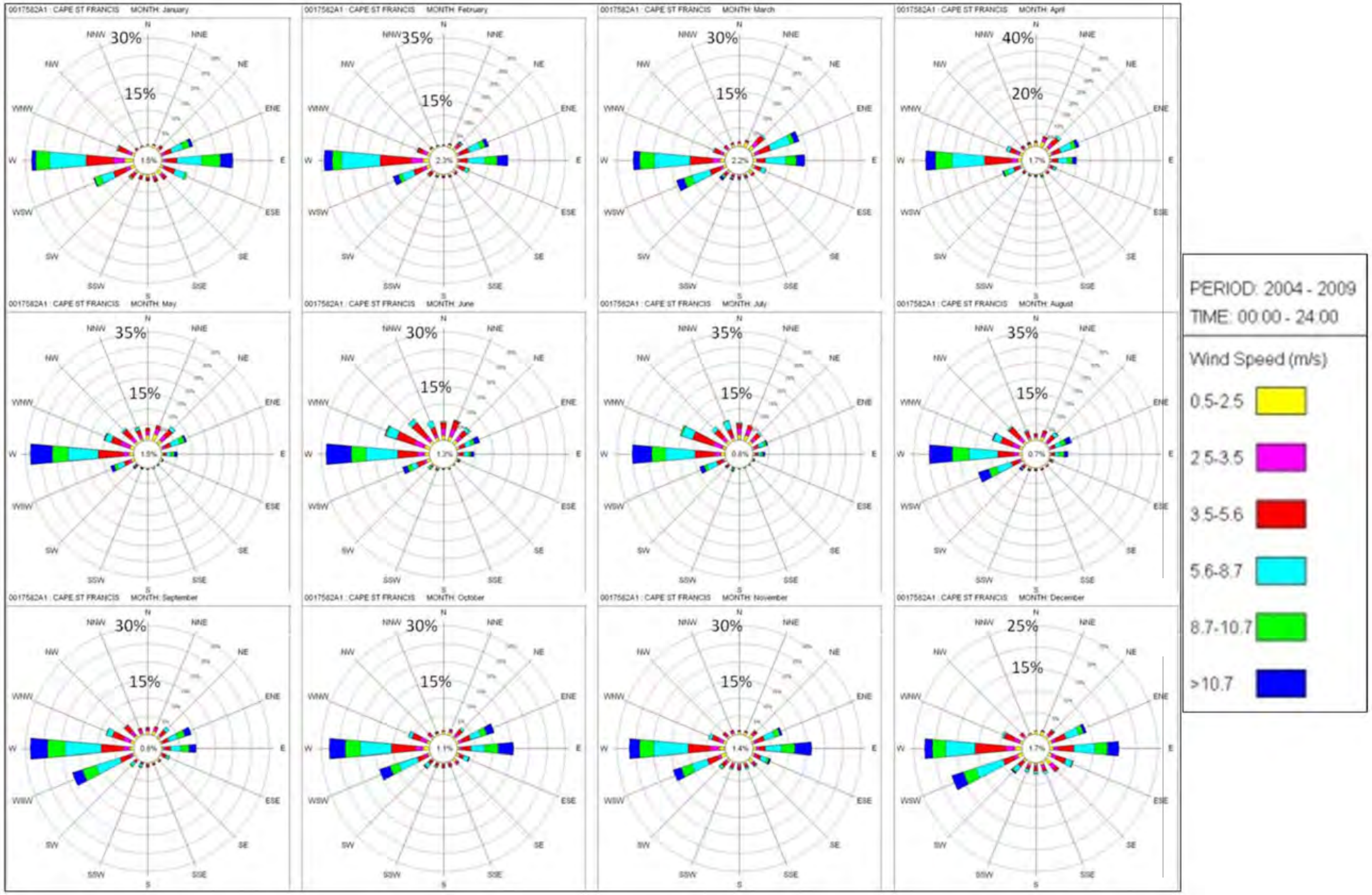


Figure 5-4: Monthly wind roses for Cape St. Francis for the period 2004 – 2009.

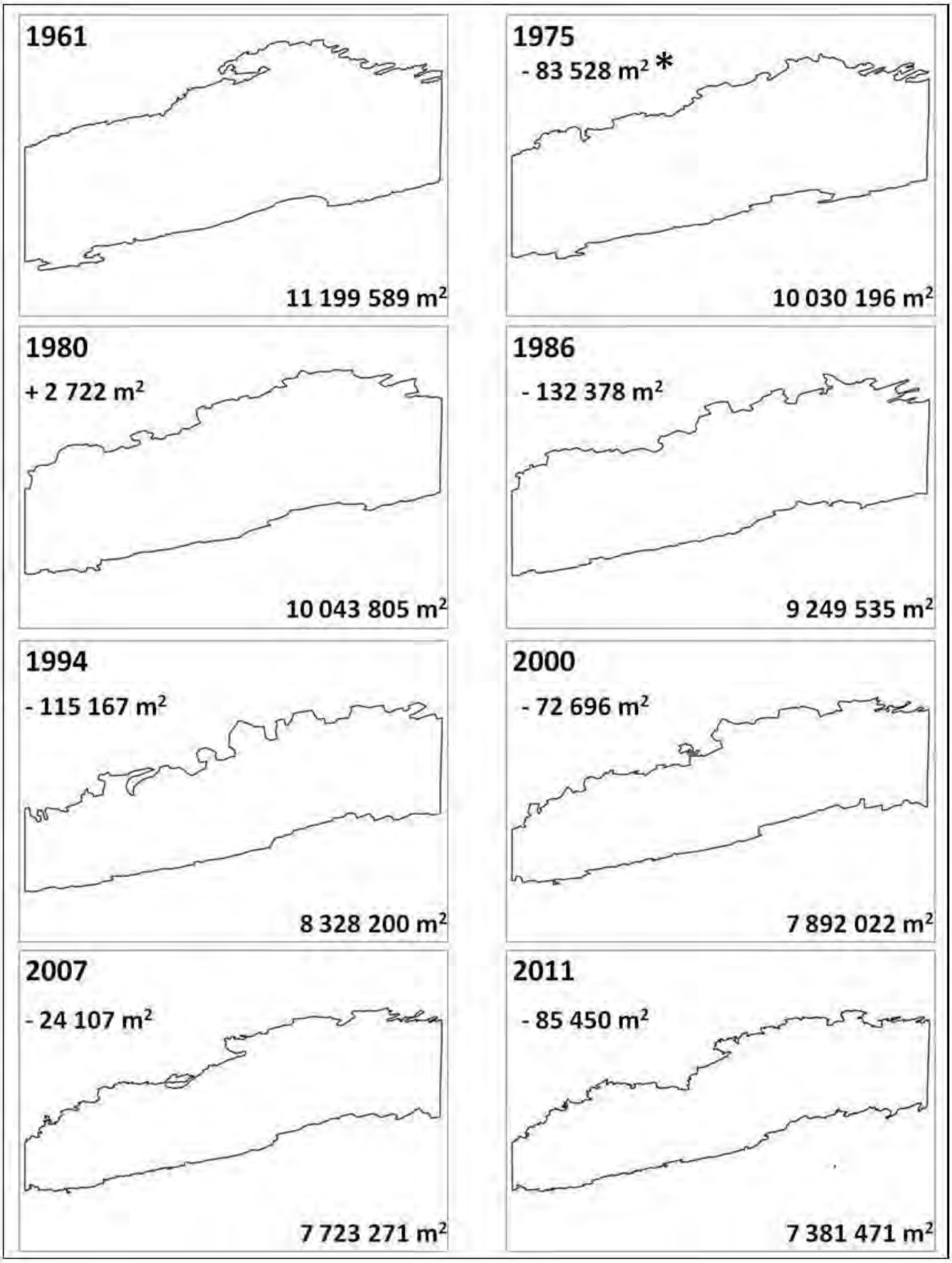
Source of figure: SAWS (2010).

5.3 OBJECTIVE 1– MAPPING THE MORPHOLOGY AND EXTENT OF THE OYSTER BAY HBD

5.3.1 The extent of the dunefield

Figure 5-5 depicts the changes (bare sand to vegetated area) that occurred in the dunefield extent (in the area under study) between 1961 and 2011. The figure includes the estimated annual rate of change (growth / reduction) in the total size of the Oyster Bay HBD for each time frame (one aerial photo set to the next). The figure shows that the annual rates of change varied across the extent of the Oyster Bay HBD. The period from 1980 to 1986 had the fastest rates of change, while between 1975 and 1980 rates were slowest.

It is also evident that the main body of the Oyster Bay HBD has decreased gradually in extent (Figure 5-5) from approximately 11 km^2 in 1961 to 7 km^2 in 2011, a 34% reduction over a period of 50 years. This represents an annual change of -0.83%, equivalent to about 75 000 m^2.a^{-1}. The change in area was largely in response to a reduction in the width of the dunefield over the period of analysis from a mean of 1870 m in 1961 to 1270 m in 2011, an average reduction of some 12 m per annum.



** average annual change in the extent of the OBHBD between consecutive aerial photographs.*

Figure 5-5: The size of the total extent of the dunefield for each available aerial photograph and the annual change in total cover as recorded between consecutive aerial photographs.

5.3.2 Topographic structure of the dunefield from west to east

5.3.2.1 Topography of the northern and southern dunefield boundary profiles

The topography from west to east for the northern and southern boundary, are shown in Figure 5-6 (a & b). The northern boundary profile consisted of uniform slopes (NB1 – NB5), disrupted by distinct and striking discontinuities (Figure 5-6a). The slope of NB1 from the west towards the point of highest elevation was fairly consistent with a slope upwards towards the east of 1.39%, with very low local relief along this section. Immediately east of the crest the slope of NB2 downwards towards the east was once again remarkably uniform at 2.02%, characterised by remarkably little local relief. There was a steep discontinuity at a distance of approximately 3 200 m along the transect. From this point eastwards the slope of NB3 eastwards was a remarkably uniform gradient downwards of 1.01%, once again exhibiting little local variation in local relief. East of this was a zone of relatively high ground with slope NB4 sloping downwards towards the east with a gradient of 0.86%, exhibiting higher local relief than the previous zones. This gave way to the east to slope NB5 which had a high slope downwards to the east of 6.20%, once again with fairly high local relief.

For the southern boundary the land surface was characterised by less distinctive discontinuities between sections of the dunefield, but a visual analysis once again revealed five zones with distinct slopes (SB1 – SB5, Figure 5-6b). The slope of SB1 from the west upwards to the crest of the dunefield was 1.40% and exhibited a very high degree of local relief. This gave way to the slope of SB2 with a downward slope to the east of 0.69%, characterised by a moderate level of local relief. The slope of SB3 downwards to the east had a gradient of 1.13% and exhibited remarkably low local relief. This then gave way at a distance of approximately 5 700 m along the profile to a zone that was slightly elevated compared to the previous zone, with the slope of SB4 downwards to the east of 1.08%, exhibiting relatively little variation in local relief. Finally, from a distance of about 6 800 m along the profile, a slightly elevated zone sloped downwards to the east with the slope of SB5 equalling 2.65%, with once again very little local relief along this section.

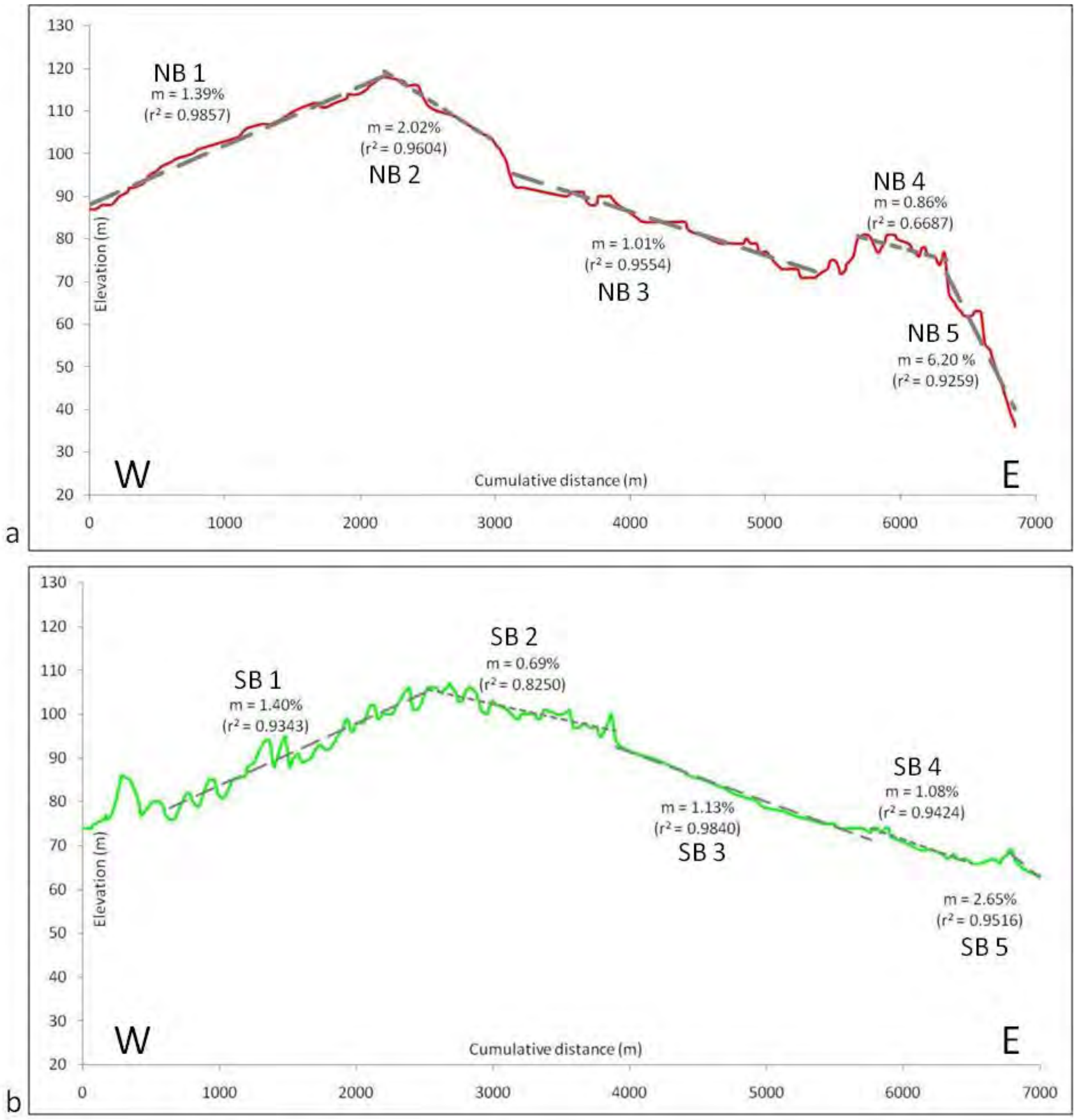


Figure 5-6 (a & b): Longitudinal profile of the northern (**a**) and southern (**b**) boundary and their respective gradients for individual sections.

5.3.2.2 Topography of the northern and southern dunefield profiles (W–E)

The west to east profiles of the dunefield appeared to exhibit a remarkably uniform curvilinear form with slope increasing progressively away from the crest of the dunefield (Figure 5-7). It was also evident that local relief was generally moderate to high due to the presence of mobile transverse dunes in the dunefield.

For the northern dunefield profile, slope upwards decreased from 1.69% (400 m to 1 000 m along the profile) to 0.83% (1 000 m to the dunefield crest). East of the dune system crest, the downward slope increased from 0.64% to 1.04% to 1.25% to 1.98% for sections from the crest to 3 500 m, 3 600 to 5 200 m, 5 200 m to 6 200 m and 6 400 to 7 000 m respectively (approximate distances). For the southern dunefield profile, the upward slope to the crest of the dunefield was 1.21% and across the head of the dunefield the land surface was almost flat at 0.23%. East of the crest of the southern part of the dunefield there was a remarkably uniform downwards slope of 1.24% over a distance of some 3 500 m. Over the last few hundred metres of the profile, slope increased to 6.45%. Table 5-4 shows the changes in the slopes for the west to east profiles.

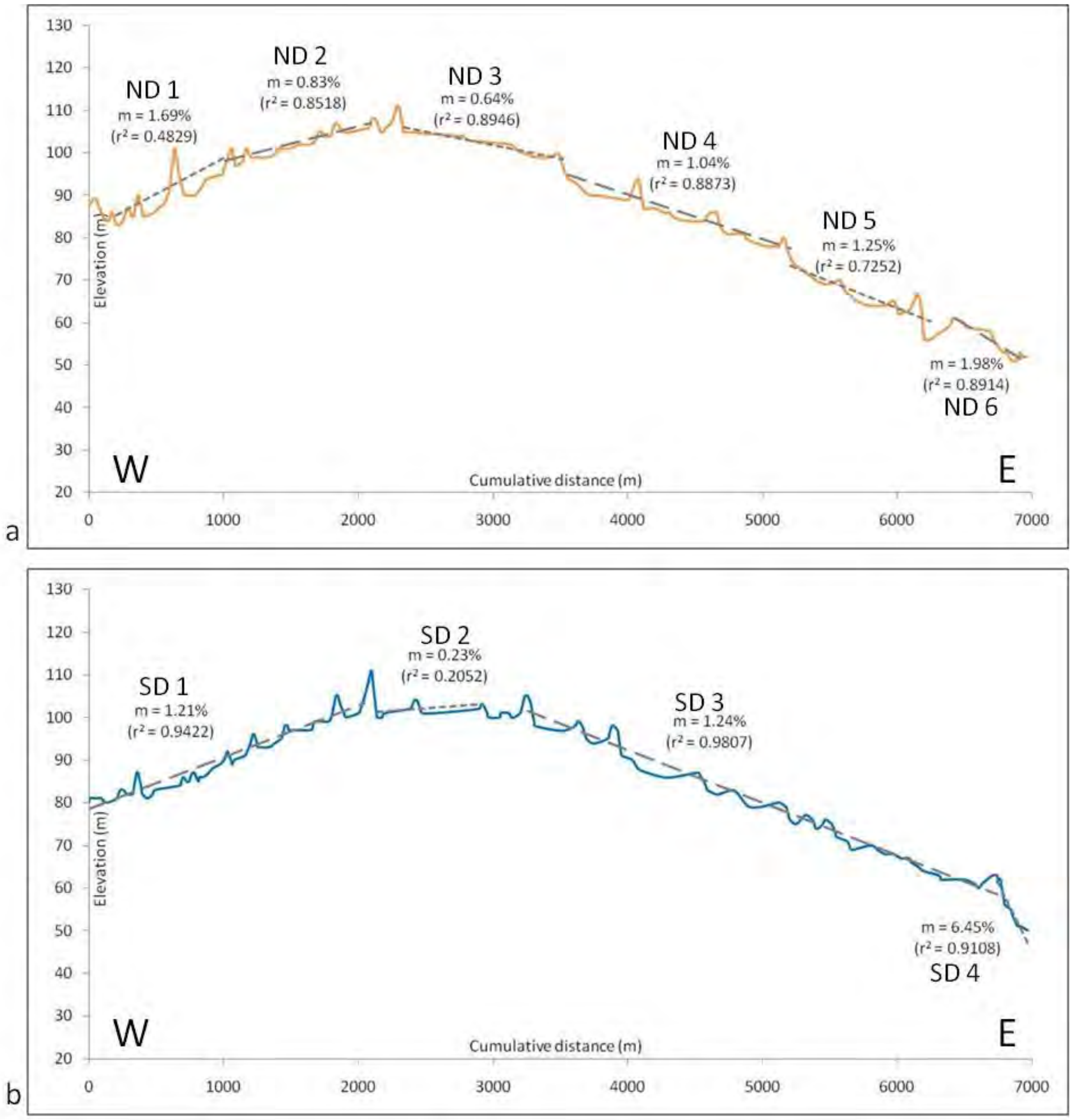


Figure 5-7 (a & b): Topographic profiles of the northern (**a**) and southern (**b**) dunefield and their respective gradients for individual sections.

5.3.2.3 Overall west to east dunefield morphology

A comparison of the morphology of the dunefield boundary and dunefield profiles provided an indication of the relationships between the dunefield and the adjacent terrain (Figure 5-6 (a & b) and Figure 5-7 (a & b)). West of the crest of the dunefield, the northern boundary was at a higher elevation than the northern dunefield, while the southern boundary was at a lower elevation than the southern dunefield. In the vicinity of the crest of the dunefield, both the northern and southern boundaries were elevated above the dunefield. East of the crest the boundaries of the dunefield were at similar elevations to the dunefield itself, although the northern boundary was somewhat lower than the dunefield except for a region of high lying ground from about 5 600 to 6 400 m along the profiles.

Table 5-4: A summary table showing the slopes of the topography for each of the four west to east orientated profile lines that were plotted.

Profile slopes	**Northern Boundary Profile**	**Northern Dunefield Profile**	**Southern Dunefield Profile**	**Southern Boundary Profile**
West to Central (upward slopes to east)	NB1: 1.39%	ND1: 1.69%	SD1: 1.21%	SB1: 1.40%
		ND2: 0.83%	SD2: 0.23%	
Central moving east (downward slopes to east)	NB2: 2.02%	ND3: 0.64%	SD3: 1.24%	SB2: 0.69%
	NB3: 1.01%	ND4: 1.04%	SD4: 6.45%	SB3: 1.13%
	NB4: 0.86%	ND5: 1.25%		SB4: 1.08%
	NB5: 6.20%	ND6: 1.98%		SB5: 2.65%

5.3.2.4 Relative location of the PZs to the surrounding dunefield morphology

The final graph in this section, Figure 5-8, shows the relative location of the piezometers in relation to the west – east generated profile lines. The graph shows that in the west, the northern piezometers were higher in elevation to the southern equivalent piezometers while all piezometers had a similar elevation and similar or lower slope to the land surface of the profile lines for the same region. In the central region the land surface and the elevation of the piezometers were very similar. In the eastern region, the northern piezometers were generally lower in elevation than the southern piezometers and all piezometers were generally lower in elevation than the land surface of the profile lines. In the south eastern region the slope of the piezometers and the land surface were similar, while in the north eastern region, the slope of the piezometers (1.42%) was notably steeper than the land surface for the same region (≈1.15%).

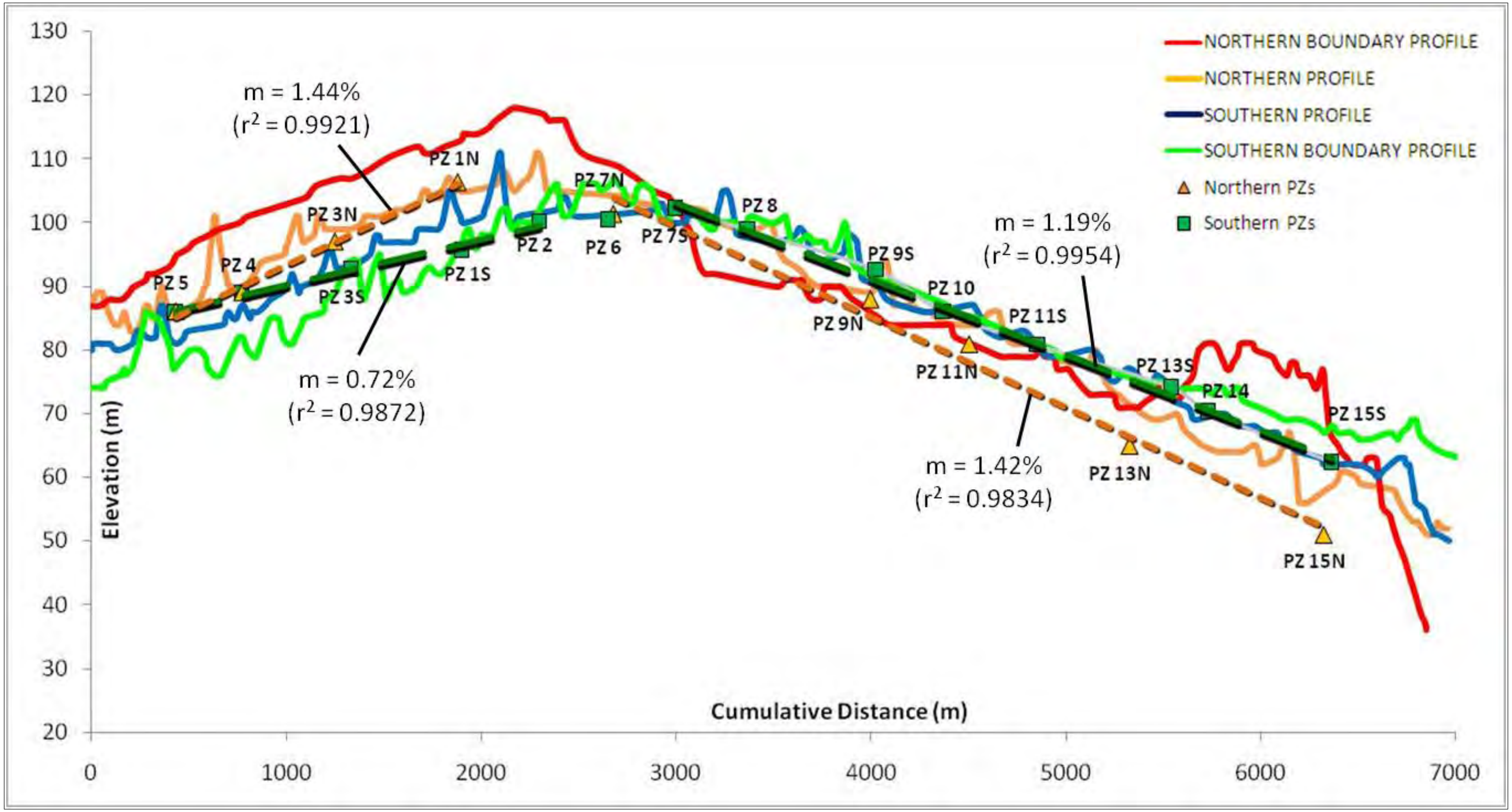


Figure 5-8: PZs in relation to the west to east generated profile lines.

5.3.3 Topographic structure across the dunefield from north to south

Figure 5-9 (Profiles 1 to 3) illustrating the north / south topography across the western zone of the dunefield, shows that a general downward slope existed towards the south that altered from the west to the east from 1.74% in the west (Profile 1), to 1.90% (Profile 2), to 1.78% in the east (Profile 3). The slope to the north in the western most profile revealed a distinct elevated area to the north of the profile (0 to approximately 250 m along Profile 1), which became less clear eastwards. To the south of the dunefield were a number of distinct elevated ridges that were oriented parallel to sub-parallel with the main axis of the dunefield. The main dunefield was situated to the north of these stabilised dune ridges, which typically rose 15 to 20 m above the adjacent dune floor. In contrast, the surface of the dune system was relatively uniform with decreasing local relief moving eastwards towards Profile 3.

The central zone of the dunefield had a slight incline to the south of 1.44% (Profile 4), becoming remarkably flat with a slight downward and upward slope to the south across the centre of the dunefield of 0.53% and 0.41% respectively (Profile 5, regression lines 5a and 5b). To the south of the dunefield, distinct elevated ridges oriented parallel to sub-parallel with the main axis of the dunefield were still evident. The extreme ends of the dunefield had reversed with regards to elevation, with the northern extreme dropping lower than the southern extreme of Profile 5.

Moving away from the central zone towards the east, the topography of the dunefield generally sloped upwards from north to south (Figure 5-11). The dunefield in the central part of the dunefield (main body) was at a slightly higher elevation than the land surface to the north (Profiles 6 and 7). Moving eastwards from the Profile 6 to Profile 10, the general elevation of the land surface of the dunefield decreased. In the far eastern region of the dunefield, the northern mobile dunes occupied a depression, with a slight incline to the south of approximately 0.55% (0.4% – 0.65%, P6 – P10), between elevated shoulders which became more distinct eastwards. The southern mobile dunes moved across a plateau that had a gradual incline to the south of approximately 1.01% (0.91% - 1.04%, P6 – P9).

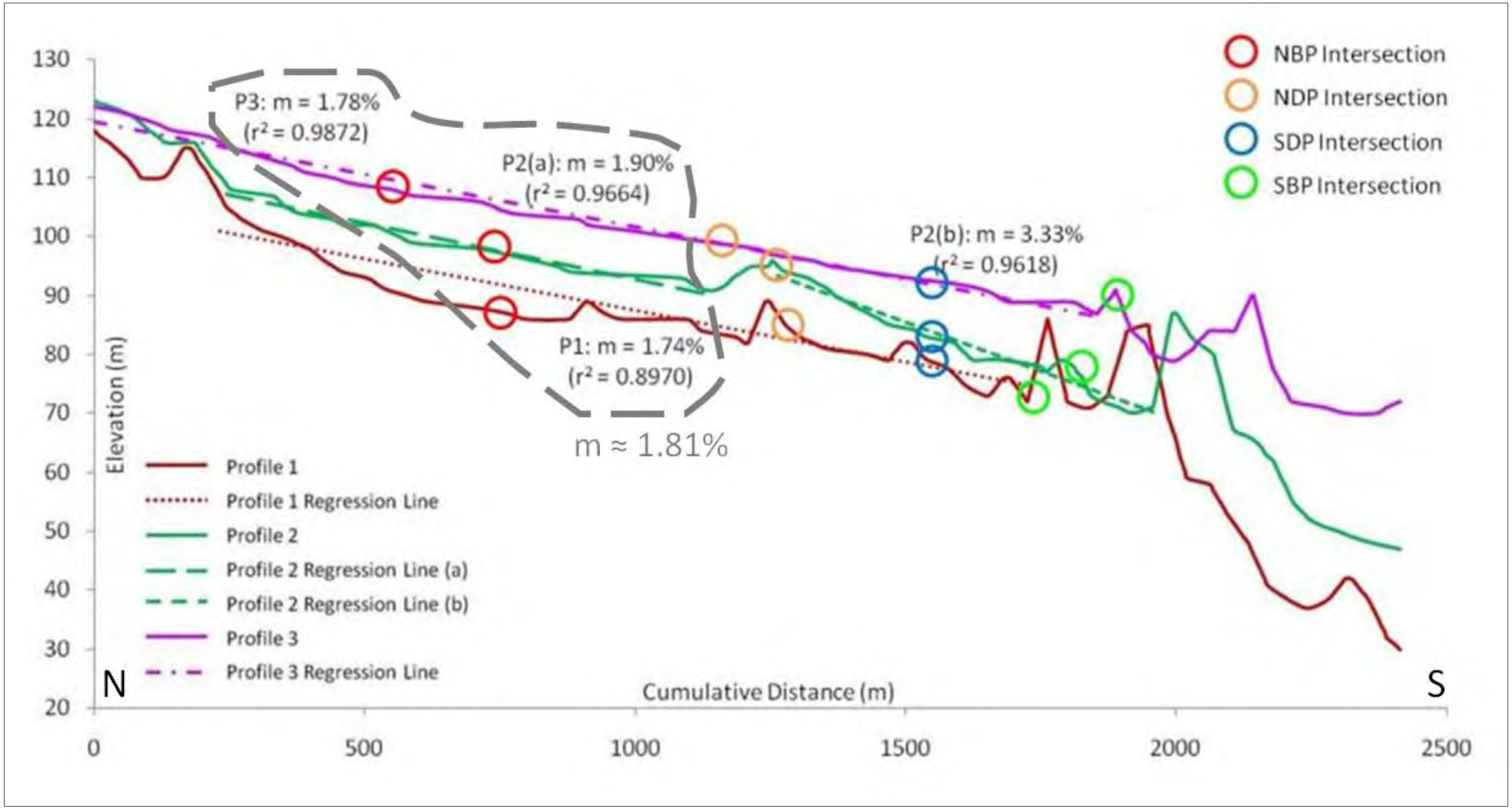


Figure 5-9: Western zone: the spatial location of the north to south orientated profiles and their respective gradients for sections, of the main dunefield, where uniform gradients could be visually established. Grey dashed lines show topography with similar slopes (m ≈ 1.81%).

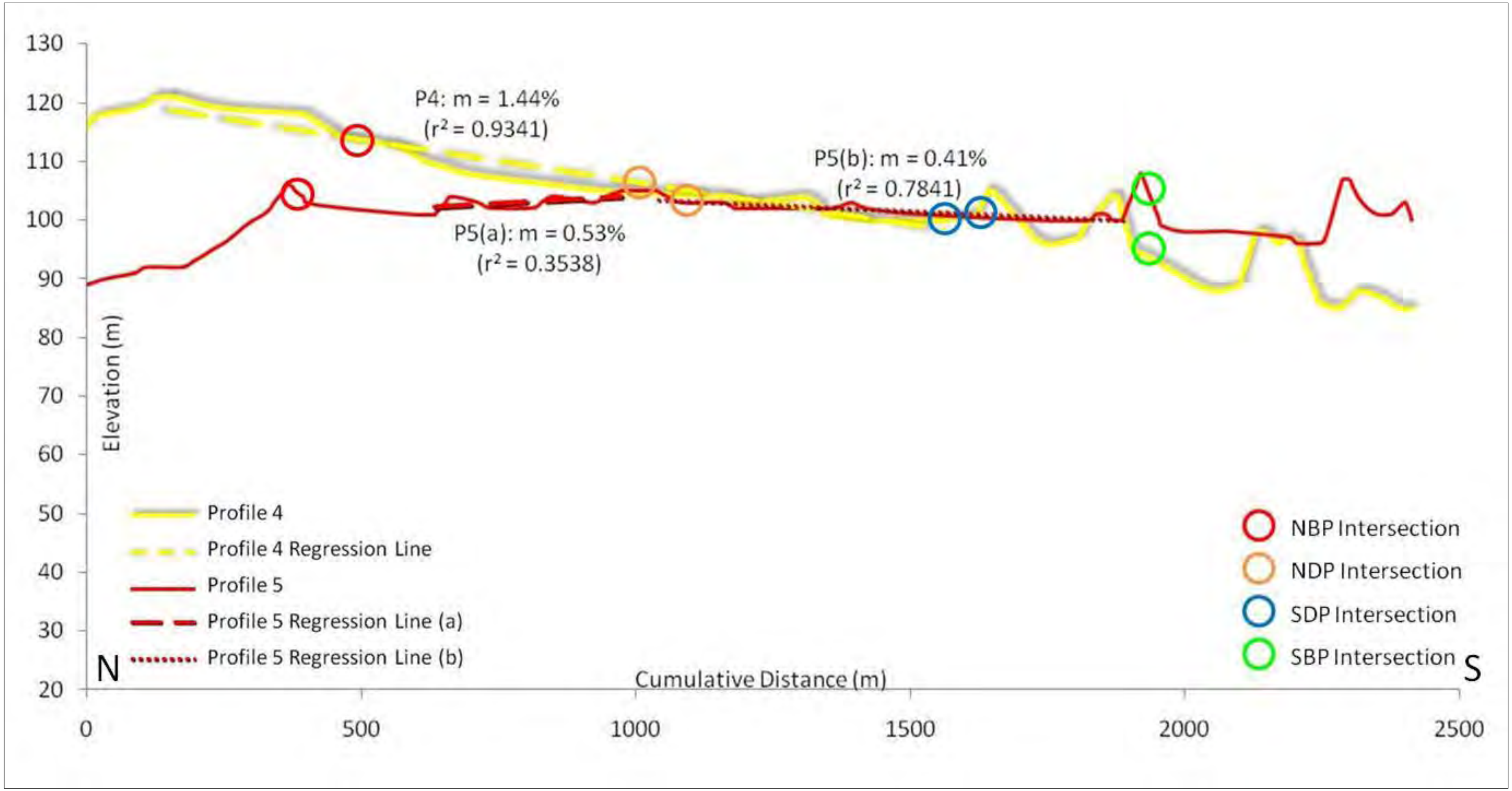


Figure 5-10: Central zone: the spatial location of the north to south orientated profiles and their respective gradients for sections, of the main dunefield, where uniform gradients could be visually established.

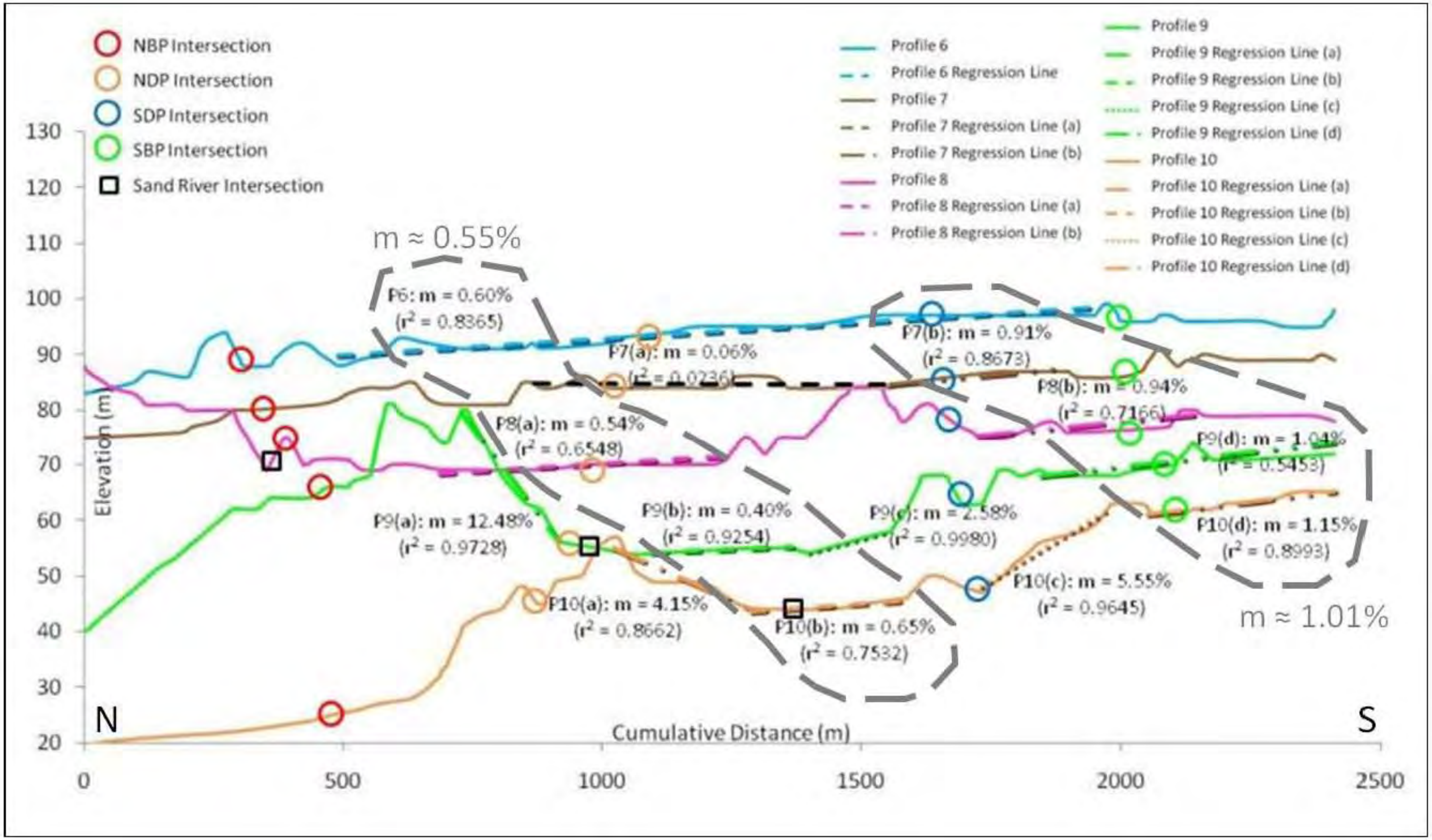


Figure 5-11: Eastern zone: the spatial location of the north to south orientated profiles and their respective gradients for sections, of the main dunefield, where uniform gradients could be visually established. Grey dashed lines show topography with similar slopes (m ≈ 0.55% & 1.01%).

5.4 OBJECTIVE 2 – MEASUREMENT OF THE RATES OF DUNE MOVEMENT AS A SURROGATE MEASURE OF SEDIMENT FLUX

5.4.1 Dune movement rates

Table 5-5 shows the average dune movement rates over intervals for each zone within the Oyster Bay HBD, as well as for the entire Oyster Bay HBD. The results show that the dunes moved slower on average in the western part of the dunefield. The greatest dune movement rates per year were recorded between 2007 and 2011 for all zones, while the central zone had the greatest rates of dune movement.

Table 5-5: Average dune movement by delineated zone over the given time periods.

	2000 – 2007		**2007 – 2011**		**2000 – 2011**	
	Total (m)	**Annual average rate ($m.a^{-1}$)**	**Total (m)**	**Annual average rate ($m.a^{-1}$)**	**Total (m)**	**Annual average rate ($m.a^{-1}$)**
Western Zone	68.46	9.78	54.55	13.64	61.50	11.71
Central Zone	88.86	12.69	68.25	17.06	78.55	14.88
Eastern Zone	90.32	12.90	66.03	16.51	78.18	14.71
OBHBD Average	**82.55**	**11.79**	**62.94**	**15.74**	**72.74**	**13.77**

Table 5-6 shows that in the western and central zones dunes moved faster in the northern part of the dunefield than in the southern part. The eastern zone differed in that dune movement rates were higher in the south than in the equivalent northern region.

Table 5-6: Variation in the annual dune movement rates (m.a^{-1}), between the northern and southern regions of the Oyster Bay HBD, for the period between 2000 and 2011.

	North (m.a^{-1})	**South** (m.a^{-1})
Western Zone	12.90	11.72
Central Zone	16.48	13.27
Eastern Zone	13.74	16.00
OBHBD Average	**14.37**	**13.66**

Figure 5-12, which includes photographs taken during the course of the field work, helps to illustrate the changes that occurred at piezometers within the south eastern region of the dunefield as a result of migrating dunes.

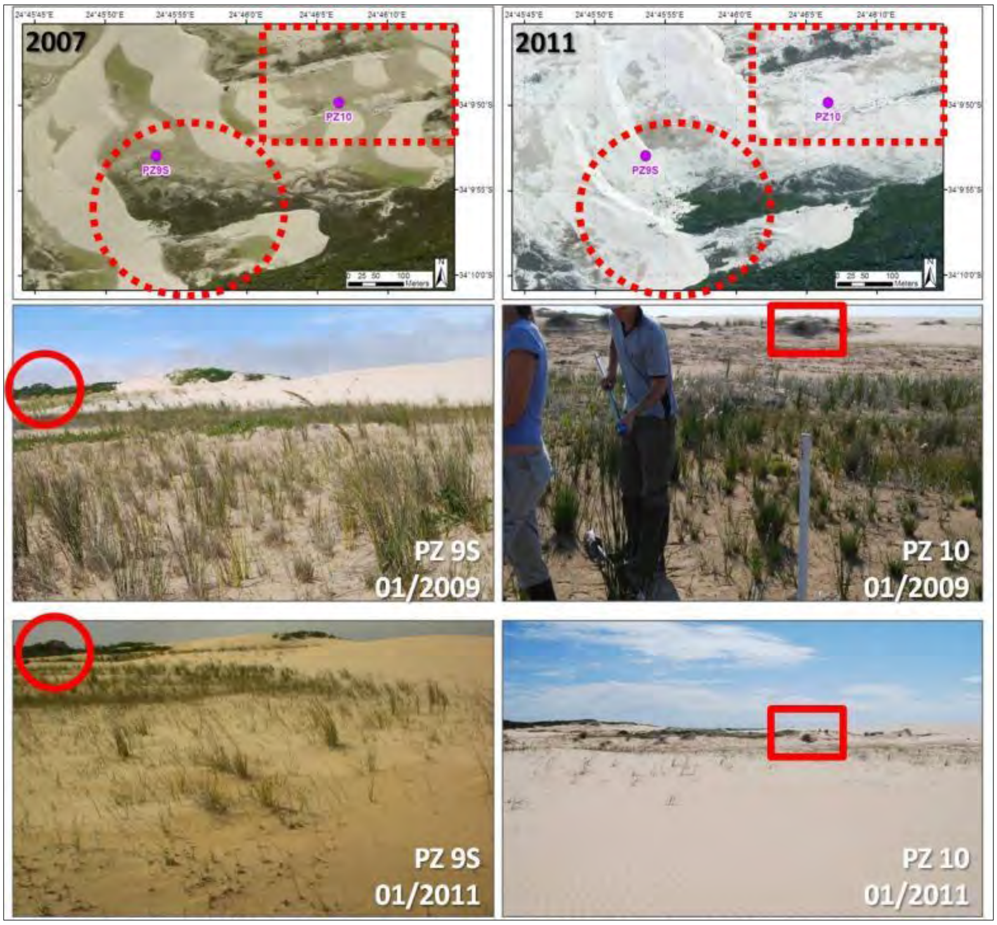


Figure 5-12: The change that occurred at PZ9 S and PZ 10 in the south eastern region of the dunefield.

5.4.2 Calculation of sediment flux

Calculation of sediment flux takes into account a bedform factor, which takes dune spacing into account. An average bedform factor was determined for each zone to be used in the calculation of sediment flux. Table 5-6 shows that the bedform factor (q_b) varied from 0.29 in the western zone to 0.15 in the north eastern zone and 0.22 in the south eastern zone. Dunes in the western and south eastern zone were spaced relatively close together while dunes in the central and north eastern zones were spaced further apart. Average bedform volume for the Oyster Bay HBD was calculated to be 21 $m^3.m^{-1}.a^{-1}$, declining systematically from west to east across the dunefield with the north eastern zone having the lowest value at 15 $m^3.m^{-1}.a^{-1}$.

Sediment flux through the system was greatest in the western zone with an estimated transport volume of 11 145 $m^3.a^{-1}$, decreasing eastwards to 7 139, 3 334 and 2 183 $m^3.a^{-1}$ in the central, south eastern and north eastern zones respectively.

In the eastern zones of the Oyster Bay HBD, the presence of vegetation impacted on the total estimated transport volume, reducing the value of estimated transport volumes by more than half in the north eastern zone specifically (Table 5-7).

Table 5-7: Estimated **s**and transport volumes within the Oyster Bay HBD system.

Zone	Dune height (m)	Bedform factor (q_b)	Bedform volume ($m^3.m^{-1}.a^{-1}$)	Average maximum width of dunefield (m)	Maximum transport volume ($m^3.a^{-1}$)		Estimated width of moving dunes (m)	Estimated transport volume ($m^3.a^{-1}$)	
					*Incl. veg. areas	°Ex. veg. areas		Incl. veg. areas	Ex. veg. areas
West	7.8	0.29	27.8	1 027	28 588	25 730	445	12 384	11 145
Cent	9.0	0.17	21.9	1 210	26 477	21 182	408	8 923	7 139
NE	7.3	0.15	15.3	881	13 511	5 810	331	5 076	2 183
SE	6.0	0.22	20.0	463	9 282	6 126	252	5 052	3 334
East^	6.7	0.19	17.7	1 058	18 715	5 968	292	5 157	2 758

* Including vegetated areas: entire width of dune taken into consideration.

° Excluding vegetated areas: excludes the calculated area of the dunefield that was determined to be stabilised / covered by vegetated areas.

^ Combined eastern zones.

5.5 OBJECTIVE 3 – INVESTIGATION OF BIOPHYSICAL ATTRIBUTES AS INDICES OF NATURAL PROCESSES (VEGETATION, WATER AND SAND)

5.5.1 Vegetation analysis

5.5.1.1 Field analysis

Figure 5-13 shows that, at the location of the piezometers, there was an overall progression in the total percentage cover from west to east to the north eastern zone of the dunefield. The north eastern zone transects had the greatest total percentage cover. These results also show that the transects within the western zone had the lowest percentage of vegetation cover.

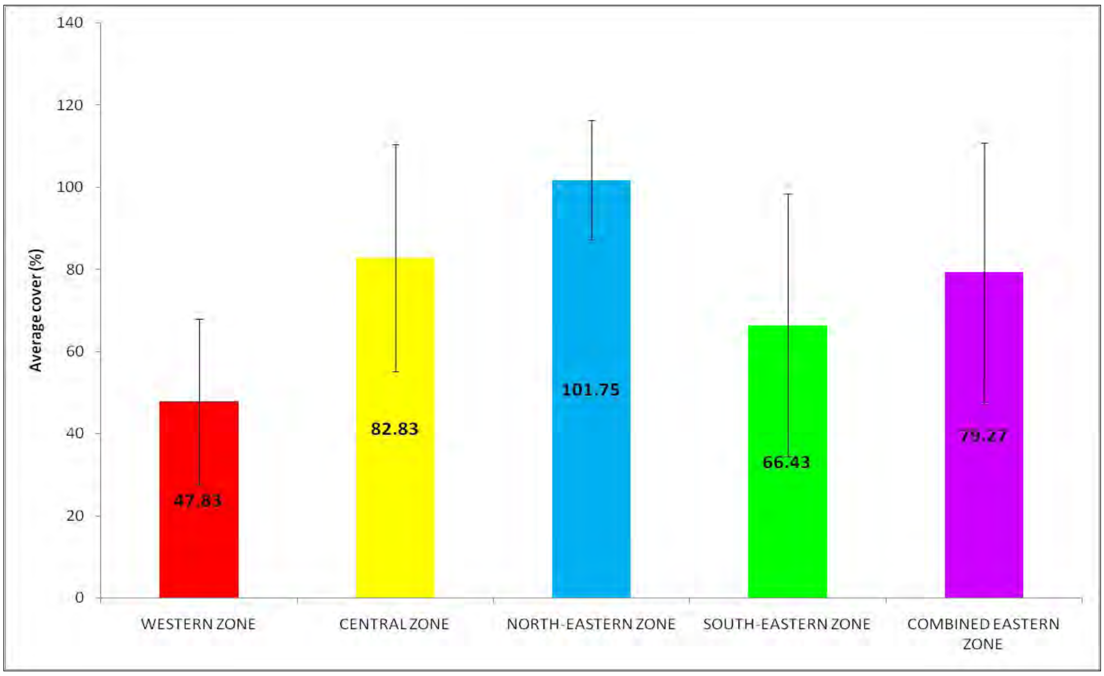


Figure 5-13: Average percentage cover of vegetation within transects by zones, with standard deviation plotted.

Figure 5-14 shows the average composition of the combined transects by delineated zones, as well as the standard error for percentage cover of each of the classified vegetation types. The graph shows that HGT plants occupied the largest area within the transects; while HGR and HFT occupied the next largest percentage cover showing similar overall values. There were no WNR classified plant types recorded within any of the transects.

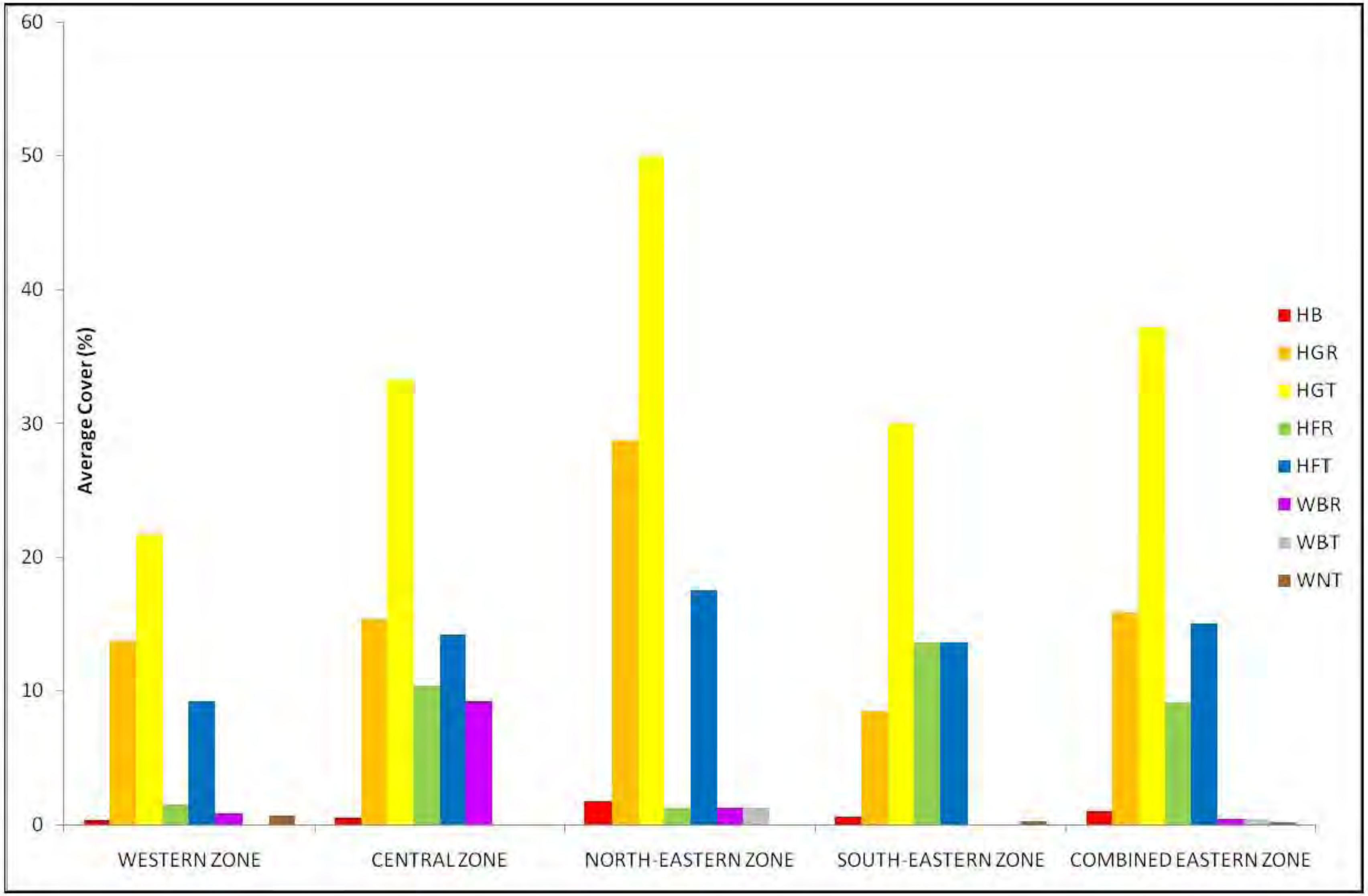


Figure 5-14: The average composition of the total transects by zone.

5.5.1.2 Vegetation change as an indicator of sediment flux

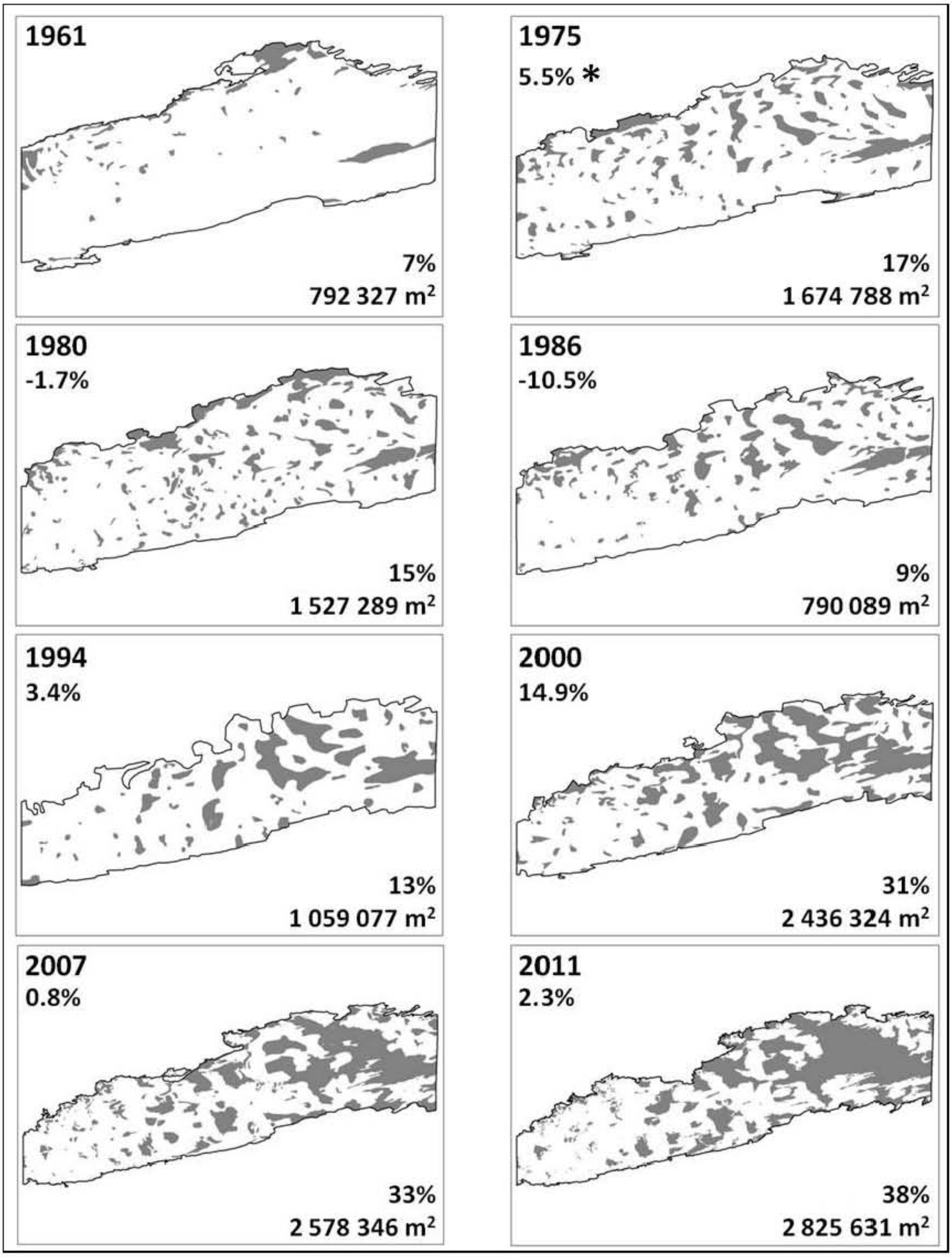
In 1961 there was relatively little vegetation present in the dunefield, with only 5.5% of the dunefield vegetated (Figure 5-15). There were two relatively large consolidated areas of vegetation cover, one along the northern boundary of the dunefield with an irregular shape and showing no strong orientation, and another near the eastern border of the zone mapped for this study with a strong east-north-east to west-south-west orientation, which is similar to the prevailing wind direction. There were a large number of very small vegetated patches that were concentrated in the northern part of the dunefield that showed no particular orientation.

The extent of vegetation cover increased by 10% over the period from 1961 to 1975, with the vegetated northern part of the dunefield in 1961 becoming totally vegetated such that it was no longer identifiable as mobile dunefield by 1975. The large area of vegetated dunefield near the eastern boundary of the mapped area enlarged noticeably, maintaining the same overall east-north-east to west-south-west orientation as in 1961. The remaining vegetated areas in the 1975 photography represented fragments of varying size, which generally had an irregular shape or a south-west to north-east orientation in the western zone, a north to south orientation in the central zone and a north-west to south-east orientation in the eastern part of the dunefield. In general, the size of vegetated areas increased from west to east in the dunefield.

By 1980 a similar area of the dunefield was vegetated as in 1975, but extensive vegetation patches occupied the northern border in the central zone. The large patch near the eastern boundary of the study area occupied a similar area with a similar orientation to that of the previous photography. Vegetation patches other than these were generally irregular, without a striking orientation, except in the east where the orientation was once again north-west to south-east.

The extent of vegetation cover decreased noticeably in the period from 1980 to 1986, largely due to the vegetation along the northern boundary in 1980 no longer being identifiable as mobile dunefield by 1986. The size of patches in the central and eastern part of the dunefield generally increased over his period, with a north to south orientation in the central part of the dunefield and a north-west to south-east orientation in the eastern part.

The extent of vegetation increased consistently over the period from 1986 to 1994 to 2000 to 2007 to 2011 from 9% to 13% to 31% to 33% to 38% respectively. There are features that provide a sense that the predominant orientation of vegetated areas in the western parts of the dunefield is from south-west to north-east, while in the eastern parts of the dunefield vegetation is predominantly orientated from south-east to north-west (perpendicular to the prevailing wind).



** annual rate of change in the extent of the OBHBD between consecutive aerial photographs.*

Figure 5-15: The total vegetation cover (as a percentage and in m^2) for each available aerial photograph and the annual rate of change in total cover as recorded between consecutive aerial photographs.

To refine the picture presented above, the proportion of vegetation change in each delineated dune zone, for specific aerial photographs (see Table 4-3 from Methods chapter), was also investigated (Figure 5-16). This analysis aimed to show the changes in vegetation cover over time as a proportion of the area of each delineated dunefield zone. The results show that the eastern zones of the dunefield are becoming increasingly vegetated with time while the vegetation cover in the western section has been variable but has generally stayed low.

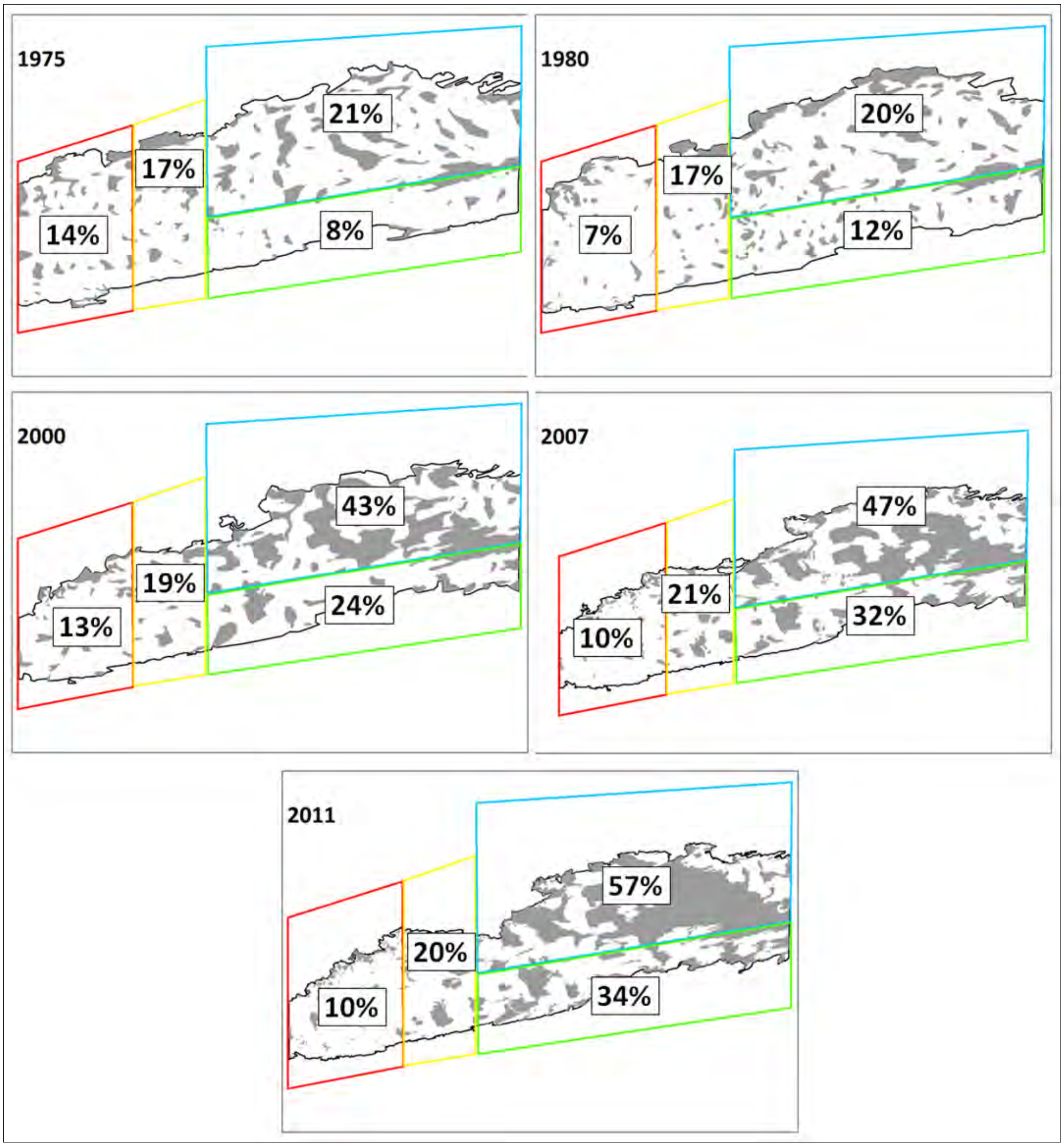


Figure 5-16: The change in the proportion of vegetation cover within each zone of the Oyster Bay HBD over time for selected good quality aerial photographs.

5.5.2 Water analysis

5.5.2.1 Groundwater table elevation

The elevation of the water table was typically less than one metre below the land surface at each piezometer point such that the piezometric surface consistently approximated the land surface. The average deviation for all piezometers from the mean depth to groundwater per month over the period in which sampling occurred showed that the water table was elevated above the mean for the period from November to January 2008 and again in July to October 2009, which coincided with periods of high rainfall, and was elevated below the mean from February to June 2009, a period of relatively low rainfall (Figure 5-17). However, despite low rainfall in the months of November 2008 and September and October of 2009, the elevation of the water table showed little variation over these periods, suggesting that the response of the water table to variation in rainfall is delayed – something that will be discussed in the next chapter.

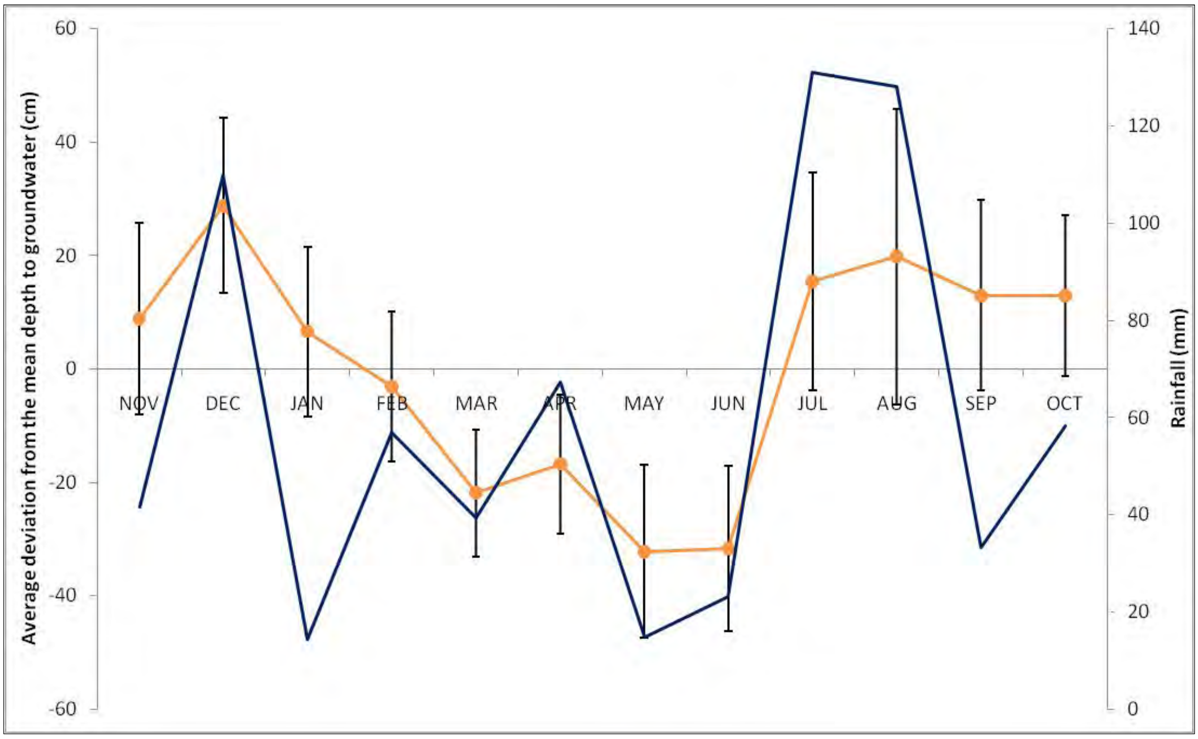


Figure 5-17: The average deviation from the mean depth to groundwater across the dunefield.

Figure 5-18 shows the temporal variation in the mean depth to the groundwater level for each zone, as well as the measured rainfall that occurred over the period between when the samples were taken. The western zone showed the lowest variation in water table elevation while the north-eastern zone showed the greatest variation in water table elevation. The south eastern and central zones showed similar variation in groundwater elevation over the period of measurement.

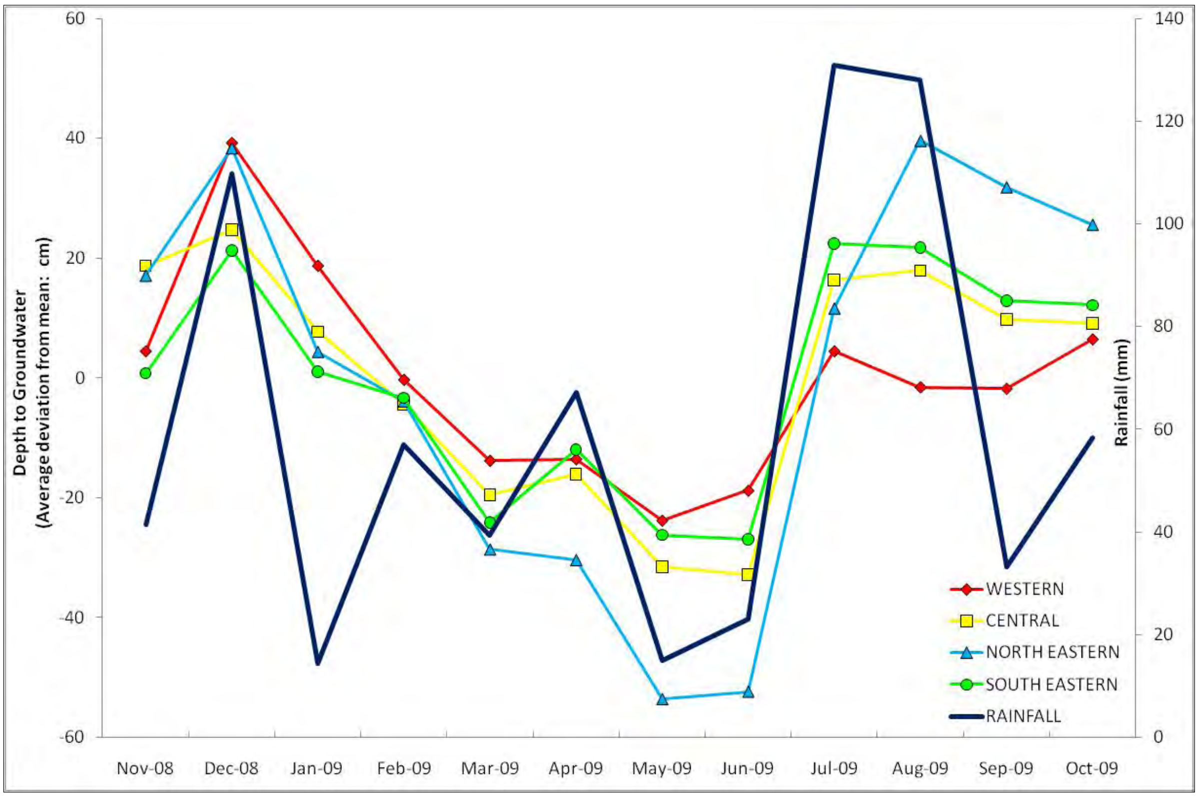


Figure 5-18: The average depth to groundwater level (deviation from the mean) by zone for each month sampled shown in comparison to regional average monthly rainfall for the same period.

5.5.2.2 Groundwater electrical conductivity

The western, central and south-eastern zones showed very similar seasonal trends with regards to EC values (Figure 5-19), being highest during and following periods of fairly high rainfall as EC values were high from November 2008 to February 2009 following a period of high rainfall in November 2008, a pattern that was repeated following high rainfall in July and August 2009. The EC values in these zones were lowest during and following periods of low rainfall as EC values were low from March to August 2009 during and following the dry period of January to June 2009.

The north eastern zone showed the greatest variation over the period of a year with the highest and lowest EC values for all sites being recorded in this zone. Furthermore, the general seasonal pattern observed in the other zones was not evident in the north-eastern zone, where EC declined sharply in May 2009 and rose sharply again in the following two months. There were minor reductions in EC values in this zone that coincided with periods of high rainfall in December 2008 and August 2009.

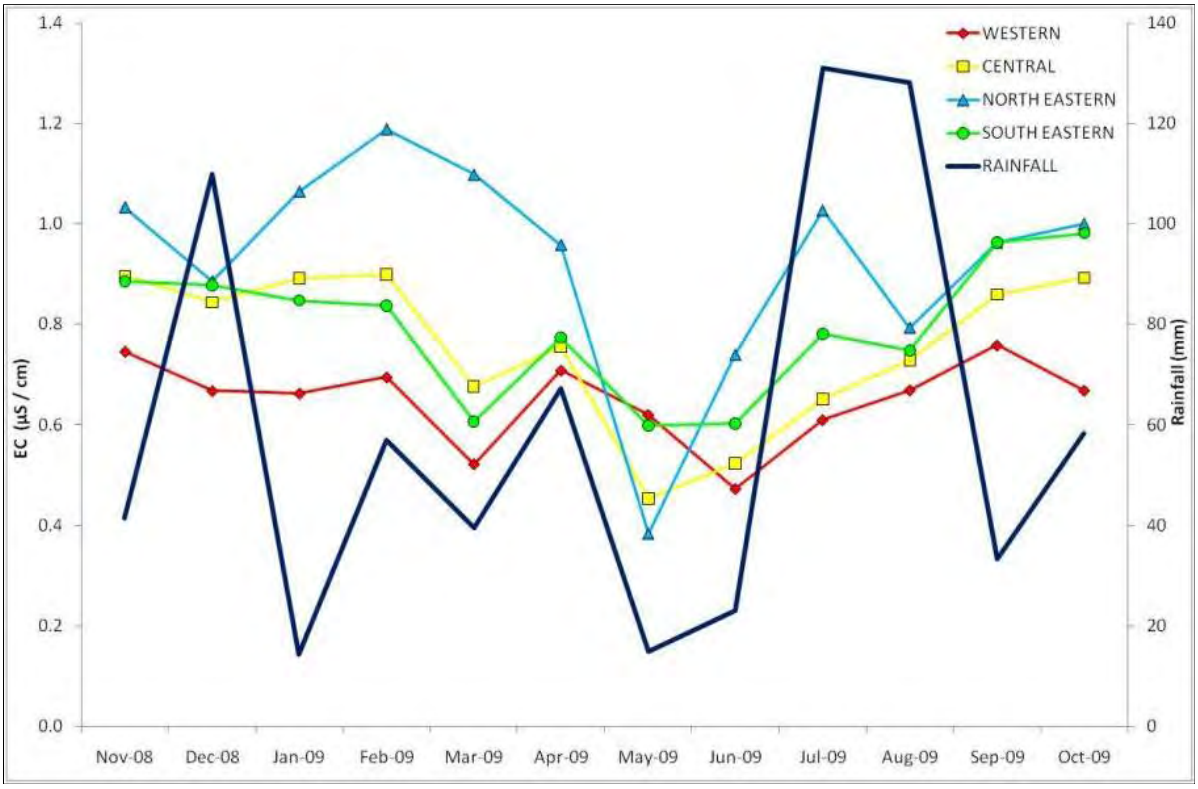


Figure 5-19: Average electrical conductivity levels by delineated zone for each month sampled and the regional average monthly rainfall for the same period.

Figures 5-20 (a & b) shows further the variation of EC down the length of the dunefield for the northern and southern piezometers during the period of one year. For both sets of piezometers the EC values increased up the slope from PZ 5 in the west towards the crest (PZ 1N and PZ 1S). In the central region of the dunefield, the EC values remained fairly constant. Moving further eastwards, the EC values then typically increased. In the south eastern region, there was clearly an increase moving towards the Skurweburg Ridge that outcrops in the region of PZ 8, after which the EC dropped but then generally increased again moving further eastwards. In the northern region, the EC value systematically increased moving in an eastward direction away from the central plateau, reaching its highest value at PZ15 N throughout the year. The western and north eastern zones were therefore showing opposite trends down the slopes away from both sides of the central zone.

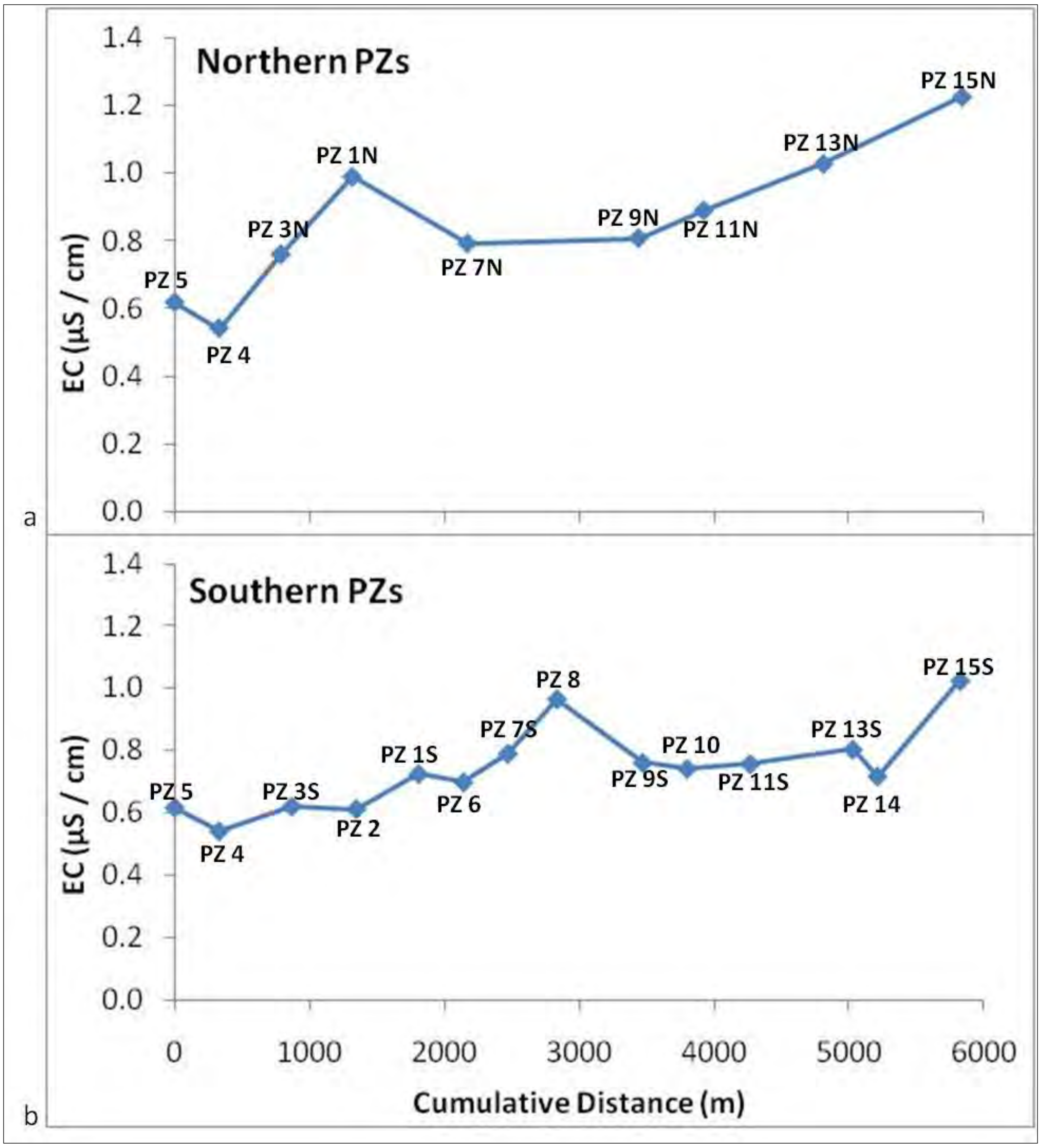


Figure 5-20 (a & b): Average EC down the length of the Oyster Bay HBD for, **a:** the northern piezometers and **b:** the southern piezometers.

5.5.2.3 Groundwater pH

Figure 5-21 shows that for all delineated zones very similar trends are observed with regards to pH values of the groundwater. In general, pH declined following periods of high rainfall and increased during dry periods, reflecting an inverse relationship between rainfall and pH.

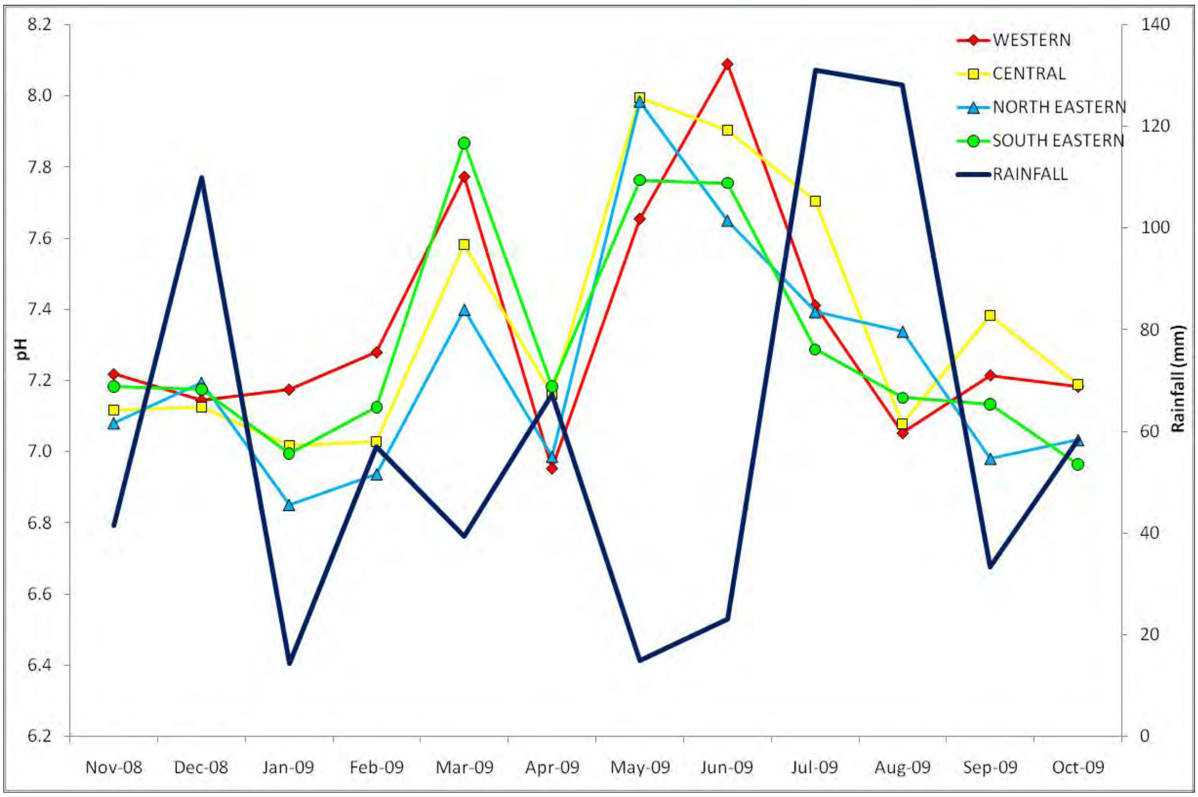


Figure 5-21: Average pH by zone for each month sampled and regional average monthly rainfall for the same period.

5.5.3 Sand Grain Analysis

Variation in the grain size down the length of the dunefield, from west to east, is shown in Figure 5-22. There was a slight overall increase in the proportion of finer sediment (≤ 250 µm, r^2 = 0.0265) and a decrease in the proportion of coarser sediment (≥ 350 µm, r^2 = 0.0271) from west to east in the dunefield. However these results are not convincing.

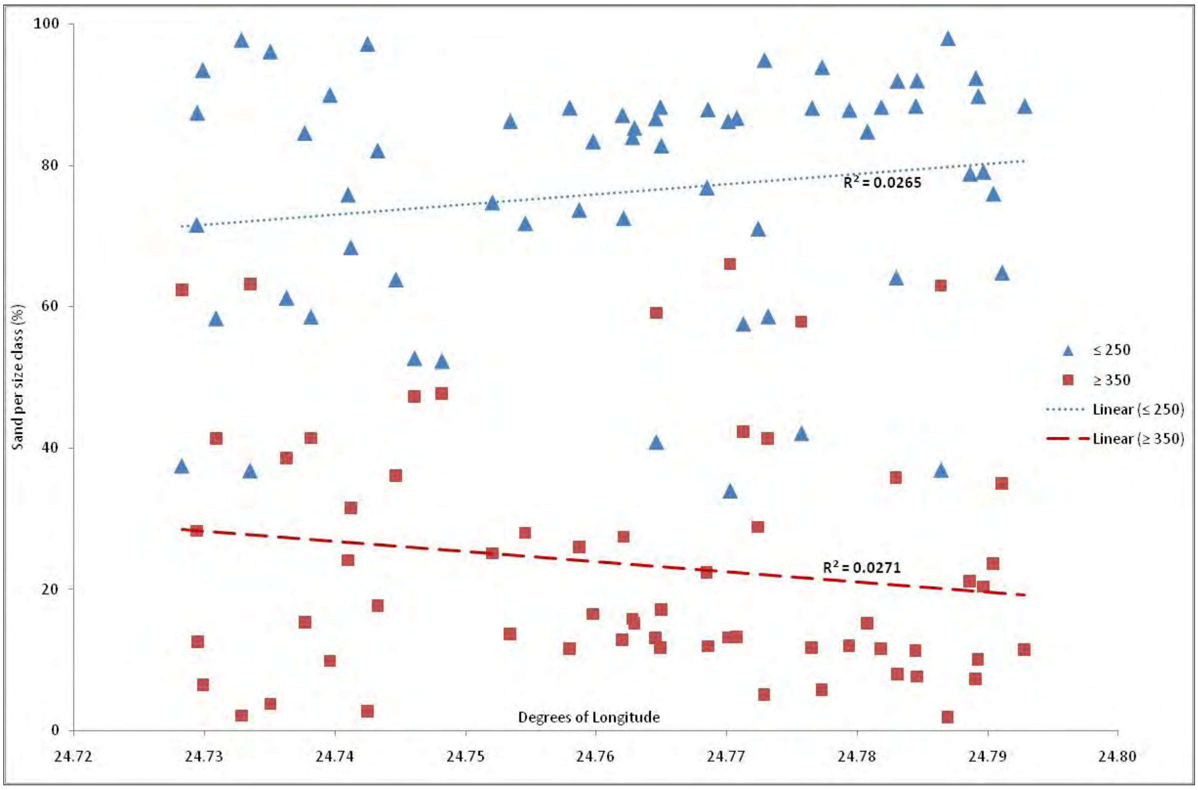


Figure 5-22: Variation in particle size from west to east down the length of the dunefield.

5.6 OBJECTIVE 4 – DEVELOPMENT OF SUMMARY DIAGRAMS AND TABLES AND A CONCEPTUAL DIAGRAM OF DUNEFIELD STRUCTURE AND FUNCTION

For this objective, a series of summary diagrams will be presented in Chapter 6, as well as one final summary table and conceptual diagram which aim to emphasise the significant drivers of change, features and / or components, and processes occurring within the Oyster Bay HBD.

CHAPTER 6: DISCUSSION & CONCLUSION

6.1 INTRODUCTION

The Oyster Bay HBD is a complex system with numerous factors that interact to determine its overall structure, functioning and dynamics. Data from a range of sources have been collected to attempt to understand this system, including:

- The morphology and extent of the system (Objective 1)
- Sediment flux across the system (Objective 2)
- Vegetation distribution, sand particle size distribution and groundwater characteristics (Objective 3).

The findings of the study have been integrated in summary diagrams for each objective and an overall summary table and conceptual diagram of the structure and function of the Oyster Bay HBD (Objective 4).

6.2 OBJECTIVE 1– MAPPING THE MORPHOLOGY AND EXTENT OF THE OYSTER BAY HBD

6.2.1 Changes in the extent of the Oyster Bay HBD

The Oyster Bay HBD has shown a moderate level of change in extent – both in respect of its length and width, but overall the length to width ratio is relatively constant at approximately 11:1. Although urban development has taken place on either end of the dunefield, there is clear evidence that the dunefield experiences regression during periods of low rainfall, and that it experiences transgression during periods of high rainfall. These findings are similar to those of Castro (2005), in the Paracuru dunefield, where sediment availability and therefore dunefield extent, were affected by rainfall.

In the present study area, changes in dunefield margins have been far greater in the north than in the south. Between 1961 and 2011, the overall southward regression across the northern dunefield was consistently greater than 500 m, which translates to a figure of approximately 10 $m.a^{-1}$ (Figure 6-1). In the extreme north eastern section however, a change of only 172 m occurred over the past 50 years, which translates to three metres per annum.

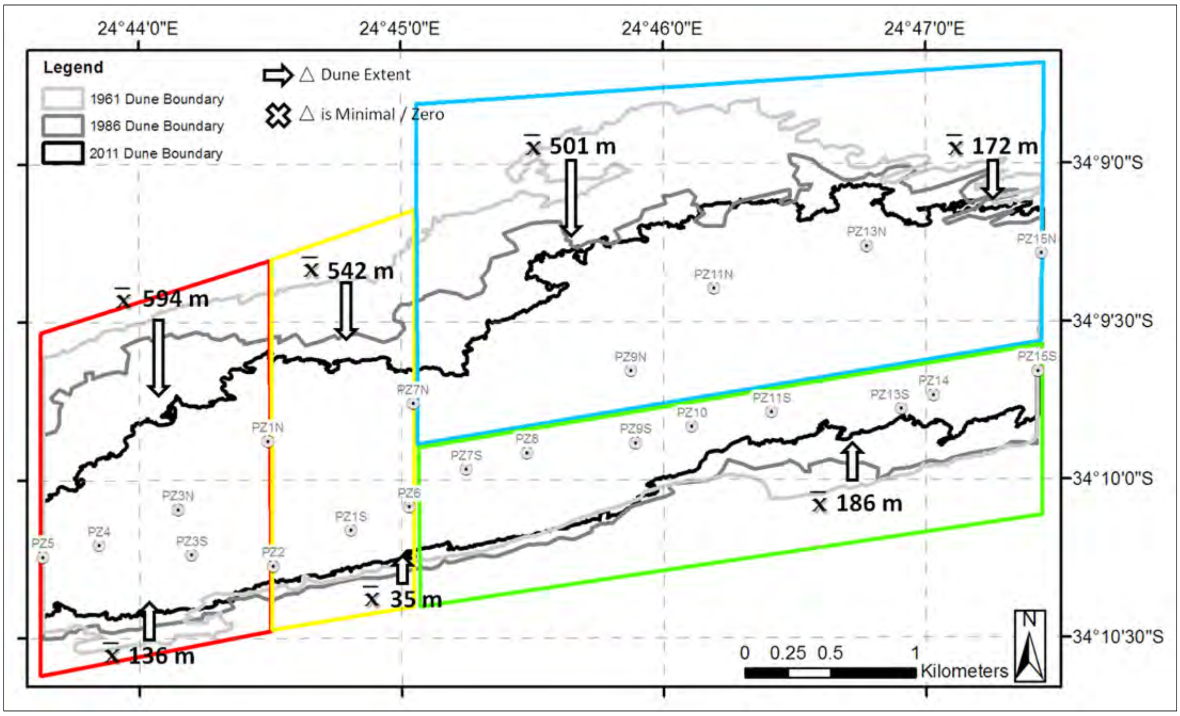


Figure 6-1: The change from 1961 – 2011 in the extent of the Oyster Bay HBD within the respective delineated dune zones.

In contrast, the southern boundary showed clear periods of transgression and regression occurring up until 1994, but from 1994 to 2011, the southern boundary generally regressed northwards. This regression predominantly occurred in the western delineated zone and in the eastern part of the south eastern delineated zone; while the central zone remained almost static (Figure 6-1).

Areas of regression are largely dominated by invasive *Acacia* species. The reason for the regression of the dunefield over the period of analysis seems likely to be related to a reduced sand supply (Burkinshaw, 1998: 117). According to Burkinshaw (1998) there has been a reduction in sand supply to the northern margin of the Oyster Bay HBD. This, together with the successful growth of the *Acacia* species has led to the reduced extent of sand and dunes in the northern parts of the dunefield and is mostly likely the reason why the northern margin continues to regress without forming a definitive sidewall (Burkinshaw, 1998: 117), while the southern, more clearly defined sidewall, has regressed at a much slower rate.

The height of the sidewall of the dunefield seems to affect the extent to which a dunefield will regress or transgress. The height of the sidewall in relation to the height of the transverse dunes in the dunefield seems particularly important in this regard (Burkinshaw 1998: 116). In the case of the Oyster Bay HBD, the southern sidewall of the dunefield in the western part if the dunefield is higher than the height of the transverse dunes in the dunefield, which means that the dunefield is largely contained by the sidewall and it therefore remains relatively stable. In contrast, where the sidewall is lower than the height of the dunes, transverse dunes buttress and overspill the sidewall giving rise to a much more dynamic boundary (Burkinshaw, 1998: 117).

The dynamics of dunefield margins is also affected by changing wind regimes and sediment supply. Where sediment supply is increased, dune size is also increased, which increases the likelihood of transgression (Burkinshaw, 1998 and Castro, 2005) However, when sediment supply is reduced, dunes become smaller and margins regressive (Burkinshaw, 1998: 117). In the case of the Oyster Bay HBD, sediment supply has been reduced as a result of urban development at Oyster Bay, which has reduced sediment flux from the beach to the dunefield at the western end of the Oyster Bay HBD system (Burkinshaw, 1998).

6.2.2. Comparison to other HBD systems

When compared to other systems within South Africa, the Oyster Bay HBD is the longest existing HBD system, even in its current form (16 kms from west to east) where it does not extend across the entire headland. The only other HBD systems in South Africa that would have been similar in length were the Algulhas Headland / Struis Baai HBD and the Driftsands HBD at Cape Recife. When the Agulhas Headland / Struis Baai HBD system was functioning, it had a length of approximately 15 km and a length to width ratio of approximately 5:1. Similarly, when the Cape Recife Driftsands HBD system was fully functional it had a length of approximately 18 km and a length to width ratio of approximately 7:1 (McLachlan *et al.*, 1994). Both of these dunefields were similar to the Oyster Bay HBD system, but do not exist at all today. The other smaller HBD systems occurring along the south coast of South Africa are much shorter and have lower length to width ratios than the Oyster Bay HBD. The length to width ratios of HBD systems do not typically exceed 11:1 or drop much below 4:1.

The Guincho-Oitavos Dunefield located on the west coast of Portugal, has also been partly vegetated and no longer passes completely across the headland. However, when this dunefield did extend across the headland, it was approximately five kilometres long and had a width of approximately 800 m, which translates to a length to width ratio of 6:1.

In contrast to the dunefields mentioned above, the Paracuru Dunefield in north eastern Brazil is approximately six kilometres long and four kilometres wide, which equates to a length to width ratio of approximately 1:1.5. Unlike all of the other HBD type dunefield investigated as a part of this research, the Paracuru Dunefield has a significantly lower length to width ratio. This is largely assumed to be due to the exposure and shape of the Paracuru Headland with an upwind beach width of 8.5 kms that produces a massive supply of sand across the entire width of the headland. This is in contrast to the Cape St. Francis Headland which has distinct bays and associated beaches on the upwind side of the HBDs that are of limited width, such as Oyster Bay, which is about four - five kilometres wide and Thysbaai (upwind of the Thysbaai Headland Bypass Dunefield), which is approximately three kilometres wide.

Castro (2005) also used aerial photographs to show changes in the extent of the Paracuru Dunefield. The Paracuru Dunefield expanded between 1958 and 1999, from 8 396 711 to 8 642 590 m^2 respectively, equating to an annual growth rate of approximately 0.07 % or some 6 000 m^2. The Paracuru system is substantially smaller and has been experiencing rates of change that are approximately ten times slower than that which has occurred in the Oyster Bay HBD, despite having an uninhibited supply of sand from the east. The Paracuru system helps to show the contrasting extent and resultant forms of HBD systems occurring on an international scale.

These systems help to highlight the similarities and differences in dune length and length to width ratios that exist within HBD settings. These examples also help to show the larger length of the Oyster Bay HBD in comparison to others around the world. The comparisons emphasise that the Oyster Bay HBD, with a fairly inhibited sand source, has been experiencing rates of change that are much greater than the Paracuru system with a predominantly uninhibited sand source. These comparisons stress the need to study each HBD system as a separate coastal dunefield system in respect to their local context, in order to better understand how local features and local drivers bring about change at the various scales of influence to individual HBD systems.

6.2.3 The morphology of the Oyster Bay HBD

Most of the morphology-related results presented in Chapter 5, on which this section of the discussion is based, were consistent with what Burkinshaw (1998: 80 - 121) concluded from her study of the Oyster Bay HBD. Analysing the north to south and west to east topographical changes helps to better understand certain processes and features present within the system.

6.2.3.1 North to south topographic changes

Along the southern boundary of the active part of the dunefield, a distinct sidewall could be viewed almost along the entire length of the Oyster Bay HBD. No such (distinct) sidewall was evident along the northern boundary of the dunefield.

It is also clear from the topographic data that in the western section of the dunefield, the elevation of the land surface sloped downwards from north to south with an average slope of 1.80% (Figure 6- 2) This most likely relates to structural control on the land surface in the form of the Table Mountain Group (Peninsula Formation) anticlinal ridge, which projects diagonally from north-west to south-east across the dunefield in the vicinity of the western to central sections of the Oyster Bay HBD (Burkinshaw, 1998: 87). The Peninsula Formation is a resistant quartzite lithology that gives way laterally westwards and eastwards to the less resistant Goudini Formation, which mainly comprises shale. In the study area, the Goudini

Formation gives way laterally towards the east to another resistant quartzite lithology, the Skurweberg Formation.

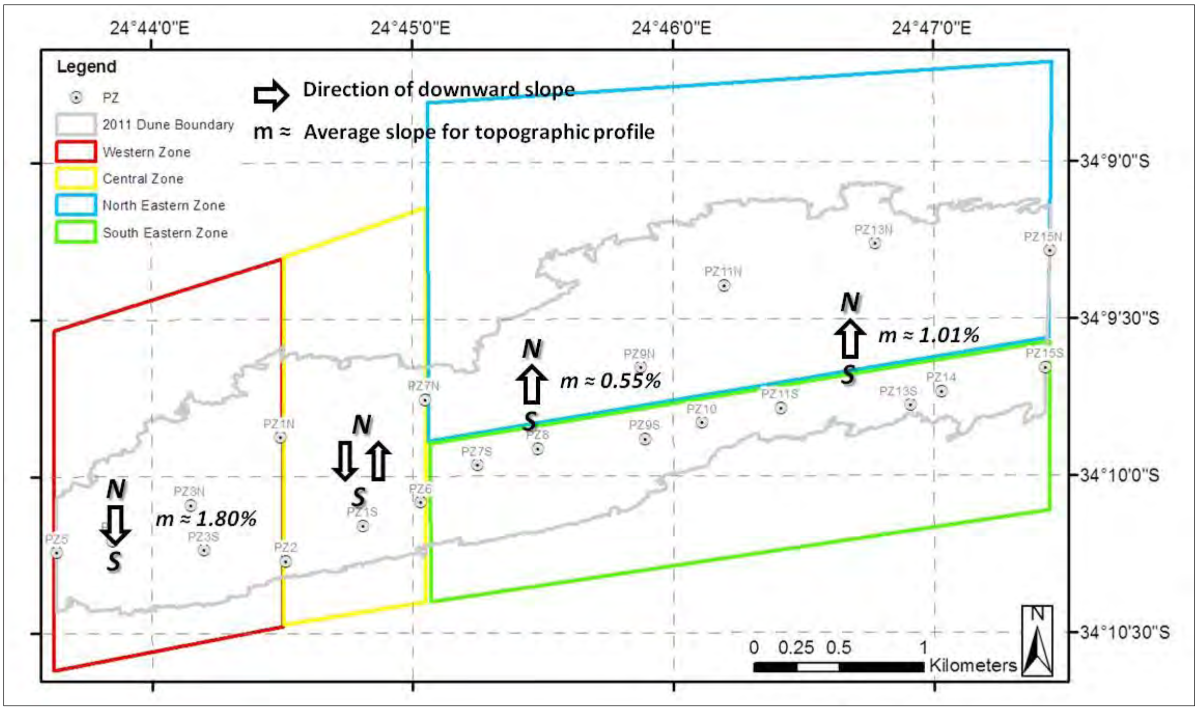


Figure 6-2: The change in the topography of the Oyster Bay HBD in both the north to south and west to east directions.

In contrast to the western and central section of the dunefield, the eastern section of the dunefield slopes downwards towards the north, with an average incline of 0.55% and then 1.01% further eastwards. This probably reflects the effect of the Sand River in lowering the elevation of the land surface in the northern part of the eastern section of the dunefield. The Sand river arises north of the active dunefield and has clearly lowered the elevation of the land surface, particularly the more easily weathered and eroded Goudini Formation but including the more resistant Skurweberg Formation ridge, which rises out as a rocky outcrop in the western part of the north eastern region (Burkinshaw, 1998).

6.2.3.2 West to east topographic changes

Of significance to this part of the discussion is the slope of the piezometers in relation to the land surface in the specific regions of the dunefield. From the results it was shown that there are similarities and differences which exist in the dunefield between the piezometric slope and elevation and the land surface slope and elevation, summarised now in Table 6-1. From the table it can be seen that for all zones, except the north eastern zone, the slope of the piezometers is generally similar or less than the relative land surface. However, in the north eastern zone, the slope of the piezometers is steeper than the relative land surface. This therefore hints at the fact that in the north eastern region, water is having an effect on steepening the land surface in this region of the dunefield.

Table 6-1: The relative slopes and elevation of the land surface and piezometers for the various zones of the Oyster Bay HBD.

	Western Zone	**Central Zone**	**South Eastern Zone**	**North Eastern Zone**
Slope of land surface in south (from W – E)	+1.21%	Relatively flat	-1.24%	NA
Slope of southern PZs (from W – E)	+0.72%	Relatively flat	-1.19%	NA
Slope of land surface in north (from W – E)	+1.69%	Relatively flat	NA	-1.04% then, -1.25%
Slope of northern PZs (from W – E)	+1.44%	Relatively flat	NA	-1.42%
Relative elevation of PZs (northern vs southern)	Southern PZs lower	Similar	Northern PZs lower	Northern PZs lower
Relative slope of PZs to the land surface	Slope of PZs similar or lower	Similar slopes	Slope of PZs similar or lower	Slope of PZs steeper

The north eastern part of the dunefield, drained by the Sand River System, has been the subject of much debate due to the destruction caused as a result of massive sediment flux initiated in this part of the dunefield on more than one occasion. The steep overall incline of this northern region means that the water table consistently operates close to a threshold slope (see Ellery *et al*. (2009) for a discussion of geomorphic thresholds in wetlands in South Africa), with debris flows a possible outcome of the threshold being exceeded.

Of significance to this study is the suggestion that debris flows only develop in landscapes with a slope of greater than 15% (Bonte *et al*., 2000). However, from an analysis of a few of the dunes in the north eastern region of the dunefield, it can be shown that local dune slopes are greater than 25%. It is also evident from many field trips that dunes, most likely due to the steep slopes, undergo processes of slumping related to gravitational forces and a need to maintain an equilibrium morphology. Luna *et al*. (2012) refer to the slumping of dunes as avalanches, stating that in instances where maximum water table heights are reached, one form of dune progression is through avalanches of the slip faces at places of instability. It is therefore likely that east of the crest of the dunefield, where dunes are moving down the slope, the presence of the groundwater table close to the land surface results in repeated 'aggregation – slumping' processes as shown in Figure 6-3 (based on theory from Luna *et al*., 2012).

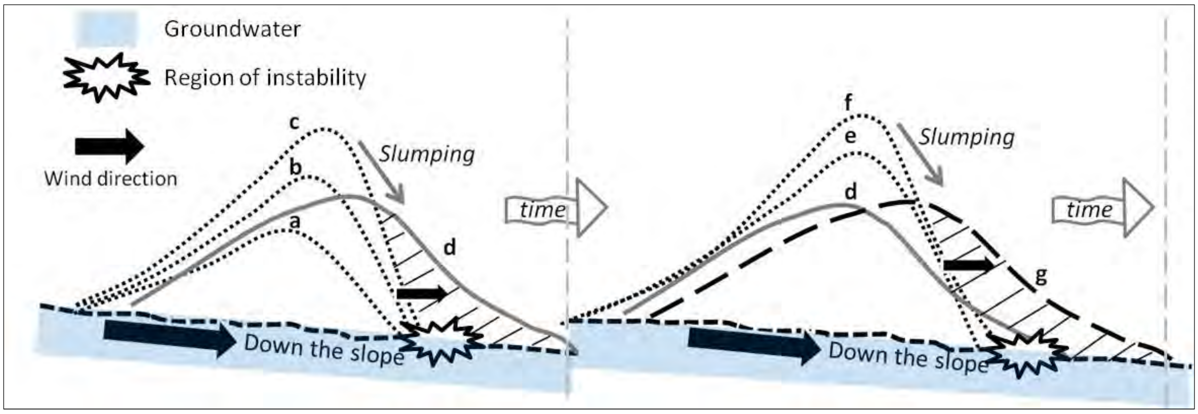


Figure 6-3: Slumping process that occurs in dunes as they move down the slope in the presence of a groundwater table that approximates the land surface. Alphabetical ordered letters indicate the stages in dune progression (aggregation and slumping) down the slope. **Source:** based on Luna *et al*. (2012).

6.3 OBJECTIVE 2 – MEASUREMENT OF THE RATES OF DUNE MOVEMENT AS A SURROGATE MEASURE OF SEDIMENT FLUX

Figure 6-4 summarises the results from Objective 2, showing rates of dune movement and sediment flux within the various delineated dune zones of the Oyster Bay HBD. The dominant dune form within the dunefield is the transverse dune and / or its variants (also shown in Burkinshaw, 1998). The dune crests lie perpendicular to the dominant wind direction and dune movement was measured along this axis (in the direction of the prevailing wind).

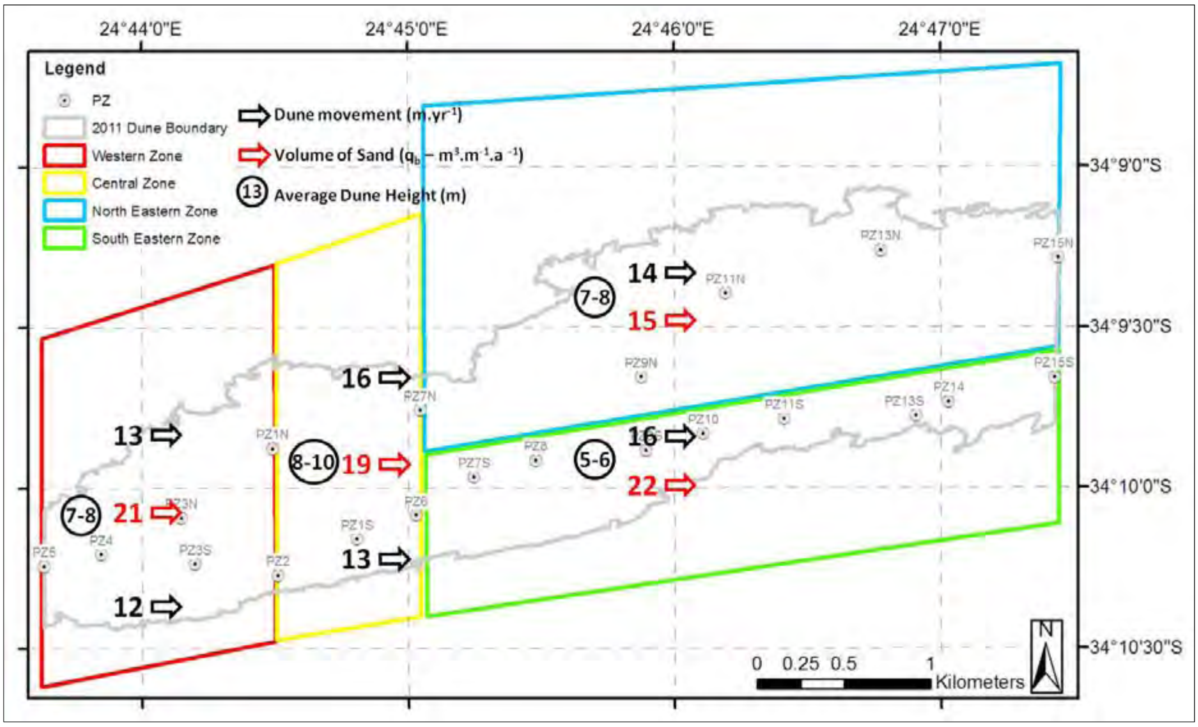


Figure 6-4: Average dune heights (2011), rates of dune movement and average bedform volumes of sand over the period 2000 - 2011 within the Oyster Bay HBD system.

6.3.1 Dune movement within the Oyster Bay HBD

Dune movement within the region under study within the Oyster Bay HBD differed within the various delineated zones with movement rates being slowest in the western region. Dune movement rates increased steadily in the southern region of the dunefield from 12 to 13 to 16 m.a^{-1} in the western, central and south eastern zones respectively. However, in the northern region of the Oyster Bay HBD, dune movement was highest in the central zone at 16 m.a^{-1} and declined from this to 14 m.a^{-1} in the eastern zone.

The reduction in dune movement in the north eastern zone may largely have been related to the ever-increasing expansion of vegetation in this part of the dunefield and the reduced effect of the dominant westerly winds in this part of the system due to the sheltering effect of the Peninsula Formation Ridge crossing the central region of the dunefield (Burkinshaw, 1998: 178). The north-eastern region of the mobile dunefield is fast becoming invaded and dominated by vegetation, which is likely to result in a reduction of sand throughput due to the fact that stable vegetation stabilises the substrate (Carter *et al*., 1990 and Arens, 2002).

The results of this dissertation were similar to those of Jiminez *et al*. (1999) in that the lowest dunes, in the northern part of the central zone and in the south eastern zone, were moving the quickest through the dunefield, at a rate of 16 m.a^{-1}. Burkinshaw (1998: 218) also found that dunes in the south eastern part moved faster than elsewhere in the dunefield, and ascribed this largely to decreasing dune height as one moves eastwards.

High dunes (up to 11 meters in height) in the southern central and western region of the dunefield generally moved fairly slowly at approximately 12 to 13 m.a^{-1}.

6.3.2 Sediment Flux

The sediment flux results show that the estimated transport volumes were greatest in the western zone. In this zone, high and wide uninterrupted transverse dunes transported approximately 11 100 m^3.a^{-1} up the western slope of the Oyster Bay HBD and onto the plateau of the central zone. Within the central zone, there was a slight reduction in the width of the dunefield and associated dunes and an increase in dune height, with the estimated total volume of sediment being transferred through this region of the dunefield estimated to be approximately 7 100 m^3.a^{-1}. It was in the eastern zones that the least amount of sediment was being transported by wind, despite the high rate of dune movement but lower dune height. The total sediment transport through the south-eastern region of the dunefield was estimated to be approximately 3 300 m^3.a^{-1}, while approximately 2 200 $m^3.a^{-1}$ was transported through the north-eastern region, which means that a total of approximately 5 500 $m^3.a^{-1}$ moved through the eastern zone as a whole.

Burkinshaw (1998: 95 – 99) found similar measurements to what has been shown in this research for dune heights within the delineated zones of the Oyster Bay HBD. However, of significance to the calculation of the volume of sand movement, was the width and spacing of the dunes in the various regions. Unlike in the research conducted by Burkinshaw (1998: 95), dune lengths almost never exceeded 500 meters in this research, with dune lengths equalling between 200 and 300 meters on average. Since 1998, dune lengths appear to have decreased in size thus resulting in a reduction in the calculated bedform factor, k, across the Oyster Bay HBD. The final bedform volume values calculated for each region of the dunefield were generally lower in comparison to those calculated by Burkinshaw (1998: 200). Where Burkinshaw (1998) calculated an average full year bedform volume of 34 $m^3.m^{-1}.a^{-1}$, in research for this dissertation the overall bedform volume for the Oyster Bay HBD was calculated to be approximately 21 $m^3.m^{-1}.a^{-1}$. The bedform volume found in the more current research was more in line with the average bedform volume figure calculated for the Alexandria Coastal Dunefield, located along the same coastline to the east of Port Elizabeth by Illenberger & Rust (1988: 514), who found the same overall bedform volume of 21 $m^3.m^{-1}.a^{-1}$.

6.3.2.1 The north eastern delineated dune zone and the Sand River system

As previously discussed, of significance to this research was the eastern region of the north eastern delineated zone of the Oyster Bay HBD, the region through which the Sand River flows. Sand from the Oyster Bay HBD system reaches St. Francis Bay and drains into the Krom River via the Sand River System. This river, as mentioned in the previous section, has been the centre of much discussion in the recent past due to occasional flooding of Sand River. The last time this occurred was in July 2011, when the bridge on the R330 passing over the Sand River collapsed (Figure 6-5), and as a result the region south of the Sand River was completely cut off.

Figure 6-5: Remains of the former bridge across the Sand River following flooding along the Sand River in July 2011.

Source of photograph: W.N. Ellery, 2011.

Table 6-2 shows the likely volume of sediment moved by wind for varying dune width scenarios. In this regard, using the previously calculated transport rate for this region of 15 $m^3.m^{-1}.a^{-1}$, the sediment flux through this region of the Oyster Bay HBD is estimated to be from 1 500 $m^3.a^{-1}$ using a dune width of 250 m to 3 264 $m^3.a^{-1}$ assuming a dune width of 400 meters.

Table 6-2: Potential volume of sand for varying dune width scenarios

Dune Width Scenarios	**Relative volume of sediment output ($m^3.a^{-1}$)**
250	1 538
325	1 778
400	3 264

Research conducted by Watermeyer *et al*. (1993, cited by Burkinshaw, 1998: 223) estimated that during periods of strong flow, the Sand River could deposit anything between 5 000 and 20 000 m^3 per flood in the Krom River estuary. The previous estimation is far lower than results from a topographic survey that was conducted, of the point where the Sand River enters the Krom River, immediately after the flood event of July 2011. The volume of sediment that was deposited by the Sand River in a large deltaic feature across the Krom River was estimated to have been in the region of 60 000 m^3 (W.N. Ellery, pers. comm., 2011; Figure 6-6).

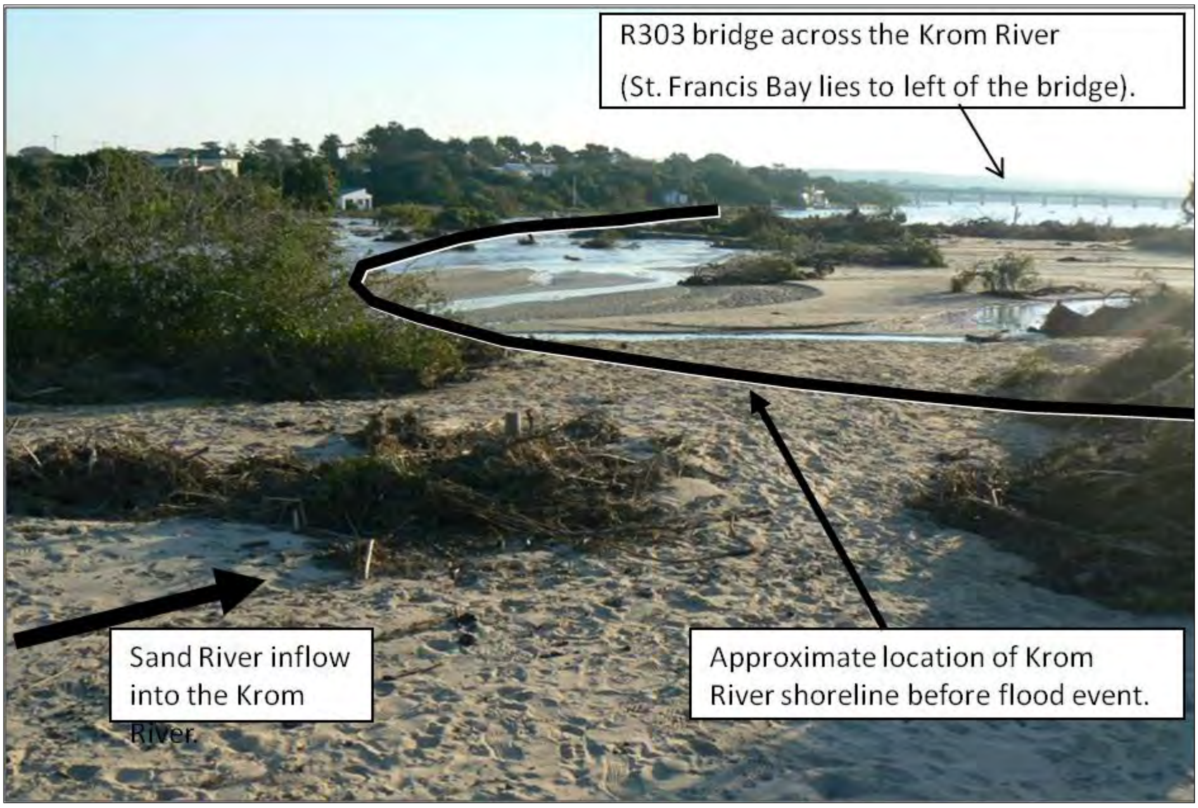


Figure 6-6: Deltaic deposit from the flood in July 2011 at the point where the Sand River enters the Krom River. From the apex of the feature the deposit extended radially into the Krom River a distance of approximately 70 m as determined using conventional dumpy level surveying techniques (W.N. Ellery, pers. comm., 2011).
Source of photograph: W.N. Ellery, 2011.

To conclude this section, the Oyster Bay HBD is still functioning in the sense that dunes are transgressing through the system, forming at angles perpendicular to the dominant westerly winds. Dune movement rates are in excess of 12 $m.a^{-1}$ across the dunefield and dune heights have remained almost unchanged between the studies conducted by Burkinshaw in 1998 and this research in 2011. Although sediment transport volumes have decreased slightly and vegetation has transgressed (specifically in the eastern delineated zones), the movement of sediment through the Oyster Bay HBD by wind is still substantial. However, a novel finding in this component of the study was that the movement of sediment by wind declines eastwards in the study area, which means that aggregation must be taking place in the region of the crest of the dunefield.

6.4 OBJECTIVE 3 – INVESTIGATION OF BIOPHYSICAL ATTRIBUTES AS INDICES OF NATURAL PROCESSES (VEGETATION, WATER AND SAND)

The following section will discuss various components of the Oyster Bay HBD and some of the drivers of change that were analysed in this research, including vegetation, water and sand.

6.4.1 Changes in the extent of vegetation cover in the Oyster Bay HBD

The artificial stabilisation of specific areas of the Oyster Bay HBD in the past was successful in the sense that it allowed for the development of the residential areas of the Santareme Village. However in respect of the Oyster Bay HBD from a coastal dunefield functioning perspective, the ‘success’ of stabilisation means that sand no longer bypasses the headland through the Oyster Bay HBD to nourish the downwind bay.

The results show that over the last 50 years, the Oyster Bay HBD has gone from having approximately seven percent vegetation cover to 38% cover in 50 years, with an annual average rate of change equalling 2.58% growth or an increase in cover by some 40 700 $m^2.a^{-1}$. Figure 6-7 summarises the distribution and extent of vegetation change that has occurred from 1961 to 2011.

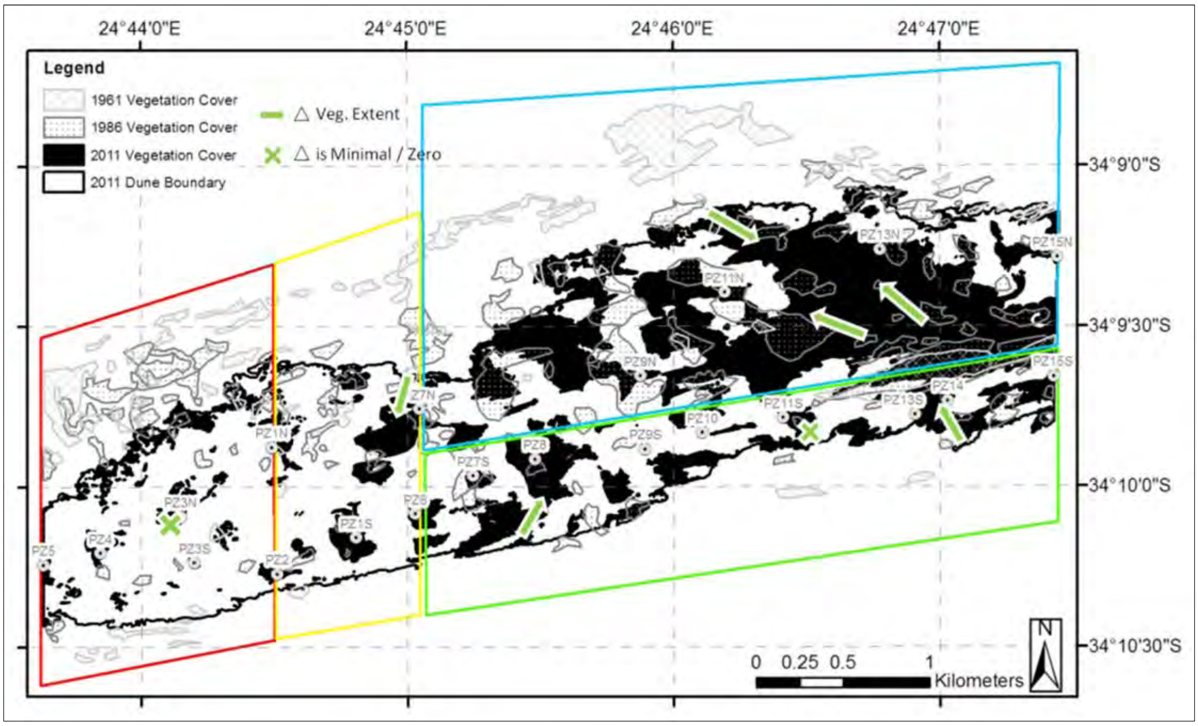


Figure 6-7: Change in vegetation cover as determined in 1961, 1986 and 2011.

It is clear that the eastern delineated zones of the Oyster Bay HBD, where most of the vegetative growth has occurred, has been undergoing a far more drastic process of change. Specifically, the north eastern part of the system went from having vegetation covering approximately 443 700 m^2 (21%) in 1961 to 1 921 400 m^2 of vegetation cover in 2011 (57%), equivalent to an average annual increase of approximately 29 500 m^2. The change in vegetation cover in the north eastern region in particular, has therefore accounted for 72% of the total change in vegetation cover for the dunefield over the period of analysis. For the same period (1961 – 2011) the south eastern zone increased from having eight percent to 34% of total vegetation cover.

With regards to dune movement rates over the last 11 years, the south eastern zone does not appear to have been affected by the increased vegetation cover as much as the north eastern section. This is likely to be related to the fact that the dunes in the south eastern zone are lower in height and therefore move quicker through the Oyster Bay HBD, limiting colonisation that in the same way is seen to have occurred in the dune slacks in the corresponding north eastern zone. This was supported by observations in the dunefield, where three (PZ 9S, PZ 10 and PZ 13S) of the eight piezometers set up in slacks within the south eastern section of the dunefield were covered by sand and / or an entire dune during the course of the field work.

If vegetation continues to spread at rates experienced over the past 50 years , one can estimate (based on current environmental settings or conditions not changing) that in 25 to 50 years the Oyster Bay HBD may become completely stabilised', in the sense that vegetation would dominate the system and limit the transverse movement of dunes. However, based on theories presented by Davidson-Arnott (2005: 1166) which were formed on theories by Bruun (1954 and 1962), one needs to base an analysis of change for planning exercises on a period of 100 years in the coastal zone as a reasonable goal for the development of integrated coastal zone management. Periods of dunefield regression may be followed by transgression depending on a range of factors, and it is impossible at this stage to be certain about the trajectory of change over time in the Oyster Bay HBD in respect of vegetation establishment and succession.

6.4.2 Water analysis

The role that water plays in the Oyster Bay HBD has not been investigated in detail in the past to fully understand its role, but the research undertaken for this dissertation does help to better understand its role. From the literature presented in this dissertation it has been shown that the Oyster Bay HBD can be defined as 'a wet aeolian system' as the water table is at or near the depositional surface (Kacurek & Havholm, 1993 cited by Burkinshaw, 1998: 243). It is understood that water has the ability to 'trap' sand and that it has the ability to move sand at mass in episodic events. It is also understood that the transport of sand in / by air or water differs due to the properties of water and air, specifically in terms of density and viscosity (Davidson-Arnott, 2010: 236). Water is denser than air and therefore sand is more buoyant in water than in air. As a result, less force is needed to move sand in water.

6.4.2.1 Electrical Conductivity and surface water / groundwater interactions

The elevation of the water table was typically less than one metre below the land surface at each piezometer point such that the piezometric surface consistently approximated the land surface. While there may be considerable local variation in the topography of the land surface due to the high hydraulic conductivity (porosity) of the material in the dunefield, the variation in the piezometric surface was not nearly as great as that on the land surface. This is predicted based on Darcy's Law (Ellery *et al.*, 2009). Given this, there is likely to be water flow away from the high lying ground in the central zone, which acts as a watershed for landscape-scale drainage (Burkinshaw, 1998: 23), which is towards the west in the western zone and towards the east in the eastern zone. The central zone therefore acts as the groundwater recharge zone for the western and eastern zones.

An analysis of EC within the Oyster Bay HBD further aids the understanding of groundwater behaviour relative to the central zone. Generally EC values increase down the piezometric surface due to weathering, which increases the solute concentration (Ellery *et al.*, 2009). The effect of local rainfall would be to dilute the groundwater solute concentration since rainfall contains very low solute loads.

In this study solute concentration of groundwater in the western zone decreased away from the central zone. In the central zone, the EC value of the groundwater marginally increased from west to east. In the eastern zone, the south eastern and north eastern zone showed slight differences. In the south east there was a general increase up to the Skurweburg Ridge, eastwards of which the EC decreased before gradually increasing again eastwards. In the north eastern zone, there was a systematic increase in the groundwater solute concentration with increasing distance away from the central zone. The western and eastern zones therefore generally exhibited contrasting groundwater EC behaviour away from the central zone.

The reason for the systematic increase in solute concentration eastwards from the central zone can be explained by the flow of groundwater eastwards from the crest of the dune system. This therefore suggests that the eastern zone was acting as an integrated groundwater flow system with limited effects from local rainfall. However, the decrease in solute concentration in the western zone with increasing distance from the central zone, suggests that groundwater recharge from local rainfall was far more important than simple unidirectional groundwater flow. In the central zone, there was seasonal variation in the groundwater solute concentrations that was consistent with rainfall in that during dry spells, groundwater EC increased, but during wet spells it decreased.

These differences in mechanisms of recharge are reflected in differences in geomorphic structure and processes in the eastern and western zones. In the western zone, transverse dunes with the greatest average lengths and smallest dune spacings were predominant. In the western zone, the large transverse dunes and small inter-dune spacings seemed to effectively trap rainwater that led to substantial amounts of groundwater recharge (Burkinshaw, 1998: 123), such that groundwater recharge from rainwater was enhanced. While in the eastern zone, this was not the case as dunes tended to be more barchanoidal in shape, with the largest dune spacing (W – E) having occurred in the north eastern delineated zone. Rainwater that fell in the eastern zone, specifically the north eastern zone, flowed down the slope into the Sand River, thereby reducing the degree of groundwater recharge from rainfall.

6.4.2.2 Surface water / groundwater interactions and dunefield functioning

These results hint at the fact that, overall, the western section is dominated by aeolian transport of sediment in the west to east direction, such that the structure and function in this region of the dunefield is dominated by wind. High, laterally extensive transverse dunes move steadily eastwards by aeolian transport of sediment. Surface water derived from rainfall is trapped in dune slacks between these long dunes, and recharges groundwater. Volumes of water in the dune slacks are never high enough to exceed the height of the dunes, reflecting the gradual loss of surface water to the atmosphere and groundwater recharge over long periods, ultimately with a likely loss of groundwater to the shoreline and ocean.

In contrast, in the eastern section where there is a reduced effect of westerly winds (Burkinshaw, 1998: 178), surface water following rainfall flows rapidly eastwards and reaches the Sand River via a network of streams, with limited recharge of the regional groundwater system because of runoff. It is therefore hypothesised that during periods of unusually heavy rainfall, there is sufficient water in the system to recharge regional groundwater, but this happens intermittently such that the groundwater EC reflects long-term groundwater flow.

The data from this research is consistent with the idea that wind transport of sediment is important and most dominant in the western part of the dunefield as far east as the central zone. Burkinshaw's (1998: 177) study on airflow down the length of the dunefield confirms that wind speed increases from the entrant point of the dunefield to at least the midpoint of the Oyster Bay HBD and that there is a decrease of westerly wind speed from the main body to the eastern region of the dunefield (Burkinshaw, 1998: 178). However, it is not possible in any landscape to accumulate sediment within a particular zone in the landscape without catastrophic effects because sedimentation leads to an increase in slope in a downstream direction (Ellery *et al.*, 2009), which translates in this context to a steepening of slope in a downwind direction. In the case of fluvial systems, the catastrophic event that results from sedimentation in localised zones in the landscape is a channel avulsion (Ellery *et al.*, 2003a and Ellery *et al.*, 2009). This principle is captured in the theory on geomorphic thresholds presented by Schumm (1979: 497), as described in the literature review. In Schumm (1979), it is clearly indicated that episodic events largely occur in response to an extrinsic variable pushing the system over a geomorphic threshold.

6.4.3 Sand grain analysis

The literature includes numerous theories on the movement of varying sized particles within different dune types. Pye (1983) argued that wind should typically remove finer, lighter grains from the beach resulting in positive skewness moving away from the sand source. However, Pye (1983) also showed that for parabolic dunes (such as those of the leading tongues in the Oyster Bay HBD), negative skewness is typical.

The results from this study showed that there was a slight overall increase in finer sediments (≤250 µm) and a slight decrease in the proportion of coarser sediment (≥350 µm) from west to east in the dunefield, however neither trend was statistically significant. This is in contrast to results presented by Burkinshaw (1998: 121) from samples collected in 1990 down the length of the Oyster Bay HBD, which showed that there was a slight coarsening of grain size from west to east in response to a relative reduction in the finer fractions downwind, the results were also not statistically significant. For both of these studies, the results are not conclusive enough to draw any decisive conclusions. However, an explanation for a decrease in the proportion of coarser fractions from west to east might be in the fact that since 1990, the amount of vegetation within the delineated region under study is now three times greater. In a study by Arens *et al*. (2002) it was shown that light grains of sand are lifted higher and fall slower than coarse grains of sand which inevitably end up becoming trapped by the vegetation.

Of interest to this part of the study are the results relating to the carbonate content of sediment from west to east in the Oyster Bay HBD (Burkinshaw, 1998). From her study it was shown that the sediment samples had varied carbonate content (17% - 41%) and that carbonate content decreased from west to east in the dunefield (Burkinshaw, 1998: 121). This suggests one of two things within the context of the Oyster Bay HBD: either the preferential abrasion of the carbonate grains, which are less hard than sand grains (Illenberger & Verhagen, 1990 cited by Burkinshaw, 1998: 123) or dissolution by rainwater or groundwater (Pye & Tsoar, 1990). The latter, dissolution by groundwater, is supported by variation in electrical conductivity values in the study area (discussed in the previous section). While an abrasion of grains may help to act as a 'lubricant' in the formation of debris flows in the absence of fine sediment particles in the Oyster Bay HBD.

6.5 OBJECTIVE 4 – DEVELOPMENT OF SUMMARY DIAGRAMS AND TABLES AND A CONCEPTUAL DIAGRAM OF DUNEFIELD STRUCTURE AND FUNCTION

Table 6-3 compares features already presented and discussed and forms a comparative summary table of key features, components and resultant processes highlighted in the discussion chapter. The most obvious differences lie between the western and north eastern zones of the Oyster Bay HBD (Table 6-3).

Table 6-3: Similar and / or contrasting factors and components within and drivers of change influencing the structure and functioning of the Oyster Bay HBD system.

Zones Factors	Western	Central	North Eastern	South Eastern
Unidirectional wind	Controlling effect	Controlling effect	Reduced effect	Moderate effect
Dune migration	12 – 13 m.a^{-1}	13 – 16 m.ar^{-1}	14 m.ar^{-1}	16 m.a^{-1}
Dune length (N – S) & morphology	Long , Transverse	Long, Transverse	Intermediate, Barchanoid to transverse	Short, Barchanoid to tranverse
Dune spacing	Close together	Close together	Wide apart (veg. between dunes)	Intermediate
Average dune height	8 m	9 m	7 m	6 m
Change in dunefield morphology (W – E), as indicated by PZ (water table) slope	N: +1.44% S: + 0.72%	Relatively flat	-1.42%	-1.19%
Change in dunefield morphology (N – S)	Slope downwards: -1.80%	Relatively flat	Slope upwards: +0.55%	Slope upwards: +1.01%
Change in dunefield extent (1961 -2011)	N: 594 m (11.9 m.a^{-1}) S: 136 m (2.7 m.a^{-1})	N: 542 m (10.8 m.a^{-1}) S:35 m (0.7 m.a^{-1})	NW: 501 m (10.0 m.a^{-1}) NE: 172 m (3.4 m.a^{-1})	SW: 35 m (0.7 m.a^{-1}) SE: 186 m (3.7 m.a^{-1})
Vegetation coverage (1975 -2011)	14 – 10%	17 – 20%	21 – 57%	8 – 34%
Groundwater recharge pattern	Continuous recharge from rainfall.	Continuous recharge from rainfall.	Episodic recharge from rainfall.	Episodic recharge from rainfall.
Change in EC down the slope	Decreases	Seasonal response	Increases	Increases

Figure 6-8 that follows is a conceptual diagram again highlighting the significant drivers of change, features and / or components, and processes occurring within the specific regions of the Oyster Bay HBD. The diagram completes the final objective of this dissertation. The discussion that follows draws on Table 6-3 and Figure 6-8 and the other significant results obtained from this research and infer some novel ideas on the structure and functioning of the Oyster Bay HBD.

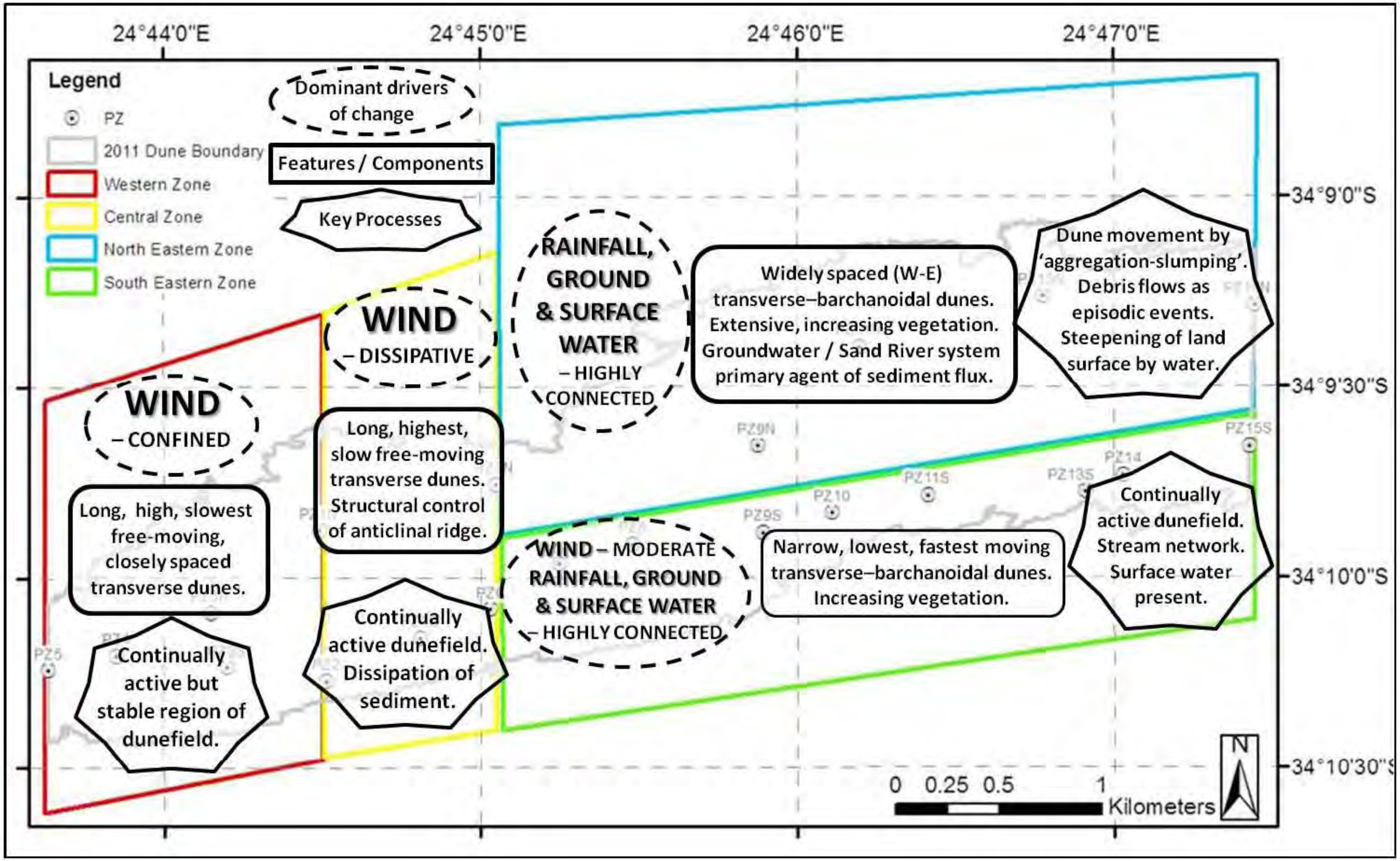


Figure 6-8: Conceptual diagram showing only dominant drivers of change, key features and / or components and relevant processes specific to each region of the dunefield.

6.5.1 Macro-scale variation in dunefield morphology

A feature of the macro-scale structure of the dunefield is the asymmetry in the slope of the dunefield across the crest, and the co-incidence of the greatest width of the dunefield with the region of greatest elevation. Much has been written about the role of geological structural control on the location of the crest of the dunefield and the zone of greatest width of the dunefield coinciding with the resistant lithology of the Peninsula Formation (Burkinshaw, 1998: 87).

The present study shows that the zone of greatest elevation and widening of the dunefield occurs to the west of the Skurweberg Formation – rocks of the Skurweberg Formation can be seen north and south of the Sand River and its tributaries, a considerable distance eastwards of the crest of the dunefield. Where these rocks outcrop, they are rounded and smooth, indicating that fluvial processes have influenced their characteristics where they occur on the surface. This suggestion is also confirmed in the geological map (Figure 6-9) where it is clear that the zone of greatest dunefield width coincides with the Goudini Formation, to the east of the Peninsula Formation and west of the Skurweberg Formation.

The Skurweberg Formation is coincident with a zone of dramatic narrowing of the dunefield, which may be consistent with the sudden change in the role of wind and water in sediment transfer. Fluvial processes, because of their ability to transport large amounts of sediment across the landscape, are likely to achieve sediment flux over a much narrower zone than is required by wind. This study suggests that the Skurweberg Formation exerts a much stronger influence on dunefield width than on landscape-scale dunefield elevation. In fact, this study suggests that it exerts very little control on dunefield elevation.

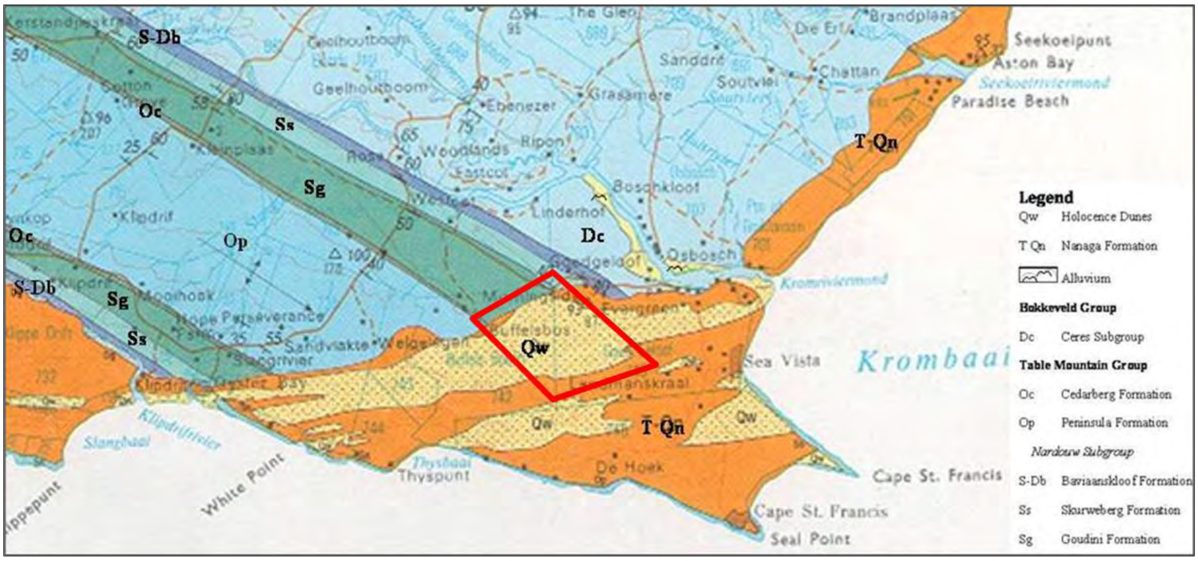


Figure 6-9: Geological map of the study area showing (polygon drawn) the co-incidence of the zone of the dunefield of greatest elevation and width coinciding with the Goudini Formation.

Source of figure: Geological Survey of South Africa (1991).

The factors that control overall (landscape scale) dunefield form seem rather to be related to interactions between wind and the elevation of the surrounding landscape, including sea level at the source area. Oyster Bay is the location of the sediment source, and once sediment is delivered from there to the dunefield, the dunefield is confined between clear sidewalls, particularly on the southern margin. The sidewalls afford a measure of confinement of the wind and are likely to affect wind power. As the height of the sidewalls gradually declines eastwards, wind power gradually spreads out and declines, resulting in gradual deposition of sediment eastwards. The zone of greatest relief is where the elevation of the dunefield coincides with the elevation of the surrounding land surface, at which point confinement of the wind in the dunefield is lost entirely. Wind therefore spreads laterally across the adjacent land surface to some degree at this point, and therefore causes widening of the dunefield. While there may be a measure of interaction between lithological controls and the elevation and width of the dunefield, results in this study suggest that the relationship between wind and the elevation of the surrounding landscape are probably as (if not more) important.

Having blown out across the adjacent land surface to some degree, wind east of the crest of the dunefield does not continue down the dunefield with the same power (as shown by Burkinshaw, 1998). Therefore, sediment is not transported as effectively by wind east of the crest.

Deposition of sediment by water or wind in a particular area in the landscape leads to steepening of the land surface downstream or downwind respectively, creating a measure of instability. Given the rainfall characteristics of the St Francis Bay area, water takes over as the main medium of sediment transport east of the crest of the dunefield. The Sand River is a dynamic and complex stream, with channels migrating and arising both within the dunefield and in the land to the north of the dunefield. Observations in this study suggest that streams also arise to the south of the dunefield, particularly during periods of high rainfall. These streams have variable discharges depending upon rainfall such that during and for hours to days following heavy rainfall, discharge is high. During periods of high flow, quantities of water and sediment that are transferred eastwards can be exceptional. For example, the quantity of sediment moved into the Krom River by the Sand River in July 2011 was estimated to be between 60 000 and 85 000 m^3 over a period of days (W.N. Ellery, pers. comm., 2011). When viewed in comparison to the Okavango River, which transports approximately 850 000 $m^3.a^{-1}$ (McCarthy & Ellery, 1998) into the Okavango Delta from a catchment of almost 200 000 km^2, the deposit by the Sand River system is relatively substantial.

The role that water plays as the primary agent of sediment flux east of the crest of the dunefield is probably what leads to the steepening of the slope (1.42%) beyond that of the surrounding land surface (1.04% then 1.25%) east of the crest of the dunefield. Measurements of the slope of the bed of the main part of the Sand River (east of the specific study area for this dissertation) consistently produce figures of approximately 1.15% (W.N. Ellery, pers. comm., 2011), which approximates very closely the slope east of the studied area of the dunefield. The coincidence of these slopes circumstantially supports the suggestion that water is the primary agent of sediment transport east of the crest of the dunefield, and that water is the primary agent shaping the landscape in this area.

6.5.2 Debris flows

The conditions under which debris flows are likely to occur (Bonte *et al.*, 2000) include:

- an unvegetated landscape,
- a steep slope (greater than 15%),
- an unconsolidated body of sediment, and
- the presence of fine sediment to act as a lubricant.

Despite large extents of the eastern parts of the dunefield becoming increasingly covered by vegetation in the extreme eastern section where the Sand River enters the dunefield system, there are still large areas that are unvegetated. Furthermore, in areas where there is vegetation, this vegetation is sparse herbaceous and shallow rooted, which provides little cohesion to soils or sediment to inhibit the occurrence of debris flows. Therefore, the conditions of large volumes of unconsolidated sediment and sparse vegetation cover are met in the present dunefield.

With regards to slope, although the average slope of the land surface is less than 1.5%, local slopes across individual dunes are as high as 50% (Figure 6-10). During heavy rainfall events dunes act as impoundments such that the slope on the water table across single dunes exceeds 25% (Figure 6-10). Given the unconsolidated nature of individual dunes, these conditions may increase the likelihood of a debris flow.

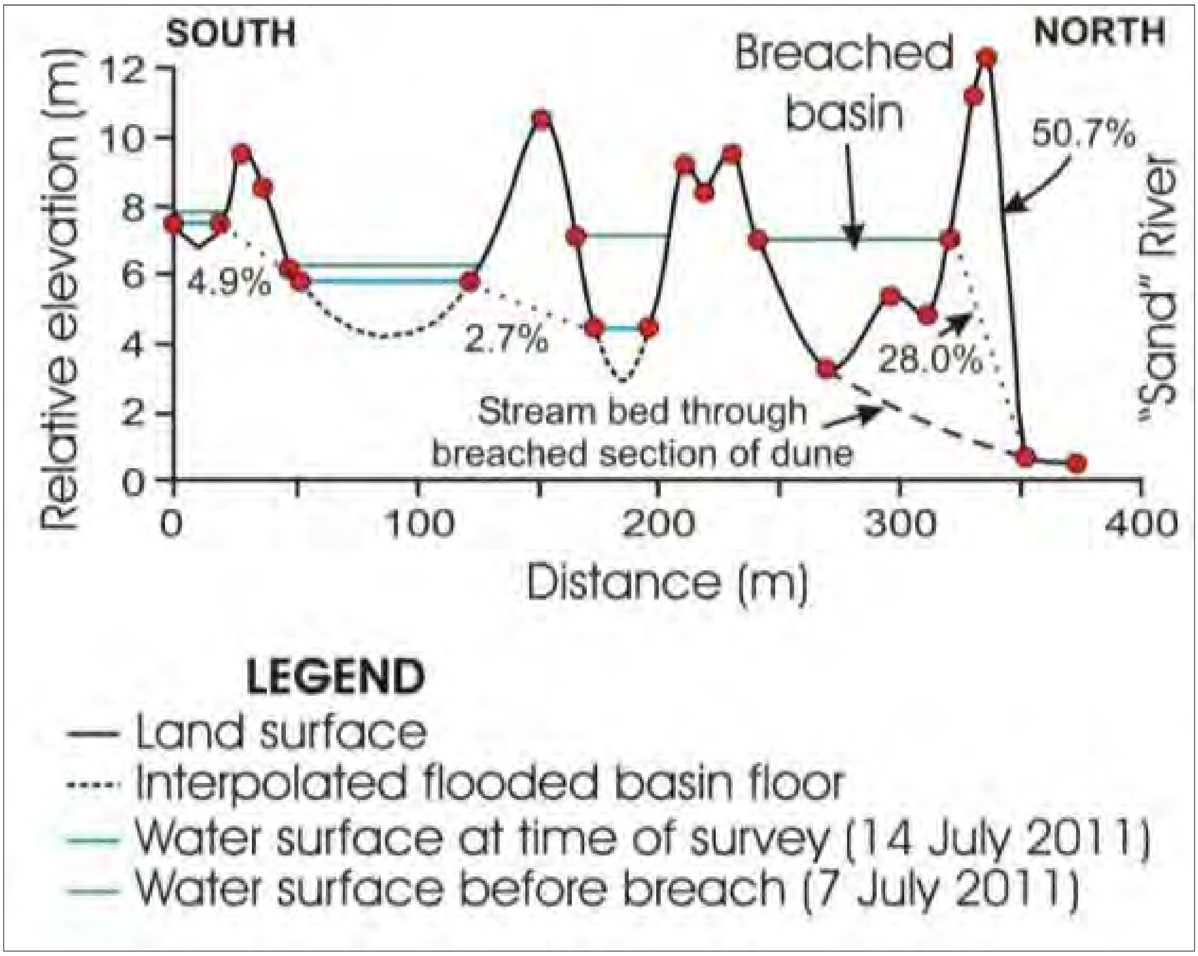


Figure 6-10: Cross-section across a dune that breached on 1 July 2011 following prolonged rainfall during the last week of June 2011.

Source of figure: Ellery & Elkington (2011)

Given the porous nature of the sandy material that constitutes the dunes themselves, the chances of creating a head of water with a slope on the water table of approximately 25% seems unlikely, given that the head of water that develops in a particular setting is dependent upon both the hydraulic properties of the outflow as well as the inflow. If a basin behind a single dune fills very rapidly, it is possible to create a head of this slope across the dune, creating instability of very short duration that may give rise to debris flows. Based upon this data set, it is clear that this happens occasionally during periods of heavy rainfall. Based upon the presence of debris flow deposits in the sedimentary record of the Sand River valley, it is suggested that these are the sorts of circumstances that are conducive to the occurrence of debris flows in the Sand River system.

The requirement that fine sediment is present to "lubricate" debris flows is difficult to demonstrate in the eastern region of the dunefield. It is possible that debris flows that develop under the circumstances described in this study (rapid filling behind a single narrow dune with a very steep slope on both the dune face and the water table, creating a massive head of water behind a singularly unconsolidated and unstable feature) do not require fine material in order for the sand to liquefy and produce a debris flow. It would be anticipated that under these circumstances, debris flows would rapidly dewater and therefore occur over a limited spatial extent.

A possible agent that may "lubricate" debris flows, which has not been recognised before, is the presence of dissolved solutes. Calcium carbonate in the form of shell fragments, readily dissolves under prolonged saturation (Burkinshaw, 1998: 121), and under conditions of capillary rise and evaporation, may increase to levels where the density of the remaining groundwater rises sufficiently to act as a lubricant. Individual measurements of groundwater electrical conductivity in this study suggest that locally, solute concentration may be sufficiently high to precipitate calcium carbonate from solution. Under these conditions calcium carbonate in solution may act a lubricant to sustain the more widespread occurrence of debris flows.

6.6 IMPLICATIONS FOR COASTAL ZONE PLANNING AND MANAGEMENT

It is important to now consider these findings and their associated implications in the context of current developments in the study area, environmental change associated with climate change and coastal zone management more generally. In terms of coastal zone management, it is essential to plan development in a manner that takes cognisance of environmental processes (Ellery *et al.*, 2003b) and to monitor coastal systems at a local level (Carboni *et al.*, 2009).

6.6.1 Changes in environmental conditions

HBDs are vital components of the coastal zone sediment budget, and interruption of their activity leads to erosion of downwind bays. Development of areas that interrupt sediment flux through these systems will have negative consequences on the shoreline of the downwind bay.

Of significance to dunefield initiation or maintenance is the availability of sand. Sand may become newly available in a few ways, including from pulses of beach sand due to processes acting in the nearshore zone, as a result of the reactivation of previously stabilised dunes, or from a combination of both (Pye, 1983 and Hesp & Thom, 1990, cited by Burkinshaw, 1998: 11). The above may occur as a result of changes in environmental factors, including increased fluvial supply to the coast, increased windiness, increased wave energy, or a change in sea-level. The main outcomes of global warming and climate change, which are currently being experienced across the globe, are changes in temperature, precipitation, intensity and frequency of storm events, and a relative rise in sea-level (Davidson-Arnott, 2010: 269). In South Africa, Mason *et al.* (1999) identified that the southern region of the Kouga Municipality falls into the category which has been experiencing an increased intensity in 10-year rainfall events since 1931.

The impacts of global warming will affect coastal dunefield systems in the following ways. Plant growth and density may potentially be impacted by changes in temperature and rainfall, both in foredune systems or further landward of the foredune system. The greatest impact however will most likely be sea-level rise (Thom, 1984 and Hesp, 2002). According to Davidson-Arnott (2010: 270), “on low-lying coasts characterised by sandy beaches and dune systems, simple inundation due to sea-level rise will produce a large displacement of the shoreline and wave erosion will result in further landward displacement”. A rise in sea level is thought to be associated with increased sediment transfer along the coastal zone, which will result in increased sediment supply to mobile dunefields. This should be anticipated and is likely to be associated with increased dunefield activity. In conjunction with the above, an increase in storm frequency and intensity will aggravate the occurrence of episodic events in the landscape, including mass movement events such as debris flows. Planners need to take note of these events and involve scientists in promoting wise planning.

In this light, predictions therefore made earlier in this study for the Oyster Bay HBD to become ‘stabilised’ within 50 years or so, which were based on environmental conditions remaining similar to that of the last 50 years, would need to be revisited taking into account the resultant increase in sediment input from marine sources that may slowly come about with time with rising sea levels and increased intensity and frequencies of storm events.

Urban development in sensitive environments will both affect and be affected by sediment flux across the headland. In this regard, infrastructure and humans will be increasingly negatively affected, particularly if they continue to ignore scientific understanding. Ultimately, in view of the uncertainty associated with global change, it is vital to adopt the precautionary principle in soft landscapes where the substratum is unconsolidated. Soft landscapes should be avoided as sites of hard interventions, particularly where these are massive and hazardous – such as the planned nuclear power facility planned for Thyspunt between Oyster Bay and St Francis Bay.

6.6.2 The Oyster Bay HBD’s impact on infrastructure and surrounding areas

Large volumes of water and sediment moving through and out of the Oyster Bay HBD system have caused much destruction in the past. This is specifically the case in the north eastern region of the Oyster Bay HBD, which has been shown to have a groundwater table located at or near the land surface. High rainfall events, which have resulted in the occurrence of floods and debris flows, have occurred as recently as 1992 (as noted by Burkinshaw, 1998), 2007 and 2011. The floods and debris flows have destroyed infrastructure, including the Sand River Bridge, on more than one occasion. Photographs included in Figure 6-11 show the devastation caused as a result of extreme rainfall events and the resultant flooding and mass movement of sediment out of the Oyster Bay HBD onto areas located to the east of the system.

Figure 6-11 (a, b & c): The destruction caused as a result of floods and/or debris flows largely related to extreme and intense rainfall events. **a:** massive flood event over Links Golf Course 2007, **b & c**: debris flows destroying the Sand River Bridge across the R303 in 2011.

In 2007, a massive volume of water and sediment moved across the prestigious Links Golf Course and homes in St Francis Bay in response to high rainfall over a period of up to a week (Figure 6-11a). In July of 2011, the bridge crossing the Sand River was demolished by the force of flooding and sediment transport (Figure 6-11b), leaving the towns south of the bridge completely isolated from the outside world. The region had experienced heavy rainfall over an extended period and flooding and sediment movement destroyed existing infrastructure. In the same month, further prolonged intense rainfall again resulted in the destruction of the temporary bridge of the R330 across the Sand River and the isolation of people to the south for the second time in a month (Figure 6-11c).

6.7 FUTURE RESEARCH

From this research it has been shown that the area of greatest significance to people within the surrounding area of the dunefield is the north eastern region of the Oyster Bay HBD and the associated Sand River system. In light of the numerous debris flows which have occurred within this part of the system and the destruction they have caused, a better understanding of this system is vital.

A more systematic investigation into the measurement of groundwater behaviour and response to rainfall in the north eastern region and down the course of the Sand River system needs to undertaken. The results from this dissertation only begin to touch on the very evident connectivity of the groundwater table in this region. A systematic investigation over time and over the area will improve the knowledge gained from this dissertation.

With similar intentions to the above, other suggested future research would be to conduct a coring exercise in the region of the Sand River system with the aim of better understanding the frequency, extent and distribution of debris flows in the past. Sedimentary cores will give a better reflection of debris flow events that have occurred in the past, including those that perhaps did not attract as much attention as those that occurred in 2007 and 2011. Coring in comparison to rainfall records and other environmental factors will help show the conditions under which debris flows have occurred in the past, and will also show their frequency, distribution and extent, and the variations in their magnitude over time.

A more comprehensive study on the variation in bedload sediment flux in relation to streamflow along the Sand River would shed important light on the role of streamflow in sediment flux on an on-going basis, as well as the processes that take place during large flood events. The study would need to be based on methods and theories presented on systems which undergo similar conditions (unidirectional winds, angle of slope of underlying morphology) to that occurring within the region of the Oyster Bay HBD.

Finally, a study modelling wind strength, direction and power given the high resolution of topographic data that is currently available, would enable confirmation of some of the suggestions made in this study about the relationship between wind, topography and aeolian sediment transport. It would therefore considerably improve our understanding of overall dunefield morphology, of the relationship between morphology and underlying lithologies, and of the likely role of factors other than wind in sediment flux.

6.8 CONCLUSION

The aim of this research was to investigate the morphology and dynamics of the Oyster Bay HBD system in order to improve our understanding of this type of system. Increasing human and environmental pressures on South Africa's coastal regions have led to changes in both the structure and functioning of natural systems in these regions, often resulting in degradation or decline (Attwood *et al.*, 2002). In the Eastern Cape of South Africa, the Cape St. Francis Headland and the functioning of its associated Headland Bypass Dune system has been impacted by infrastructural developments and alien vegetation invasion. Current management issues with regard to the Oyster Bay HBD exist in the eastern region of the dunefield, where the Sand River connects the dunefield system to the Krom River. Flooding of the Sand River and associated debris flows out of the Oyster Bay HBD have disrupted and destroyed infrastructure including houses, bridges and roads. This study has contributed to understanding the nature of some of the components of the system which influence this type of event.

While previous studies focussed on the role of wind as an agent of sediment movement, this study has demonstrated that water is also significant. It has highlighted a need for further quantitative studies that investigate the movement of sediment through dunefield systems, by both wind and water. The research has also highlighted the need to continue studying this system, in line with theories presented by Davidson-Arnott (2005) and Bruun (1954 and 1962), which state that in the coastal zone an analysis of change for planning exercises should be based on periods of 100 years or more as a reasonable goal, due to the dynamic nature of these systems.

The Oyster Bay HBD is the largest (specifically, the longest) functioning system of its type in South Africa and one of the largest in the world. Like most coastal systems, this system is a dynamic and ever-changing ‘process-response’ system (Chorley & Kennedy, 1971). Any management decisions made with regards to the Oyster Bay HBD and the associated Sand River system should take into consideration the spatial and temporal scales at which a range of processes are operating. Of equal importance is the scale at which the various components of the system respond to those processes and changes.

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