FOREDUNE FORMATION AT TUGELA RIVER MOUTH

by

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PREFACE

The research work described in this dissertation was carried out in the Department of Geography, University of Natal, Durban, from March 1992 to December 1998, under the supervision of Professor G.G. Garland.

This thesis represents original work by the author and has not been submitted in any form to another university. Where use was made of the work of others it has been duly acknowledged in the text.

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ABSTRACT

This study examines foredune evolution along a 2100 m section of coast adjacent to the Tugela River. The foredunes vary in both height and shape along the study area and form the southern most extension of the Tugela foredune-ridge plain. Sand accumulation and erosion was measured at regular intervals over a 30 month period by tacheometric surveys.

The foredunes and beaches are comprised of over 99 % sand. The sediment was predominantly composed of quartz and feldspar with subordinate lithic fragments. The quartz grains display conchoidal fractures and mechanical v-shaped pits and curved grooves. The beach and dune sand is well sorted and slightly negatively skewed with a mean grain size of 1.62 ϕ.

The vegetation structure and floristic composition of the foredunes are explored. A range of factors influencing foredune morphology and evolution, including canopy density, height and distribution, wind velocity and a variety of ecological and environmental processes are examined. Ridge and swale morphology as well as alongshore variation in the dunefield could not be related to biological processes.

The development of a foredune-ridge topography depends on a large sediment supply from the Tugela River over the long-term. Periods of high discharge introduce a fresh source of sediment to the littoral zone. Reworking of fluvial sediment landwards results in wide beaches. Onshore winds transport the sand from the beaches to the foredunes. *Scaevola thunbergii* encourages rapid vertical accretion and hummock dunes are formed. Lateral extensive invasion by seedlings may result in the hummock dunes joining to form coast parallel foredunes. Under periods of reduced sediment discharge erosion of the shoreline results in steep narrow beaches. Despite a negative beach budget foredunes continue to accrete vertically. Marine erosion results in either the complete destruction of embryo foredunes or their landward shift. Natural breaks in the dune crestline were attributed to changes in the delivery of sediment to the beaches. The processes operating in the study area conform to Psuty's (1988,1989) sediment budget model of foredune development. Sediment availability to the coastline produces characteristic morphologies.

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CHAPTER 1.

INTRODUCTION

1.1. BACKGROUND

Coastal dunes are among the most dynamic and complex geomorphic phenomena that form at the interface of the terrestrial, marine and atmospheric systems. Variations in inputs from the systems result in frequent form changes which are often difficult to quantify (Pye, 1983). Coastal dunes constitute a well-defined component of the sand transport system (Psuty, 1996). Dunes develop where there is a suitable sand supply and sufficient wind energy to transport the sand. Sandy beaches typically form the source of sand for coastal dunes.

Coastal sand dunes are ecologically complex environments consisting of a number of serially related communities which may accommodate endemic, rare and / or specialised plants and animals (van Teylingen *et al.*, 1993). Frontal dunes constitute an important component of the littoral active zone. Together with beaches they form a protective buffer and shield all landward resources and developments from the direct impact of marine and wind energy (Tinley, 1985). Coastal dunes are particularly susceptible to indiscriminate development with coastal cities and holiday resorts being located on ancient, stable dunes or stabilised active dunes. Mining activities have had deleterious effects on the biodiversity of dune ecosystems as well as altering the hydrological nature of the dune system. The recreational use of off-road vehicles in sand dunes is an additional factor resulting in vegetation destruction, accelerated erosion and faunal disturbances (van der Merwe, 1988).

Foredunes are particularly sensitive environments as they are fixed by sparse ephemeral vegetation. The sand trapped in dune systems build-up during calm periods where it is stored, only to be released under stormy erosive conditions (Strydom, 1992). In this way foredunes provide a protective barrier to secondary dunes under erosive conditions and are able to replenish the beaches at the same time.

The Department of Water Affairs and Forestry (DWAF) have proposed the construction of the Mvumase and Sunbury dams on the lower reaches of the Tugela River. This would trap almost 100% of the sediment, thus starving the estuary and adjacent coastline of sediment. While a report by the CSIR (1983) has evaluated the probable impact of dam construction on the Tugela estuary and adjacent coastline, it fails to monitor process and relate this to changes in form. Both the observation of form and the surveying of change can assist in questions related to coastal zone management (Cooke & Doornkamp, 1990).

1.2. AIMS AND OBJECTIVES

In order to properly assess the effect of impoundments of the lower Tugela River on the coastline, it is necessary to have a process-based understanding of the beach-dune system. The overall aim of this thesis is to investigate the morphodynamics of foredune development north of the Tugela River mouth.

The objectives of this study are:

(i) to determine the composition, texture and distribution of sediments on the dunes in the study area.
(ii) to examine the biological and geomorphological processes involved in the formation of foredunes.
(iii) establish the nature of dune vegetation-succession in the study area.
(iv) to assess the impact of episodic events on the coastline under study.
(v) to propose a model for the development of foredune-ridge topography.

The environmental setting of the study area is outlined. The sediment composition, texture and distribution on the beach is compared with that of the dunes. The vegetation structure and floristic composition of the foredunes is discussed. The study focuses on the relationship between the beach and foredune component of the total sediment budget. A model of coastal foredune development for the study area is proposed and compared to other models of foredune development.

1.3. STATUS OF PAST RESEARCH IN THE TUGELA DUNEFIELD AND ENVIRONS

Prior to the mid 1980's research on KwaZulu-Natal estuaries had been in the form of biological, ecological and environmental studies (Cooper, 1986). However, in 1985 a SANCOR-funded programme (the SEAL programme - Sedimentation in Estuaries And Lagoons) was initiated in order to examine a theory that the KwaZulu-Natal estuaries were experiencing increased rates of siltation due to catchment mismanagement (Heydorn, 1973a, b; Begg, 1978, Begg, 1984a,b ; Perry 1985a; Martin, 1987; Schumann, 1988). This resulted in a number of studies that have concentrated on the sedimentary dynamics of KwaZulu-Natal estuaries (Cooper, 1986; Grobbler, 1987; Wright, 1990; Cooper, 1991b; Callow, 1994; Pillay, 1996). One of the major estuaries in KwaZulu-Natal is the Tugela estuary, and although authors (Orme, 1974; Begg, 1978; CSIR, 1989, Cooper, 1991b) have discussed the estuaries and surrounds, little information on the composition, texture and distribution of sediments in the Tugela estuary or adjacent coastline exists.

Several studies on the regional assessment of shoreline changes (Tinley, 1985; Cooper, 1991c; Cooper, 1995), have been conducted. A cursory examination of the morphological changes in the Tugela River channel was undertaken by the CSIR (1990), and the study provides an historical account of the development of the estuary mouth.

Although sandy beaches backed by dunes constitute approximately 80 % of the South African coastline (McGwyne & McLachlan, 1992) there are very few studies that examine the morphology and the development of coastal foredunes. Tinley (1985) provides a descriptive overview of the ecology of South African coastal dune ecosystems. Details of some of the regional studies on vegetation-succession are described in Chapter 2.

CHAPTER 2.

LITERATURE REVIEW

2.1. FOREDUNES

2.1.1. Introduction

A review of the international literature on coastal dune taxonomy reveals two distinct definitions for foredunes (Illenberger, in prep.). According to Bird (1990), the major source of sand to the beaches and dunes of the European coast was derived from the sea floor with small amounts from fluvial and cliff erosion. Eustatic lowering of sea levels during the Pleistocene exposed large areas of the continental shelf bordering Europe. A variety of glacial, fluvial and sandy material was deposited on the emerging sea floor, where onshore winds transported some of this material landward (Fig. 2.1a). During the interstadials, marine transgressions shifted sandy sediment shoreward to form wide beaches, from which dunes were formed (Fig. 2.1b). Although large Pleistocene dune formations exist in the southern Mediterranean, most European coastal dunes formed during and after the last (Flandrian) marine transgression (Christainsen & Bowman, 1986; Bird, 1990; Wilson, 1990).

Researchers working on the European coast interpret foredunes as ephemeral features involving a constant exchange of sediment between the beach and the dune system. European coasts are composed of sand barriers that are presently shifting landward in response to the Holocene transgression (Bird, 1990; Illenberger, in prep).

Models of coastal foredune development proposed by Australian workers (Hesp, 1982, 1983; Short & Hesp, 1982; Pye, 1983; Short, 1988;) recognised a number of different foredune types. Hesp (1982, 1983) distinguishes between incipient and established foredunes (Fig. 2.2). Incipient foredunes, otherwise referred to as initial or embryo foredunes, develop through the

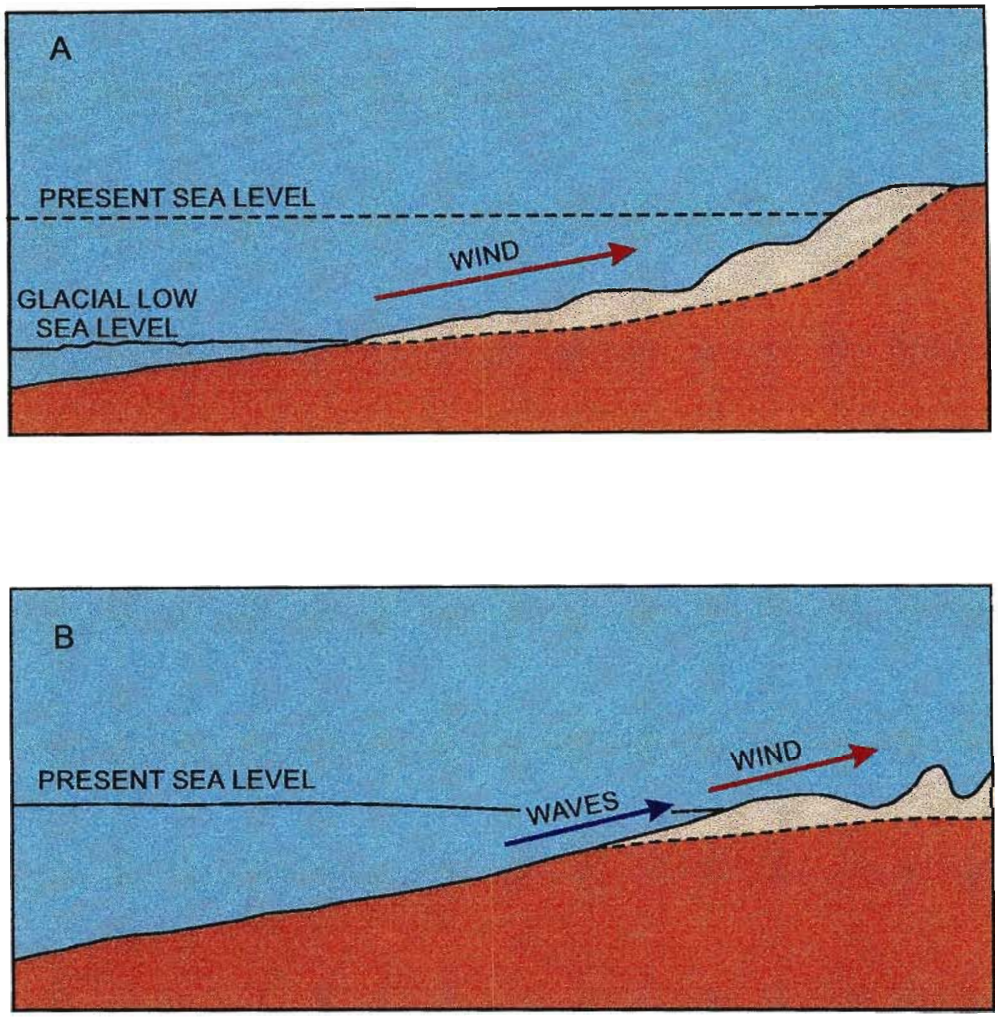


Figure 2.1 Sand movement from the sea floor to beaches and dunes (after Klijn, 1990).

A - during low sea level phases of the Pleistocene, when sand was winnowed from the emerged sea floor.

B - during and since the ensuing marine transgression, when sand was carried shoreward by wave action.

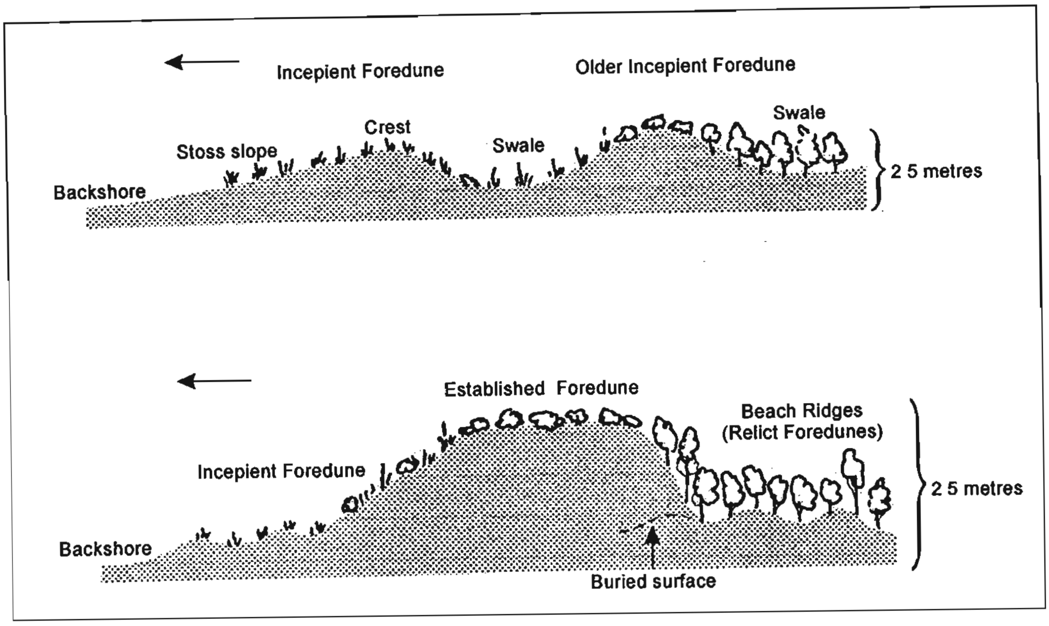


Figure 2.2 Terminology of foredunes as used by Hesp (1984).

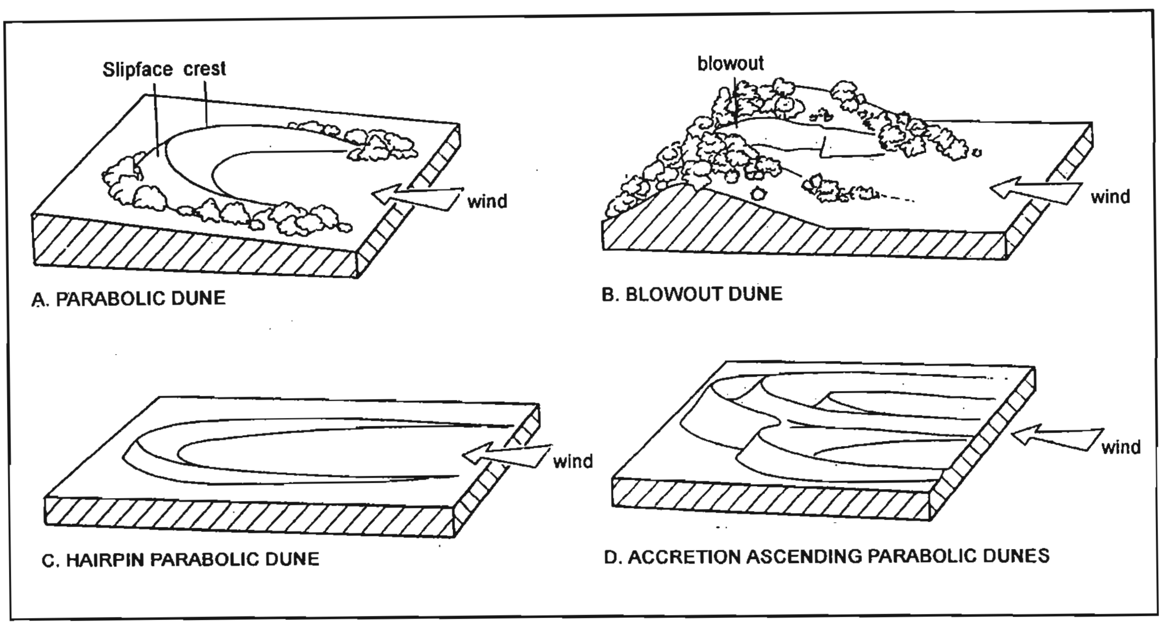


Figure 2.3 Parabolic dunes (Illenberger & Burkinshaw, 1996).

A) The parabolic dune shape arises from the interaction between wind-driven sand and vegetation.
B) As vegetation is destroyed on a retention ridge or foredune so a blowout is formed. This may develop into a parabolic dune due to continued deflation of sand.
C) Hairpin parabolic dunes form where there are strong uni-directional winds.
D) An accretion-ascending parabolic dune forms when a new parabolic dune over-rides vegetated parabolic dunes.

capture of sand by pioneer plants. Over time these dunes are colonised by an intermediate class of woody, mat or tufted plant species, usually following the formation of a new incipient foredune. Hesp (1982) regards established foredunes as more permanent features, typically colonised by shrubs and trees. The dunes of the Australian coast are much larger than those of the European coast; and have generally been more stable during the Holocene. Illenberger (pers comm.) suggests that in order to avoid confusion the Australian definition of foredunes should be abandoned in favour of the traditional definition, as intuitively foredunes have an incipient nature. Notwithstanding, Hesp's definition of foredunes has generally been accepted by coastal geomorphologists in both Europe and America. Furthermore it allows for the distinction between relict and new foredunes.

Illenberger (in prep.) advocates a morphodynamic definition in which foredunes are viewed as small shore-parallel dune ridges, seaward of the storm line, ephemeral and not exceeding 50 years in age. They are typically less than 5 m high and 20 m wide.

2.1.2. <u>Beach Ridge Topography</u>

Where a series of shore parallel foredunes forms plains these are traditionally known as beach ridges (Davies, 1957; Guilcher, 1958; Tanner & Strapor, 1971; Strapor, 1975, 1982; King, 1986; Nice, 1991; Anthony, 1995; Meldahl, 1995; Tanner, 1995; Thompson & Baedke, 1995). Hesp *et al.* (1989) refer to the dunes between the Tugela and Mtunzini as a relict foredune plain and notes that such dunefields are referred to as 'beach ridges' in Australian literature. However, Psuty (1992) makes a distinction between beach-ridge topography and foredune-ridge topography. Under conditions of rapid coastal accretion the morphological end unit is a beach-ridge landscape with low foredune ridges. Under moderate progradational rates, there is more time available to allow sediment accumulation in the foredunes, to form a foredune-ridge topography.

Tanner (1995) recognises four sandy beach ridge categories:

- Swash-built ridges are characterised by low angle cross-bedding, generally parallel, low-to-almost imperceptible, and occurring in sets (5-25 ridges) and/or systems (up to 250 or more ridges). Each swash-built beach ridge is a relict beach which is stranded by a younger beach formed seaward of it.
- Settling-lag ridges are similar in external appearance to the swash-build ridges, but display horizontal discontinuous bedding planes, with no cross-bedding, and are formed by the settling-lag mechanism as opposed to wave action (Tanner & Demirpolat, 1988).
- Storm-surge ridges are typically single isolated features, up to 10 m tall with concentric convex-up bedding.
- Dune ridges with internal cross-bedding, hummocky topography are characteristic of aeolian activity.

Cheniers are not included in Tanner's (1995) analysis of beach ridges. Cheniers should not be confused with beach ridges even though they are geomorphologically similar. Orvos & Price (1979: in Meldahl, 1995) note a distinct genetic difference. Cheniers are transgressive ridge-shaped features that consist of coarse beach deposits that progradationally overlie landward mudflat/marsh sediments, whereas beach ridges are ridge-formed coarse beach sediments that progradationally cover seaward shoreface deposits. Thus beach ridges and cheniers differ in their underlying lithology.

2.1.3. Origin of Beach Ridges

Until the 1980's many authors followed the work of Guilcher (1958) and Bird (1984) who suggested that old storm berms could account for the formation of beach ridges. Tanner (1995) regards this line of thought as erroneous in that repeated and frequent erosion associated with storm activity cannot account for long-term accretion, which is essential for the formation of a beach-ridge plain.

Tanner (1995) argues that the origin of beach ridges is not related to nearshore bars, as in many parts of the world there are no beach ridges adjacent to many such bars. Ruessink & Kroon (1994: in Tanner, 1995) noted that nearshore bars migrate seaward rather than landward. Tanner (1995) suggests that beach ridge spacing, period and accretion rates could be linked to El Niño- Southern Oscillation (ENSO) cycle at 3-7 years, or the sunspot cycle at 11.3 years, or the lunar nodal cycle at 18.6 years. However, this does not appear in all systems from around the world and shows that most beach ridges form in the range of 30-60 years and are associated with sea-level rise and fall couplets with an amplitude of 5-30 cm. Tanner (1995) concludes that dune ridges and storm-surge beach ridges do not occur in sets, and as such do not reveal much detail concerning their formation as in the case of swash-build ridges and settling lag ridges. An examination of the variables controlling foredune morphology could perhaps reveal a greater understanding of the evolution of foredune ridges.

According to Psuty (1996) beach ridges provide strong evidence for former shorelines and represent changes in the rate of sediment transfers in the dune system. The author suggests that the landscape provides strong evidence relating periods of dune accretion to episodes of sediment transfers into the system.

Davies (1958: in Psuty, 1996) examined a series of foredunes in Tasmania which decreased in height in a seaward direction. He concluded that the ridges evolved as sea level was declining and that the decreases in elevations for both the ridge crest and swales was related to sediment build-up on the emerging slope. Psuty (1996) argues that the differences in dune dimensions in the formation of a series of foredunes must be associated with sea level fluctuations or temporal changes in sediment inputs, as the relict foredunes are stranded inland at elevated altitudes.

2.1.4. Factors Influencing Foredune Morphology

A variety of factors have been identified as important in coastal dune formation: firstly, the availability of a distinct sediment source; secondly, marine transportation of sand towards the beach and the erosion of existing dunes; thirdly, sufficient wind energy and frequency to trigger sand mobility; and lastly, the influence of vegetation in trapping sand and encouraging dune growth (Klijn, 1990).

2.1.4.1. *Sediment dynamics*

Carter (1990) notes that nearly all Irish dune systems are presently receiving very little fresh sand, resulting in few progradational forms. Notwithstanding, sediment recycling occurs extensively and is directly related to the burial tolerance of the coastal vegetation. He divides the coastal dune geomorphology of Ireland into three categories, namely high, moderate and low sediment supply regions.

Where sediment input is high two basic forms occur: firstly an accumulative form, where the coastline accretes, and secondly a throughput form where sediment recycling dominates with very little change in the shoreline position. Carter (1990) reports that examples of accretionary forms have been recorded by Carter (1975) and Carter & Wilson (1990) at Magilligan in Co. Landonderry, by Shaw (1984) from Clonmass, Co. Donegal and by Harris (1974) from North Bull Island in Co. Dublin. In each case the dune system experienced rapid accretion broken by small phases of retreat.

A moderate sediment supply results in a transitional form where the vegetation is capable of absorbing additional inputs of aeolian sand as at Portrush (Carter, 1980). The shoreline is characterised by a large single dune ridge where foredunes are generally absent (Carter, 1990).

Many coastal dunes in Ireland have a lack of a suitable sediment supply. There systems, are often characterised by a gradual release of sediment through marine erosion or following vegetation loss. Blowouts in the shore parallel ridge allow for the inland channelling of sediment to form wide plumes. Sand-poor systems may also form a chaotic coastal topography, displaying neither the shore parallel manifestation of coastal dunes, or the wind-aligned forms associated with a mobile aeolian-driven environment (Carter, 1990). These findings suggest that the amount of sediment available to dune systems produce characteristic morphologies.

Klijn (1990) notes that the sea influences foredune formation in a number of ways. It determines the sand budget, encourages aeolian processes in beaches by maintaining bare surfaces and impacts weathering and vegetation growth with salt spray. The influence the sea has on the coastal sediment budget is by far the most conspicuous. Psuty (1996) claims that coastal foredune evolution is related to the sediment budget of the dune/beach system. He notes that there is a wealth of literature relating pulses of sediment to phases of dune building from many localities around the world, includes Ireland (Carter & Wilson, 1990), Scotland (Wal & McManus, 1993), China (Xitao *et al.*, 1991), United States (Orme, 1986), Australia (Hesp, 1989) and South Africa (Tinley, 1989).

The Alexandria dunefield is the best example of an accretionary sheet dunefield along the South African coastline. Illenberger (1986, 1988) claims that the dunefield developed in a series of sediment pulses, starting approximately 6500 years ago. He proposes that neotectonics is the principal factor influencing the availability of sediment to the nearshore environment. A 30 m high vegetated precipitation ridge that has formed on the landward margin of the dunefield represents the first pulse of sediment. Two further pulses of sediment have been identified in the form of megaridges. The Alexandria dune field has also experienced two episodes of stabilisation, recognised in the form of remnant tongues of vegetation extending across the dunefield.

The barrier islands off coastal New Jersey and coastal New York in the United States provide an additional perspective on the temporal and spatial changes in foredune evolution. Psuty (1996) notes that although it is difficult to separate the effects of neotectonics and climate change on the barrier island sediment budget, it is quite possible to equate certain features of barrier island formation to variations in sediment supply to the nearshore zone.

Psuty (1992) recognised that variations in spatial and temporal scales of foredune development produce a sequence of distinct developmental forms with characteristic morphologies. Implicit to spatial models of foredune sequence is the various combinations of dune and beach sediment budgets. Psuty (1992) notes that coastal foredunes persist and shift inland even in areas that experience continued beach erosion. This would suggest that foredune morphology may be conceptually separated from the budget of a beach. The optimum condition for foredune growth is a slightly negative beach budget where there is a continuous transport of sediment from the beach into the foredune. Therefore, the development of foredunes is dependent on the erosional character of the coastline.

Although sediment supply is generally acknowledged as essential to the development of a beach ridge plain its importance is often overlooked. Anthony (1995) notes that this especially the case where sediment supply is moderate, like the south Australian coast, where beach-ridge plains are supplemented by nearshore carbonate platforms, or in southwest Florida, where beach-ridges are influenced by changing sea-levels (Stapor, *et al.*, 1991). Examples of beach ridges associated with river supply of sand are scarce (Anthony, 1995) and have only been reported in relation to wave-dominated drift-aligned deltas (Psuty, 1966, Martin *et al.*, 1985, 1987; Wright, 1986). Psuty (1992) notes that variations in the beach and foredune sediment budget are influenced by the type of sediment system. Rivers introduce varying quantities of sediment to the alongshore component of a beach/dune budget and can result in spatial variations in foredune morphology. This will be explored in greater detail in Chapter 7.

2.1.4.2. *Wind regime and vegetation*

Hesp (1984) suggests that the variation in ridge and trough morphology has been ascribed to a variety of variables: rate of coastal accretion (Davies, 1957, 1980; Thom, 1965; Bird, 1976); changes in berm convexity (Davies, 1957); rate and volume of wave erosion (Wright, 1970; Bird, 1976); beach state (Wright, 1970; Short & Hesp, 1982); temporal factors, specifically the length of the time a foredune remains in the seaward most portion (Davies, 1957, 1974, 1980; Thom, 1965; Wright, 1970; Shephard, 1981); changes in local and regional wind velocity (Shepherd, 1970, 1981). Hesp (1984) contends that while these factors are important in producing changes in ridge and swale morphology, biologic processes and plant aerodynamics are recognised as the most important variables controlling initial morphologic variations in foredunes.

Hesp (1983) notes that near surface wind speed and plant canopy penetration decreases as plant density increases. It follows that near surface velocities are higher in regions of low plant density and declines in areas of high plant density. Saltating sand particles are trapped more rapidly and over shorter distances in high density plant canopies. Moreover, saltation decreases sharply downwind in dense canopies, while it may be sustained, to a degree, in low density canopies. As plant density and distribution alters in the dune succession and alongshore, these changes result in corresponding variations in dune morphology. Hesp (1983) asserts that foredune height is directly related to an increase in plant density accompanied with a decrease in dune basal width. Variations in the crest, stoss and lee slope morphologies are principally a result of changes in plant density and distribution.

Finnigan (1979: in Hesp, 1983) argues that variations in wind velocity effect changes in volume of sand transported. When wind velocity is increased over vegetation the canopy is penetrated more efficiently and shear stresses are an order of magnitude greater that under low wind speeds. Furthermore as wind velocities increase, the vegetation is flattened and roughness lengths are reduced (Sellers, 1965 ; Thom, 1971, 1972). Hesp (1983) postulates that as wind velocity increases, dune height decreases and basal width increases.

2.2. SOUTH AFRICAN COASTAL DUNES

2.2.1. Introduction

The South African coastline is approximately 3000 km in length and more than 80% of the shoreline is composed of sandy beaches backed by mobile or stable sand dunes (Tinley, 1985). Dune types around the South African coastline are quite diverse due to varying sand supply, vegetation growth and wind regime. Large well-vegetated retention ridges of up to 183m high have been formed along the north-east coast, where the tropical climate, moderate winds and adequate sand supply have enhanced dune growth. The southeast and southern coasts are characterized by a somewhat drier and colder climate, with moderate to strong winds. Types of dunes include foredunes, retention ridges, buttress dunes, parabolic systems, headland-bypass and transgressive dunefields. The west coast is marked by more arid conditions than the rest of the South African coastline, with wind speeds increasing as one moves northwards. Further north, the Namib sand sea extends for 500 km, with unvegetated active dunes of up to 300m in height. Although it is polygenetic, it is a partly transgressive coastal dunefield, supplemented by sediment from the downwind shore over the last few million years (Illenberger, *et al.*, in prep).

2.2.2. Dune Classification

Rust & Illenberger (1996) developed a morphodynamic classification of coastal dunes that is based on and evolved from previous dune taxonomies (Davies, 1972; Pye, 1983; Tinley, 1985, Bird, 1990). The term "morphodynamic" is defined as the interaction between process, or dune shape, sand availability, vegetation and wind regime. Rust & Illenberger (1996) classify coastal dunes into two morphodynamic types, namely retentive and transgressive (Fig. 2.2). Retentive systems comprise coastal dunes, where vegetation is recognised as the dominant process encouraging sand accumulation. This morphodynamic class includes foredunes, hummock dunes and retention ridges.

Retentive systems occur in areas that are protected from the dominant wind, or that have a low wind regime, or in places where the prevailing wind is offshore. Plant species associated with retentive systems are able to cope with small amounts of wind-blown sand. However, if the onshore wind component is too great the plants are inundated, destroying the retentive system, allowing for the development of a transgressive system (Illenberger *et al.*, in prep.).

In transgressive systems the rate of sand influx is too great for plants to establish a permanent existence, hence the dunes are unvegetated and mobile. Examples of transgressive systems include parabolic dunes, reverse transverse dunes, barchans, seif dunes, accretionary sheet dunefields and headland bypass dunefields. Illenberger (1998) notes that most trangressive systems contain vegetated, retentive elements; but only on a limited scale. Transgressive dune systems develop where strong alongshore or onshore winds predominate along a sandy coast. Buttress dunefields occur when winds prevail alongshore, with individual transverse dunes moving parallel to the coastline. When onshore winds are dominant across a long beach, an extensive transgressive dunefield develops contiguous to the beach. If the onshore winds have a limited sand source, a narrow corridor of dunes develop downwind of the source beach. Parabolic dunes characterise areas where the sand source is very narrow. Most of these dunes and dunefield types occur in the Algoa Bay region (Illenberger *et al.*, in prep.).

Illenberger (1998) asserts that the advantage of such a morphodynamic classification is that it can be modified to include continental dunes and desert areas. Furthermore, the classification of retentive and transgressive systems assists in the development of management strategies, as the two types of dune systems have contrasting physical sensitivities.

2.2.3. Dune Types of the Tugela Coastal Dunefield

2.2.3.1. *Hummock dunes*

Hummock dunes are rounded or oval vegetated mounds formed when dune plants trap sediment. They typically grow up to 3 m in height with diameters ranging from 1-8 m. (Illenberger & Burkinshaw, 1996). Under favourable conditions the embryo dunes are colonised by pioneer dune plants, like *Scaevoli thunbergii* and accrete to form isolated hummocks. These mounds eventually coalesce to form an intermittent pioneer foredune belt. Tinley (1985) refers to such forms as parallel beach ridge hummocks, where individual ridges are separated from the other by troughs forming a catena sequence, typical of the coastal sector between the Tugela and Mlalazi rivers. It is suggested that the driftline embryo dune type introduced by Tinley (1985) be subsumed into this category.

Illenberger & Burkinshaw (1996) assert that hummock dunes are temporary features that can be destroyed under severe storms or by plant dieback. Pioneer plants such as *Scaevoli thunbergii* can live for up to 25 years (Pammenter, *pers comm.*), thus under relatively stable conditions hummock dunes may be considerably older than was previously suggested by Tinley (1985).

2.2.3.2. *Foredunes*

Foredunes that are not backed by a retention ridge form only on prograding and transgressing coastlines. On rapidly accreting coasts there may be insufficient time to permit significant vertical growth of a foredune, before a new ridge system is formed by marine deposition. High foredunes are rarely found on eroding coasts (Pye, 1983). In the case of transgressing coasts there is a landward-moving barrier complex, like on the east coast of North America. Illenberger *et al.* (in prep.) argues that on stable coasts like South Africa and Australia, foredunes are generally backed by retention ridges as in the Tugela coastal dunefield.

2.2.3.3. *Retention ridges*

Retention ridges differ from foredunes in that they are more permanent features (100-1000 years) occurring above the stormline. They range from 10-100 m in height and are 30-300 m in width (Illenberger & Burkinshaw, 1996). Illenberger *et al.* (in prep.) warns against confusing retention ridges with precipitation ridges as in the case of Tinley (1985) and Strydom (1992). Although their morphodynamics are analogous, precipitation ridges migrate slowly landwards as well as accrete vertically, whereas retention ridges are characterised by vertical growth with very little landward movement.

Retention ridges share the same modal development with that of foredunes, where plants retain sand and accrete to form vegetated ridges. Illenberger *et al.* (in prep) proposes that their development is closely associated with eustatic changes in sea level and recent local sea-level history. On stable coasts, like South Africa and Australia, where sea level fluctuations have been minimal over the last 6500 years, retention ridges have attained heights of over 100 m.

2.2.3.4. *Parabolic dunes*

Parabolic dunes are u-shaped or upsiloidal dunes with elongate trailing arms anchored by vegetation (Hesp *et al.*, 1989). The leading edge is a concave mound and represents the mobile element, migrating slowly downwind. Although parabolic dunes may originate from several different causes they have one factor in common - the formation of an opening or gap in the plant cover. The destruction of vegetation may occur through undercutting and slumping of stabilised berms resulting in wind breaching, fire, footpaths and vehicle access routes. Illenberger & Burkinshaw (1996) recognised a number of different types of parabolic dunes, namely blowouts, hairpin and accretion-ascending (Fig. 2.3, refer pg. 6). The Tugela coastal dunefield is characterised by parabolics which have been stabilised and later re-activated.

2.3. DUNE VEGETATION SUCCESSION

Ecological succession has been defined as: 'the non-seasonal, directional continuous pattern of colonization and extinction on a site by species populations' (Began *et al.*, 1996). The classical concept of plant succession to climax was pioneered by Cowles (1899) and Clements (1916). The first studies of plant succession concentrated on the structural aspects of a community (Cowles, 1899, Cooper, 1939; in Hyeong-Tae & Kim, 1985). Lindeman (1942; in Hyeong-Tae & Kim, 1989) adopted a trophic dynamic approach and focused on the functional aspects of succession. The author provides a detailed account of energy accumulation and its transfer between trophic levels. The energetic concept of succession was further developed by ecosystem ecologists like Margalef (1963, 1968), Odum (1962, 1968, 1969), and Whittaker (1975). They examined general trends in community development and the changes in ecological attributes over time (Hyeong- Tae & Kim, 1989).

Hyeong-Tae & Kim (1985) note that succession has been classified by a number of authors into different categories: primary succession (Cooper, 1939; Crocker and Major, 1955; Crocker & Dickson, 1956, Taylor, 1956; Olson, 1958 a,b; Ishizuka, 1962; Kumler, 1969); secondary succession (Keever, 1950; Roux & Warren, 1963; Lee *et al.*, 1979; Peet & Christensen, 1980; Aweto, 1981a, b; Kang & Lee, 1982) and successional hypothesis (Vitousek & Reiners, 1975; van der Valk, 1981). Vegetation succession has also been studied in relation to the formation of soil (Crocker & Dickson, 1956; Olson, 1958a,b, Willis *et al.*, 1959; Ishizuka, 1962; Ranwell, 1960, 1972, Kumler, 1969; Hewett, 1970; Walker *et al.*, 1983; Smith *et al.*, 1985; Sacheti & Scott, 1986).

Several studies have been conducted in South Africa describing vegetation succession on coastal dunes (Donnely & Pammenter, 1982, Lubke, 1983; Tinley, 1985; Esler & Moll, 1986; van Daalen *et al.*, 1986; Lubke & Avis, 1988; Camp & Weisser, 1991; Mentis & Ellery, 1994;

Hertling, 1997). The prograding dunes at Mtunzini on the KwaZulu-Natal coast, provide a good example of a successional pathway, and have been the topic of much research (Weisser, 1978; Weisser & Marques, 1979; Weisser *et al.*, 1982; Weisser & Backer, 1983; Weisser & Müller, 1983; Avis, 1992, Todd, 1994). Weisser *et al.*, (1982) found that the changes in dune vegetation could be related to the chronology of dune formation. Avis (1992: in Lubke *et al.*, 1997) reports that *Scaevola plumieri* establishes itself on the drift line, and encourages the formation of hummock dunes. The hummock dunes coalesce to form parallel foredune ridges. The second dune ridge is characterized by a number of herbaceous species, grasses and some shrubs. Avis (1992) recorded eight communities along a gradient increasing in complexity landward from: pioneer, enriched pioneer, open dune scrub, closed dune scrub, bushclumps, bushclump/forest margin transition, forest margin and forest.

Daines (1991) notes that succession does not necessarily occur once plants become established on the foredunes. Along eroding coastlines there may be phases of erosion and deposition of sand where pioneer communities are destroyed and reestablished to maintain a state of dynamic equilibrium (Lubke *et al,* 1997). Tinley (1985) claims that succession is a multi-directional response to erosion, accretion and secondary disturbances.

[illegible] affects succession.

CHAPTER 3.

STUDY AREA

3.1. LOCALITY

The study area extends for 2 km north of the Tugela River mouth (29° 13' 26" S; 31° 30' 7" E), on the KwaZulu-Natal coast (Fig. 3.1). This area has been identified as one of only two accreting sections on the entire South African coastline (Tinley, 1985).

3.2. COASTAL CHARACTERISTICS

3.2.1. Morphology and Hydrodynamics of the Continental Shelf

The east coast of southern Africa was formed through a process of rift faulting. The present configuration of the coastline was completed by the end of the Cretaceous (Dardis & Grindley, 1992). The features of the continental shelf and margin were controlled by the type of rifting, terrestrial and marine sediment supply, drainage network, sediment loading and subsidence together with currents, chemistry and sea-level of the Indian Ocean (Martin & Flemming, 1988). Along the KwaZulu-Natal coast the shelf break occurs at a depth of 100m, where a steep continental shelf drops to over 1000 m. North of 28° 30'S and south of 30° 20'S, the shelf narrows to 3 km and the continental shelf is steep (Fig. 3.2). However, between 28° 30'S and 30° 20'S, the shelf widens to a maximum of 40 km off the Tugela River and the continental shelf slopes more gently (Table 3.1).

The broader shelf area is known as the Tugela Cone, a triangular shaped plateau stretching 220 km south-east of the Tugela River (Goodlad, 1986: in Martin & Flemming, 1988). The Tugela Cone has a varied topography comprising terraces, hummocks, peaks, valleys and scarps, and is incised by two large canyons - the Tugela canyon and a further at 29° 30' S.

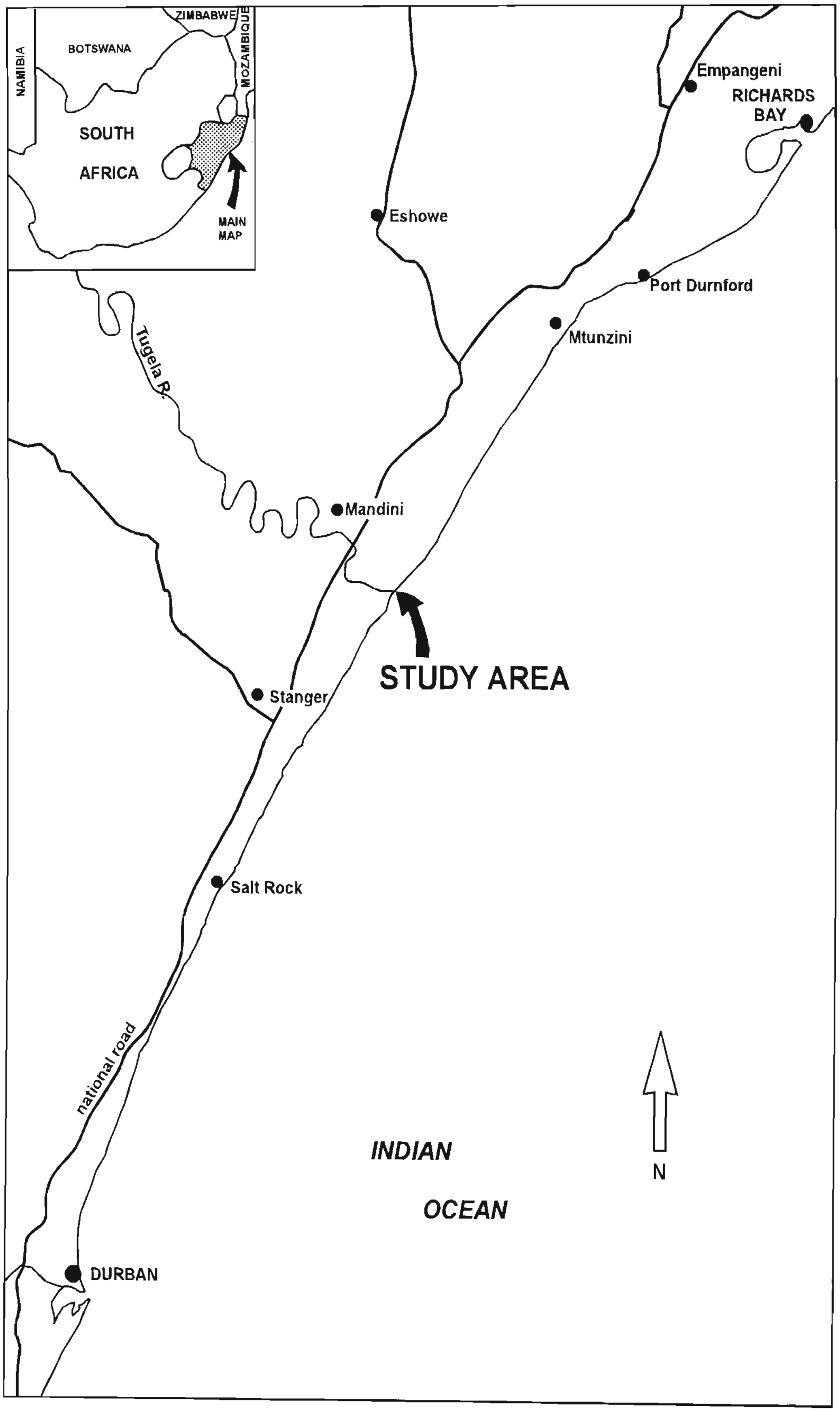


Figure 3.1 Location of the study area.

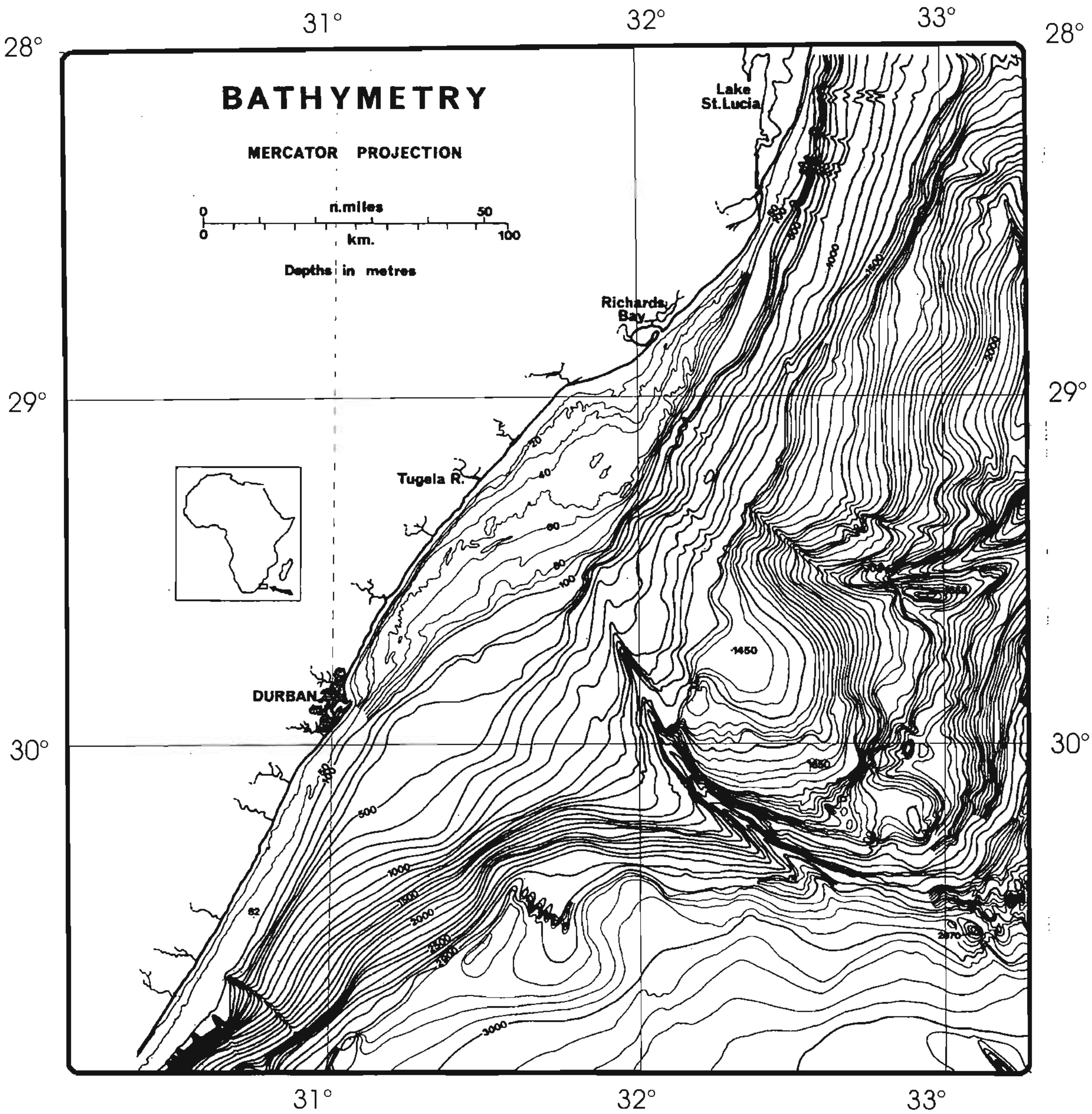


Figure 3.2: Bathymetry of the continental shelf off KwaZulu-Natal (modified after Goodland,1986).

Table 3.1 Bathymetric data of the continental margin for KwaZulu-Natal north coast (modified after Martin & Flemming, 1988).

CONTINENTAL SHELF				CONTINENTAL SLOPE	
Area	Width (km)	Shelf Break Depth (m)	Maximum Relief (m)	Average Slope	Maximum Slope
North of 28°30'S	2-7	45-112	800-1500	1:21 (2.9°)	1:10 (5.7°)
28°30'S-30°20'S	Up to 45	100-112	2400-2900	1:60 (1°)	1:17 (3.37°)
South of 30°20'S	10	80-90	2900	1:14 (4.1°)	1:35 (16°)
World Average	74	132	Av. 4000	1:13 (4.3°)	

Morphologically, the continental shelf can be divided into an inner and outer zone. The two zones are separated by a drowned and partially reworked Pleistocene aeolianite ridge, that runs sub-parallel to the coastline at depths of 40-60 m (Flemming, 1981). The ridge is not continuous, and crests of 5-20 m relief are typical north of 29° 30' S. Moir (1975: in Felhaber, 1985) suggests that the sediment ridge forms part of a southward extension of the Zululand coastal plain barrier lagoon system that existed in the Pleistocene.

The core of Agulhas Current flows along the shelf break on the KwaZulu-Natal coast (Felhaber, 1985). Surface current velocities have been measured exceeding 2 ms^{-1}, while surface velocities of 0.55 ms^{-1}, decreasing to 0.34 ms^{-1} at 4 m above the seabed in water depths of between 25 and 40 m, yield an estimated shear velocity of 23 mms^{-1} (Schumann, 1986: in Martin & Flemming, 1986). Multiple cyclonic eddies have been observed in the lee of structural offsets (Fig. 3.3), and these in turn induce north flowing counter currents landward of the mainstream of the Agulhas Current (Schumann, 1982). Duncan (1970) and Pearce (1977) calculated that these return flow currents include the whole water column, reaching maximum surface velocities of >1 m/s.

3.2.2. Sediment Distribution on the Continental Shelf

Flemming & Hay (1988) identified a number of potential sediment sources to the continental shelf: fluvial discharge, coastal and shallow marine erosion, aeolian transport, biogenic production and *in situ* authigenic mineral formation at the sea-floor. Flemming (1981) claims that aeolian input and authigenic mineralization as possible sources of input are small. Fluvial

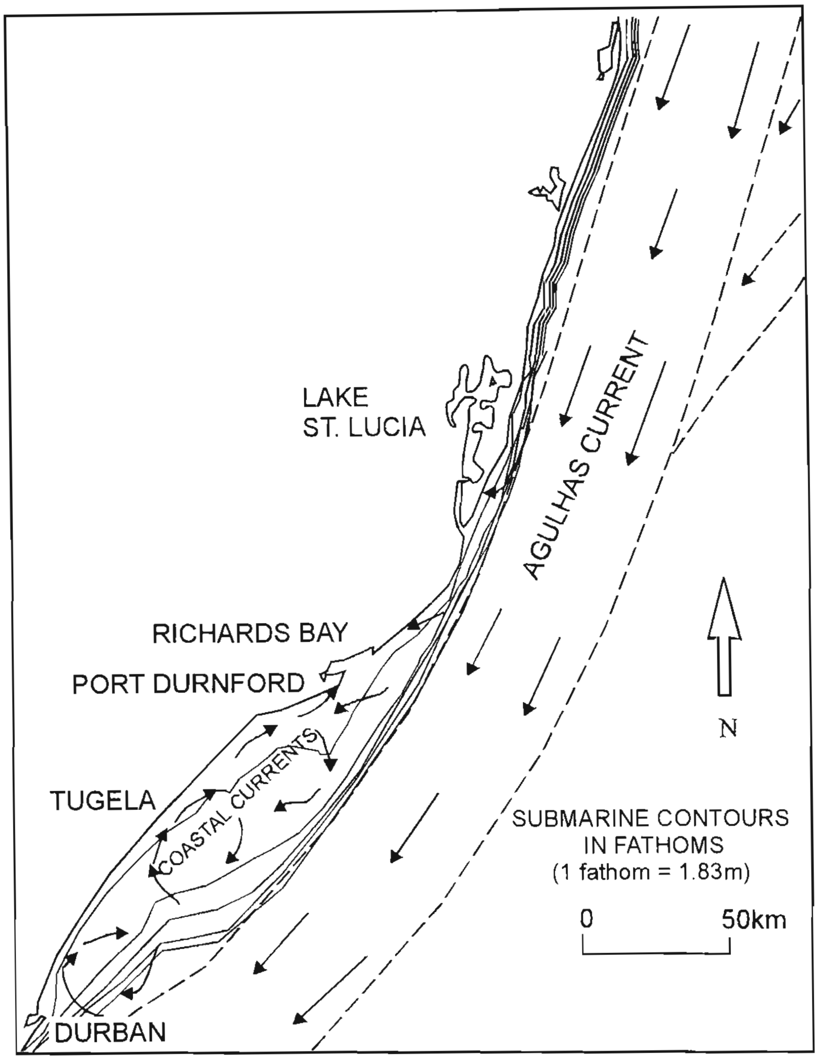


Figure 3.3 Currents off the KwaZulu-Natal north coast (after Orme, 1973).

discharge and biogenic input are recognised as the most important short-term sources of sediment to the continental shelf (Flemming, 1981; Flemming & Hay, 1988).

Dingle & Scrutton (1974) calculated the annual sediment yield from the Tugela River as 62 x 10^6 m^3 yr^{-1}. However, Nicholson (1983) estimated that the annual volumetric sediment discharge is in the order of 5.1 to 6.3 x 10^6 m^3, which is similar to the values obtained by Goodlad (1986) of 5.9 x 10^6 m^3 and Flemming & Hay (1983) of 5.6 x 10^6 m^3.

Felhaber (1985) conducted a detailed study on the sedimentology and mineralogy of the shelf sediments off the Tugela river (3.4 a,b). The study revealed that the gravel, very coarse sand, coarse and medium sand are concentrated on the mid-shelf region around the relict aeolian ridge (Fig. 3.5 a-d). Lower concentrations occur on the outer shelf along the shelf break. Felhaber (1986) argues that since there exists a high correlation between the submerged cordon and the course sediments, eddy dynamics could be closely linked to sediment dispersal in the area.

The fine and very fine sand is found on the inner-shelf, north of the Tugela River mouth (Fig. 3.6 a,b). A further two areas of high concentration are found on the mid-shelf and on the outer-shelf. Large areas of mud deposition are located near the fine sand (Fig. 3.6c). The inner mud depocentre is linked to suspended sediment discharged by the Tugela river, while the mid- to outer-shelf region consists of course relict sediment (Felhaber, 1985).

3.2.3. Coastal Morphology

The coast under consideration has been classified by Cooper (1991b) as a prograding beachridge coast. He postulates that the flat low-lying area to the north of the Tugela River, represents a former extension of the Amatikulu Lagoon over 5000 years ago, when sea level was approximately 2 m above present levels. It follows that beach ridges on the modern coast have developed since that time and originated as a result of a minor regression of the sea to present levels.

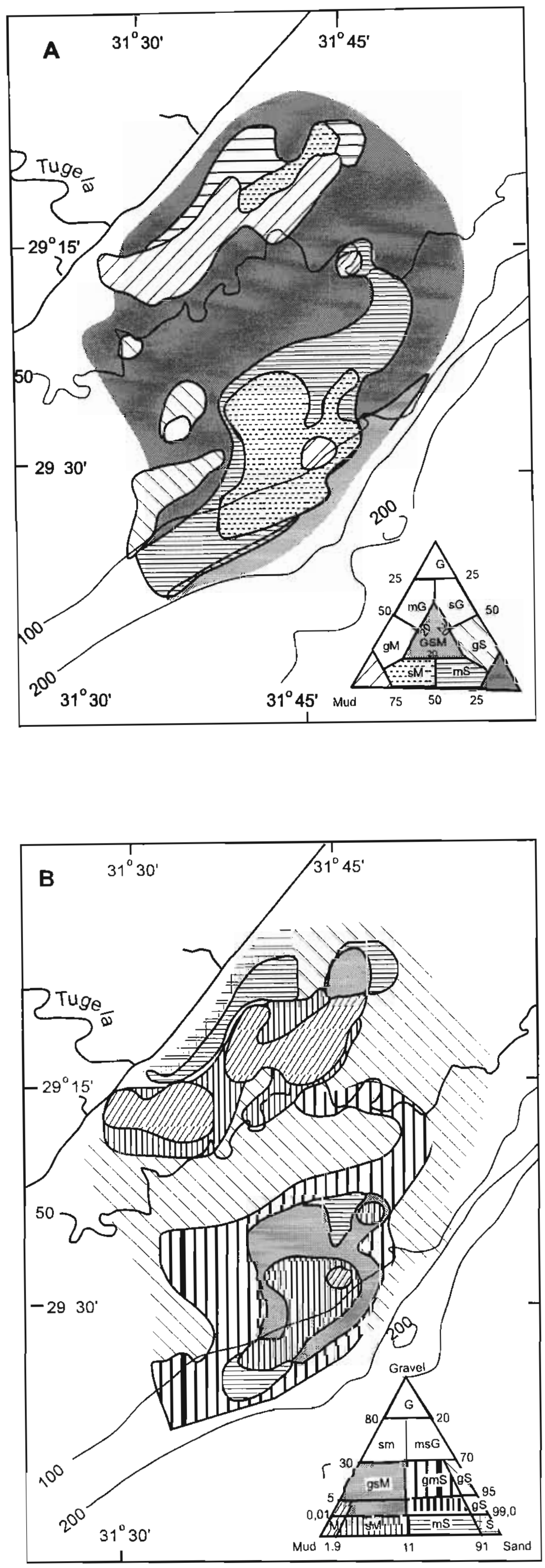


Figure 3.4 Textural composition of sediments off the Tugela River Mouth: (A) according to Shepard (1954); (B) according to Folk (1954) (after Felhaber,1986).

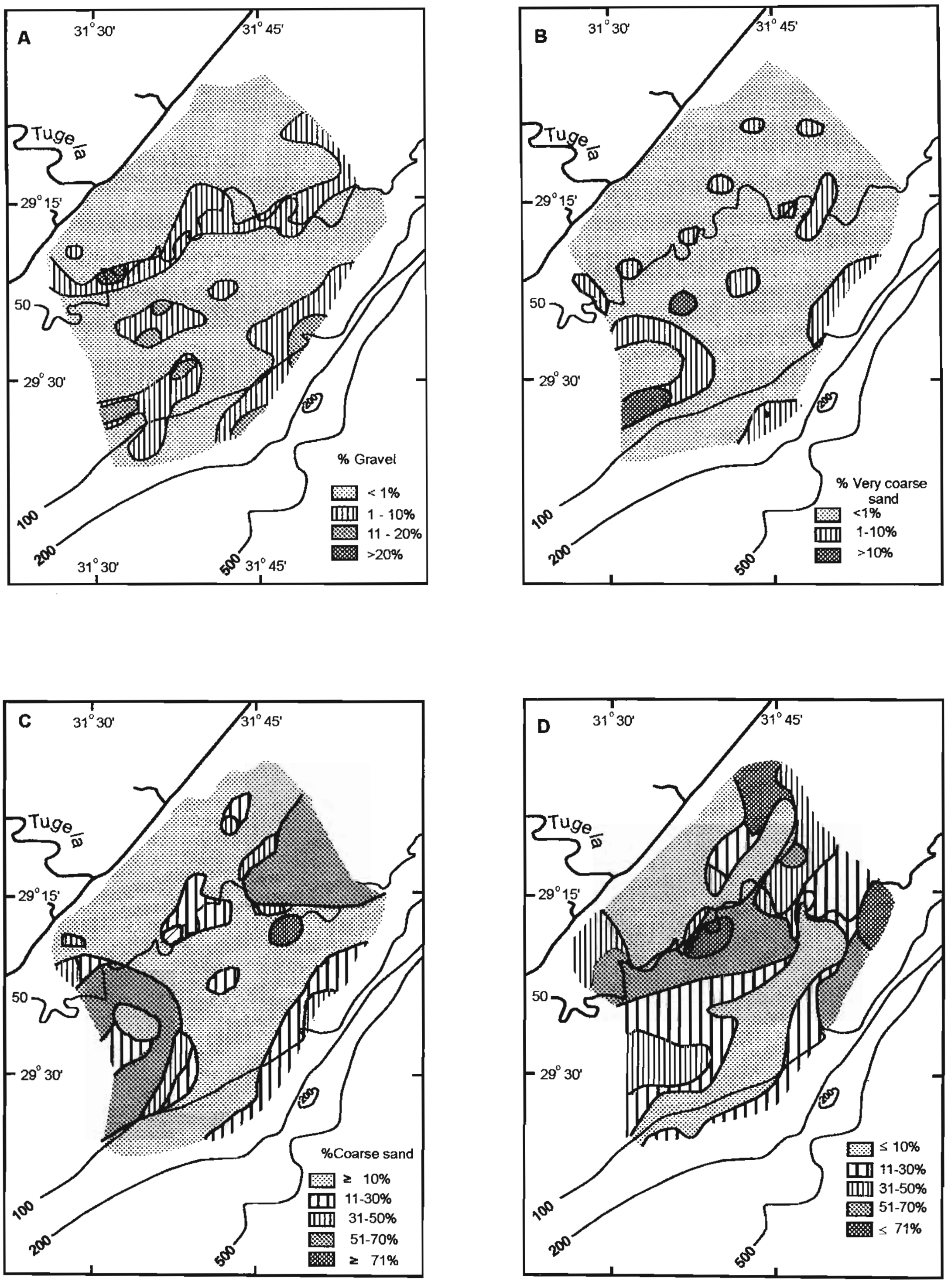


Figure 3.5: Distribution of: (A)gravel; (B) very coarse sand; (C) coarse sand; (D) medium sand, off the Tugela River mouth (after Felhaber, 1986).

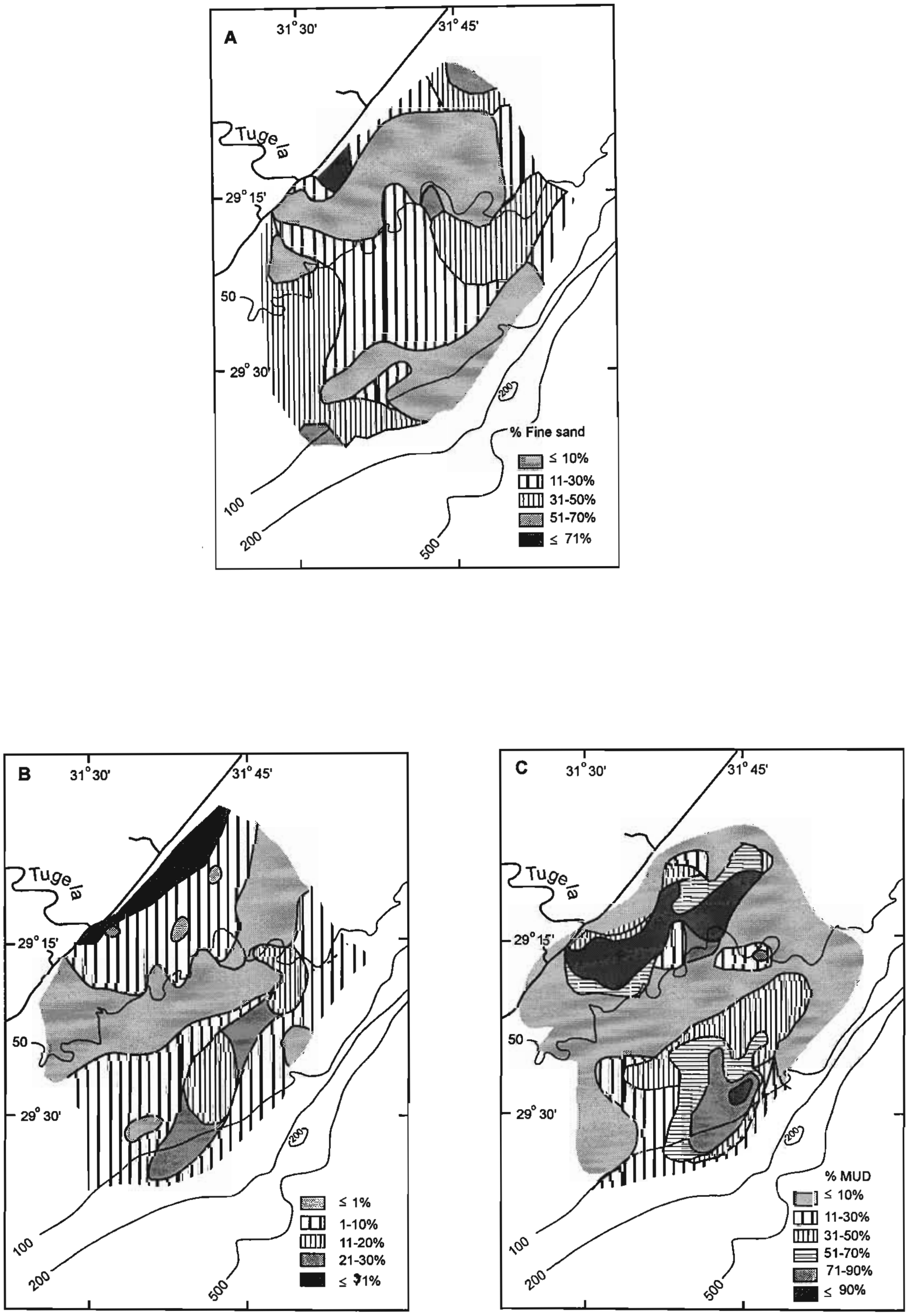


Figure 3.6 Distribution of: (A) fine sand; (B) very fine sand; (C) mud, off the Tugela River Mouth (after Felhaber, 1986).

A large beach is situated to the south of the Tugela River mouth, and is backed by a stabilised vegetated dune that forms part of a river mouth barrier. South of the Tugela River mouth, beaches are narrow and backed by an almost continuous densely vegetated coastal dune. The morphology of the coast to the south of the Tugela River is irregular, and controlled by bedrock outcrops (Cooper, 1991d).

The northern bank of the Tugela River mouth is fixed by a rocky promontory. To the north of the Tugela River the shoreline is that of a linear sandy coastline, interrupted by the mouths of the Amatikulu/Nyoni, Siyai and Mlalazi rivers (Fig. 3.7). Calculations of coastal orientation for linear sections of the coast between marked points of inflexion are given in Table 3.2. The beaches in the study area average less than 80m in width and are backed by a series of low (average height 5 m) beach ridges, aligned parallel to the coastline (Cooper, 1991c). Within a belt of approximately 1 km, between 7 to 16 phytogenic dune ridges may be found, displaying a spatial and temporal succession of coastal strand and dune scrub plants, culminating in coastal dune forest on the innermost ridges (Orme, 1974).

Generally, a negative correlation exists between stream discharge and the distance over which estuaries have been diverted by littoral drift, but this relationship weakens with increasing distance from the Tugela. The Nyoni river, with a catchment area of 114 km^2 (Begg, 1978) is diverted for 10 km NE into the Amatikulu which, owing to the greater discharge from its larger catchment of 850 km^2, is only deflected for a further 4.5 km (Orme, 1974). During floods, the

Table 3.2 Measurements of coastal orientation for the study area (modified after Cooper, 1991c).

Coastal Sector	Orientation (°E of N)
Tugela River mouth - Siyai	42°
Siyai to Mlalazi mouth	68°
Mlalazi to Richard's Bay sanctuary	71°

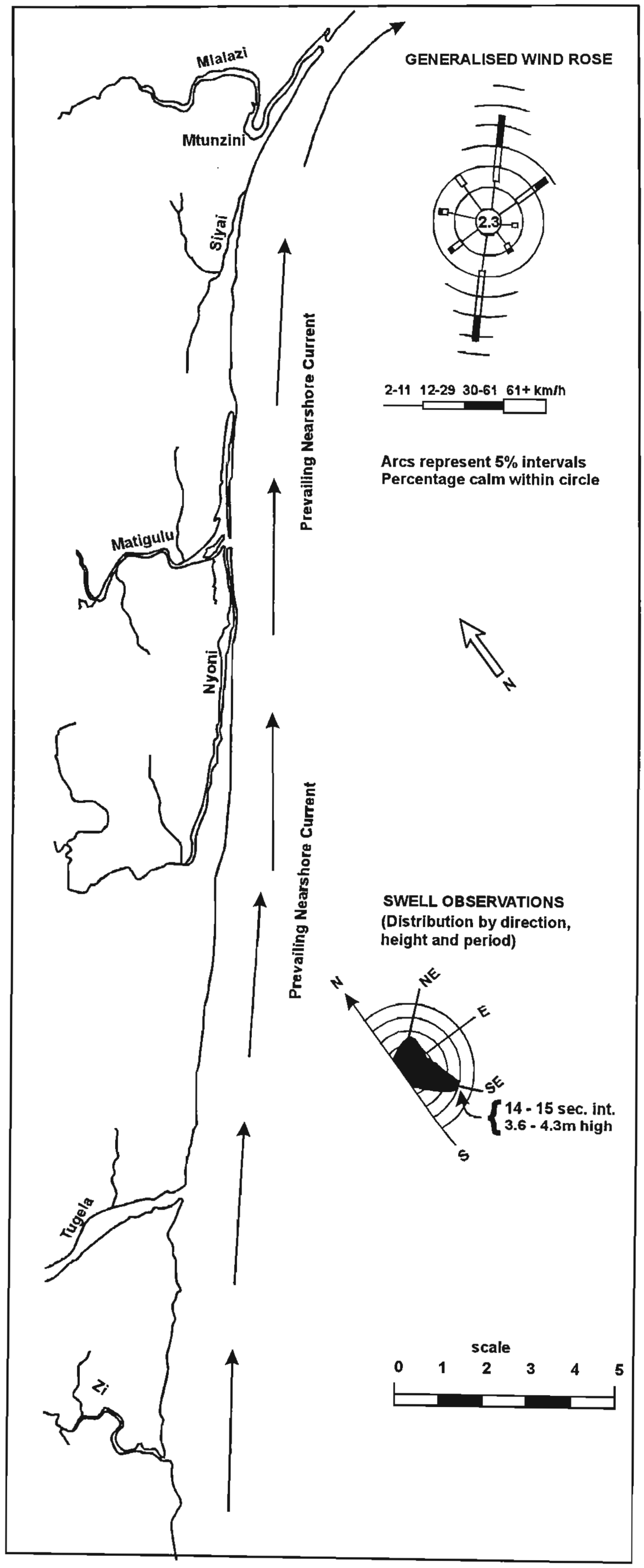


Figure 3.7 Coastal configuration (after Begg,1984).

Amatikulu may breach the single unstable barrier at the diversion point. To the north of the Amatikulu River the coastal beach ridges are backed by an area of low-lying land 200 m wide. This in turn is backed by a cliff line partly buried in blown sand (Cooper, 1991c). The small Siyai is diverted NE for 2.5 km, while the larger (420 km^2) Mlalazi catchment is diverted ENE for 3.5 km. Sedimentation in these estuaries behind the beach barriers is minimal. A small lagoon along the lower reaches of the Mlalazi has been infilled with sediments, enhanced by mangrove and reedswamp encroachment (Orme, 1974). North of the Mlalazi the coast consists of a narrow beach, backed by a cliff cut into dunes of the Port Durnford Formation (Hobday & Orme, 1974).

3.2.4 Shoreline Changes between Tugela River Mouth and Amatikulu Lagoon Since 1937

Analysis of aerial photographs from 1937- 1991, reveal a long term accretion along the whole section of this coastline with maximum net averaged rates of accretion in excess of 5 myr^{-1}, 5-8 km north of the Tugela River mouth (Cooper, 1991c). However, it should be noted that small net retreats have been recorded indicated by short term fluctuations related to episodic events such as storms and floods. Cooper (1991c) notes that in most cases the standard deviations of shoreline migration are significant, indicating a major influence of episodic events.

The 3 km stretch to the south of the Amatikulu river has experienced rapid short term alterations, as a result of mouth migration, and a large influx of sediment during river floods. The area to the north of the Amatikulu lagoon has displayed continued erosion since before 1937 and is probably related to the morphology of the coastline, as in this area the coast is slightly convex, consequently wave action is focused in this region (Cooper, 1991c).

3.2.5 Coastal Hydrodynamics

3.2.5.1. *Tides*

Tides on the KwaZulu-Natal coast are semi-diurnal. Expected tidal elevations for Richard's Bay, the nearest recording station to the study area, are presented in Table 3.3 The mean spring tidal range is 1.80 m and the mean neap tidal range is 0.52 m (Cooper, 1991b). The coastline can be classified as intermediate between microtidal and low mesotidal types (Davies, 1964; Hayes, 1975, 1979). The highest and lowest astronomical tides are respectively, the highest and lowest values that can be forecast to occur under average meteorological conditions and under any combination of astronomical situations. However, De Cueves (1986: in Cooper, 1991b) warns that a notable deviation from the predicted level (up to 0.35 m) may develop, because of low pressure systems travelling along the coast.

TABLE 3.3 Predicted tidal elevations for Richard's Bay (South African Navy Tide Tables, 1988, after Cooper, 1991b). LAT = lowest astronomical tide; MLWS = mean low water springs; MLWN = mean low water neaps; ML = mean level; MHWN = mean high water neaps; MHWS = mean high water springs; HAT = highest astronomical tide.

LAT	MLWS	MLWN	ML	MHWN	MHWS	HAT
-0.11	0.19	0.83	1.09	1.35	1.99	2.37

3.2.5.2. *Wind roses and wind energy*

Martin & Flemming (1986: in Cooper, 1991b) note that the coastal winds in KwaZulu-Natal are cognate to alternate dominance of cyclonic frontal and anticyclonic high pressure systems. An investigation of the wind data at Cape St Lucia (Hydraulics Research Unit (HRU), 1968) reveals that the dominant wind is from the SW, with a subordinate peak in frequency from the NNE. Additional wind data from Ballito (CSIR, unpublished data: in Cooper, 1991d) shows that the dominant winds blow shore parallel from with NE and SW with almost equal distribution. Average speeds are given as 40 km/hr (11.1 ms^{-1}) with recorded maximum speeds of over 60 km/hr (16 ms^{-1}).

The closest stations recording the coastal wind regime to the Tugela River mouth are located at Richards Bay (28°47'S; 32°01'E) and Shaka's Kraal (29°27'S; 31°12E). Both these stations are operated by the South African Weather Bureau, where wind direction and speed are recorded on an hourly basis. The anemometers are located 10 m above ground level and are situated 7.5 m amsl for Richards bay and 53 m amsl for Shakas Kraal. The Richards Bay data is considered the most reliable, as although the station is located 2 km inland it occurs on a coastal plain with minimal frictional elements when compared to the Shakas Kraal station which is 57 m amsl and located on side of a hill covered by sugar cane.

A comparison of the wind rose data between the two stations reveals that there is a greater amount of calms at Shakas Kraal. Since the mean annual normalised (10 m) wind speeds for wind run stations at Amatikulu (3.0 ms^{-1}) and Mtunzini (3.3 ms^{-1}) exceed that of Richards Bay (2.4 ms^{-1}) it is proposed that the wind speeds experienced in the Tugela dunefield exceed that of Richards Bay (Table 3.4). Although it is recognised that this assumption may not be accurate it is perhaps the most prudent approach to adopt when calculating sand transport for the study area.

Table 3.4 Mean annual normalised (10 m) wind speeds and station characteristics for wind run stations (after Diab, 1995).

STATION NAME	LAT (°S)	LONG (°E)	ELEV (m)	FROM	TO	NORMALISED SPEED
Amatikulu	29°02'	31°32'	45	01/67	04/84	3.0
Mtunzini	28°57'	31°43'	36	01/66	04/84	3.3
Skakas Kraal	29°27'	31°12'	50	01/66	04/84	2.3

Swart (1987) estimated that the potential sand transport by wind in the Durban area is roughly equally divided between a NE flux of 45 $m^3m^{-1}yr^{-1}$ and a SW flux of 35 $m^3m^{-1}yr^{-1}$. Onshore winds are slightly stronger than offshore winds, indicating a potential sand loss of 3 $m^3m^{-1}yr^{-1}$ for the Durban beach. Cooper (1991b) argues that the actual transport rates are much lower than this, as the aforementioned calculations do not consider sand moisture, vegetation, beach width, humidity or surface armouring. Van Heerden & Swart (1986) calculated the resultant drift potential of sand at St Lucia Estuary mouth to be 20 x 10^3 $m^3km^{-1}yr^{-1}$. However, Wright (1990: in Cooper, 1991b) estimated 13 x 10^3 $m^3km^{-1}yr^{-1}$ for the same area (Cooper, 1991b).

3.2.5.3 _Wave regime and wave-induced currents_

The KwaZulu-Natal coastline may be classified as a wave-dominated (Davis & Hayes, 1984), high energy coastline. The HRU (1968) recordings of clinometer readings at Cape St Lucia indicates that the dominant wave approach is from the SE for both winter and summer.

Secondary wave approach from the ENE was also noted (Cooper, 1991c). These findings are supported by the National Research Institute of Oceanography (1981: in Lord *et al.* 1988) who claim that the dominant wave direction at Richard's Bay is from south to east, with the predominant direction being SE. Van Heerden and Swart (1986; in Cooper, 1991b), using data from voluntary observed ships (VOS), suggest that the main deep-sea swell approach at St Lucia Estuary mouth is from the S and SW.

Recordings from 1968 to 1981 indicate that 90% of wave heights range from 0.5 to 2.0 m, with the majority of wave periods ranging from 8-13 seconds (NRIO, 1981). The HRU (1968) determined significant wave heights, expressed as the mean height of the highest one third of the waves arising in a stipulated recording period (typically 15 minutes), for KwaZulu-Natal coast. The maximum wave height was found to be 1.6 times the significant wave height. The significant wave heights predicted to be exceeded at least once per anum for each direction are presented in Table 3.5.

TABLE 3.5 Significant wave heights and periods for the Durban area to be exceeded once per year (after Cooper, 1991b).

Direction	Significant Wave Height (m)	Significant Wave Period (seconds)
NE	4.45	14.1
E	4.11	18.1
SE	5.3	20.6
S	7.25	15.1

As a result of the dominant SE wave approach the dominant direction of longshore drift would be to the north. The CSIR (1983) calculated the annual longshore flux of 1.1×10^6 m^3 of sand from areas to the south of the Tugela river mouth. Cooper (1991b) argues that this value is probably an overestimate, as the coastline to the south is predominantly rocky. Furthermore there are only two large rivers in the 100 km stretch to the south (Mgeni and Mvoti) which raises the question as to the source of this north moving sediment. Moreover, these rates are calculated from refraction diagrams and do not take into consideration the availability of sediment or grainsize.

3.3. TUGELA RIVER

3.3.1. Catchment Characteristics

3.3.1.1. *Catchment topography and climate*

Mean annual rainfall varies from 600-2000 mm per year, with most of the rainfall occurring between September and February. Mean annual temperatures vary from 13°C to 23°C, with highest temperatures recorded in river valleys and along coastal lowlands, where seasonal variations are minimal. The lowest temperatures occur in the high lying, mountainous area of the Drakensburg (Broderick, 1987). This subtropical environment has existed since the Miocene, which has resulted in thick soil profiles (Partridge & Maud, 1987).

Estimates of the Tugela catchment area range from 28 000 km^2 (Orme, 1974) to 29100 km^2 (Brand, 1967; Midgley and Pitman, 1969; Robertson, 1970; NRIO, 1986). The Tugela river is 405 km long and its source is at an elevation of 3109 m (NRIO, 1986). The overall gradient is 1:130 Fig. 3.8). In the lower 13 km the gradient is reduced to 1:573. The estimated mean annual runoff is 5071×10^6 m^3 (Midgley and Pitman, 1969). However, recent computations reveal that the original calculations were overestimates and mean annual runoff was reported to be 3900 x 10^6 m^3 (Midgley, Pitman and Middleton, 1994). This simulated annual runoff data is shown in Figure 3.9 and Figure 3.10 for the period 1952 to 1986. The mean annual discharge is between 184 m^3s^{-1} (Brand, 1967) and 226 m^3s^{-1} (Midgley & Pitman, 1969). The mean winter discharge is 73,6 m^3s^{-1}, compared to 481 m^3s^{-1} in summer (Orme, 1974).

There are 216 registered dams in the Tugela catchment of which 9 have capacities greater than 10 x 10^6 m^3 (Quinn, 1997). Brand (1967) notes that the Tugela River has a "terrible floood peak", where walls of water of 1.5 m have been reported to move downstream, carrying with them large trees, animals and detritus. Although the John Ross Bridge was washed away during the September 1987 floods (9440 m^3s^{-1}), the March 1925 flood was estimated at approximately 15 170 m^3s^{-1} (Perry, 1989). Other large floods were recorded in November 1921, January 1934

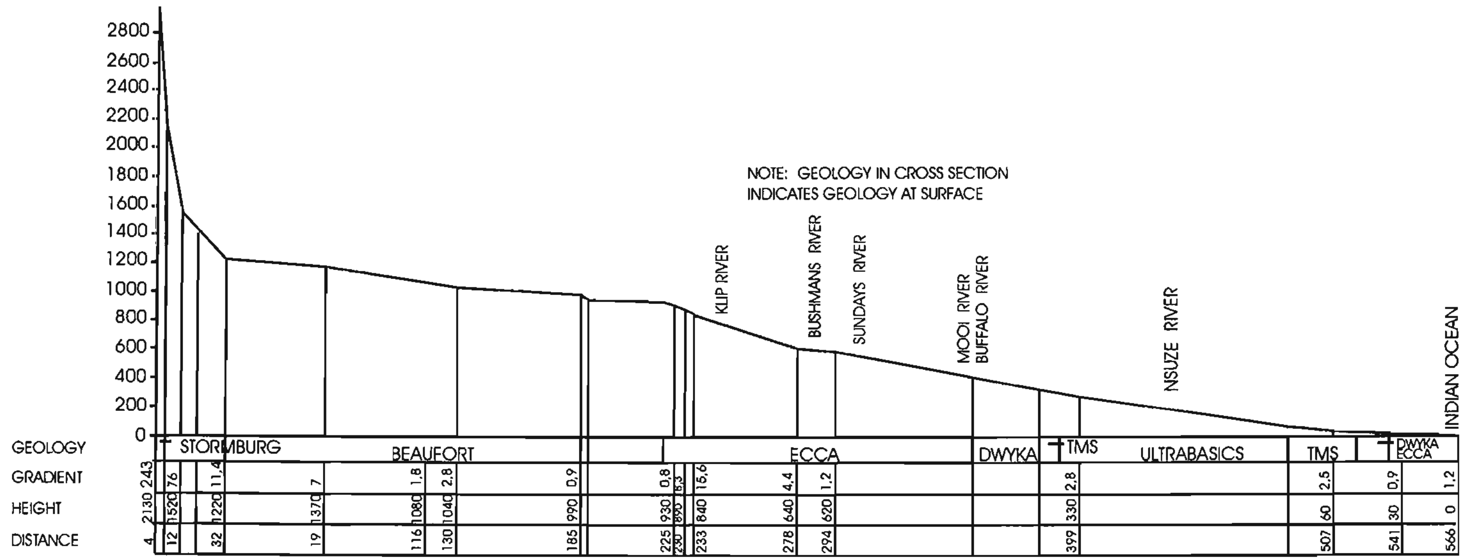


Figure 3.8 Longitudinal profile of the Tugela River (Thorrington-Smith et al., 1978).

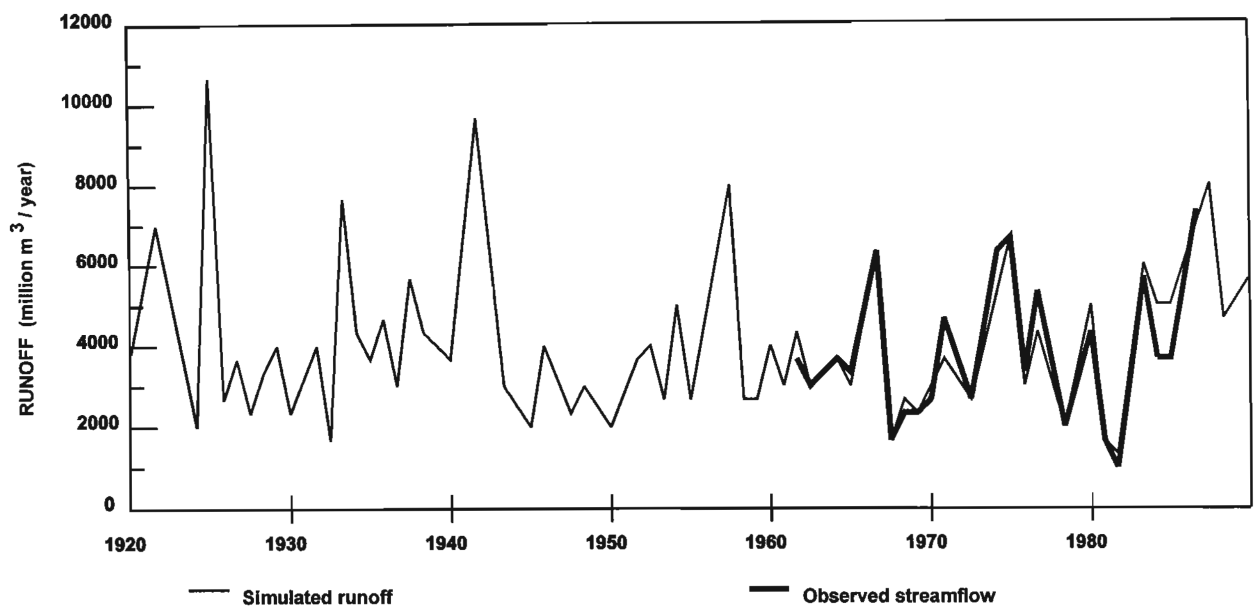


Figure 3.9 Simulated runoff from the Tugela River. Flow recorded at the gauging weir closest to the estuary is indicated as a thicker line (after, Quinn,1997).

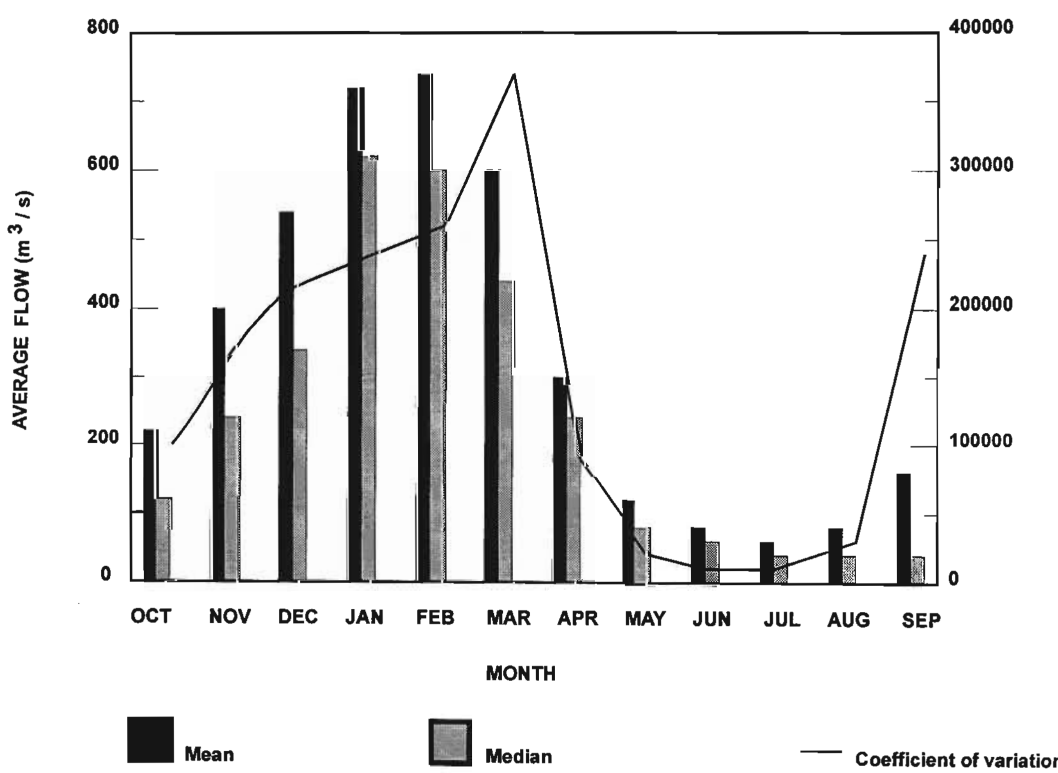


Figure 3.10 Key characteristics of simulated runoff to the Tugela River (after, Quinn, 1997).

and December 1956, with smaller floods occurring in February 1939, April 1943, February 1955 and March 1976 (Perry, 1990).

Due to the large amounts of sediment discharged by the Tugela, the bed level of the estuary shelves sharply upwards, limiting the extent of marine influence (Begg, 1978). From 1955 to 1958, the mean annual bedload, of the Tugela was estimated at 10.5 x 10^6 tons per annum (Midgley and Pitman, 1967; Orme, 1973), with a mean annual concentration of dry suspended silt by weight of 0.23% (Middleton and Oliff, 1961)

Over the summer months sediment plumes of 3-5 km offshore and 15 km alongshore have been recorded off the Tugela River (Orme, 1974; Orme and Loeher, 1974). Orme (1974) estimated erosion of the Tugela catchment to be in the order of 375 tons per km^2 per annum and compared it with other large catchments in the world (eg. Zambezi at 75 tons per km^2 per annum; the Mississippi at 154-230 tons per km^2 per year; the Colorado at 271 tons per km^2 and the Indus at 420 tons per km^2 per annum).

Land use in the upper catchment has been classified as largely rural with cattle and game ranching. Eksteen *et al.* (1990: in Quinn, 1997) note that the middle to lower portions of the catchment are under communal tenure, marked by high stocking rates. Nearly 42000 ha are under irrigation. Eksteen *et al.* (1990: in Quinn, 1997) report that potentially there exists 39 400 ha suitable for further afforestation.

3.3.1.2. *Catchment geology and soils*

The upper reaches of the Tugela river traverse rocks of the Ecca and Beaufort Groups which are lacustrine; fluvial and aeolian sedimentary rocks (Fig. 3.11). These are intruded by Late Jurassic Karoo dolerite. In the central part of the catchment the river flows through gneisses and granites of the Natal-Namaqua Basement complex and Natal Group Sandstone. Downstream the river traverses diamictite of the Dwyka formation as well as shales and sandstones of the Pietermaritzburg Formation. The lower reaches of the river valley cut through shales of the

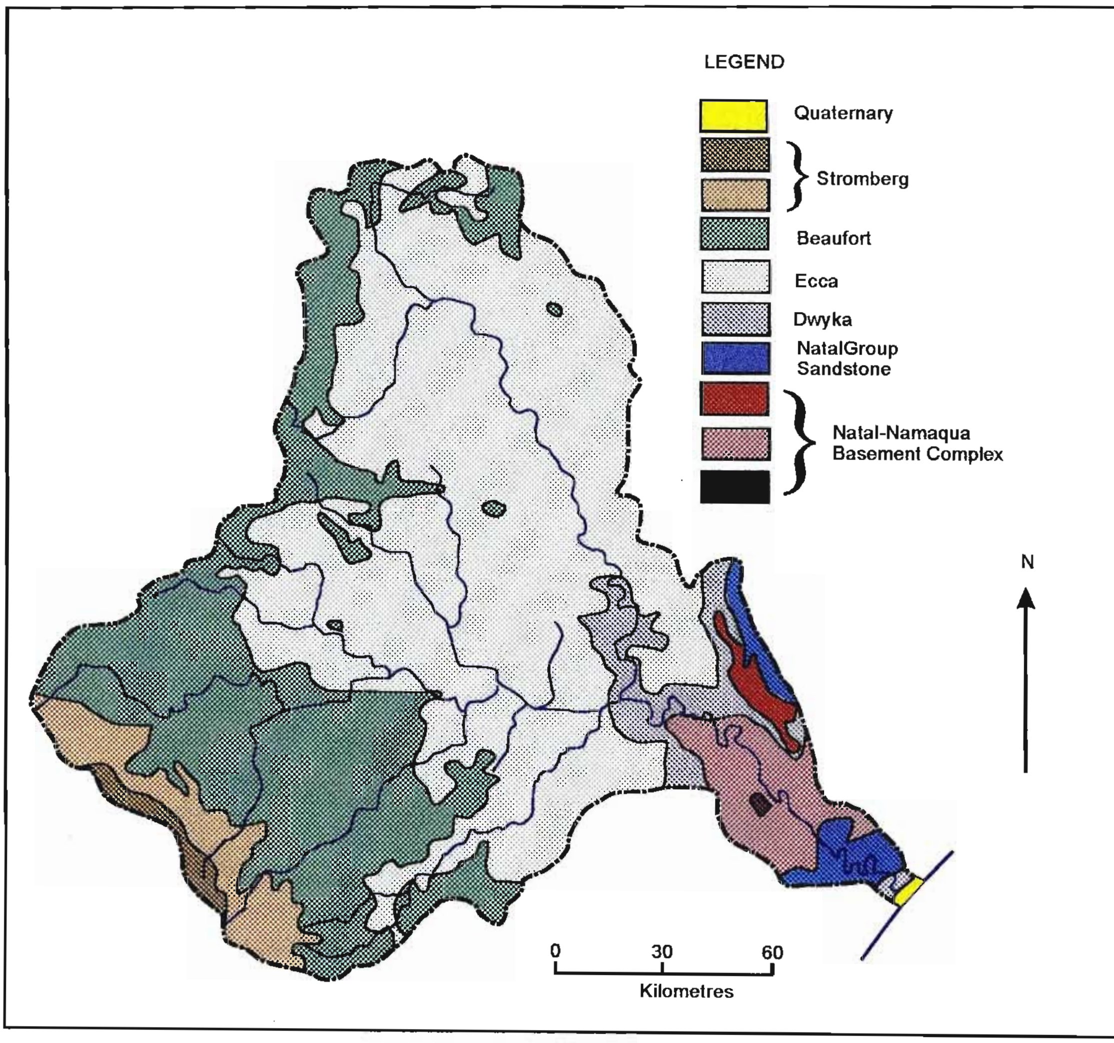


Figure 3.11 The geology of the Tugela catchment.

Vryheid Formation, which at the coast are unconformably overlain by Plio-Pleistocene coastal dunes, consisting of Berea red sand.

Fourteen of Fitzpatrick's (1978: in Broderick, 1987) soil types occur in the Tugela basin (Fig. 3.12). Soil types 2, 7, 9, 14 and 16 are low to moderately erodible, while soil types 6, 8, 10 and 12 are highly erodible. Duplex soils are defined as stratified deposits, characterized by an erodible sublayer. Severe gully erosion is typically associated with duplex soils in the Tugela catchment (Broderick, 1987).

3.3.2. Morphology of the Tugela River Mouth

The lower reaches of the Tugela are cut into Ecca shales of the Karoo system. Although Brand (1967) claims that there is no floodplain on the lower Tugela, Orme (1974) reports that the floodplain is 1500 m wide. The wide floodplain can be attributed to the high erodibility of the Pietermaritzburg shales into which the river cut during former low sea-levels.

The southern end of the river mouth consists of a 700 m stable sand bar, anchored by coastal dune forest. This spit is extended for approximately 70 m by foredune vegetation, from which sand accretes to confine the river mouth to 50 m (Orme, 1974).

Prior to the 1920's the Tugela mouth followed a pattern of the majority of KwaZulu-Natal's rivers, with a southerly extending spit (Van Roooyen, pers. comm., in Goldbold, 1974). However, after the reclamation of land behind the spit for sugar cultivation since the 1930's, the spits have been recorded extending in both southerly and northerly directions. Perry (1990) claims that since 1937 the position of the mouth has migrated over a 800 m range from N to S and a 500 m range landwards to seawards. Although the mouth is rarely closed to the sea, recent years have seen an increased occurrence of mouth closure for a few days at a time during the winter months. Quinn (1997) claims that this scenario is likely to change over the coming decades.

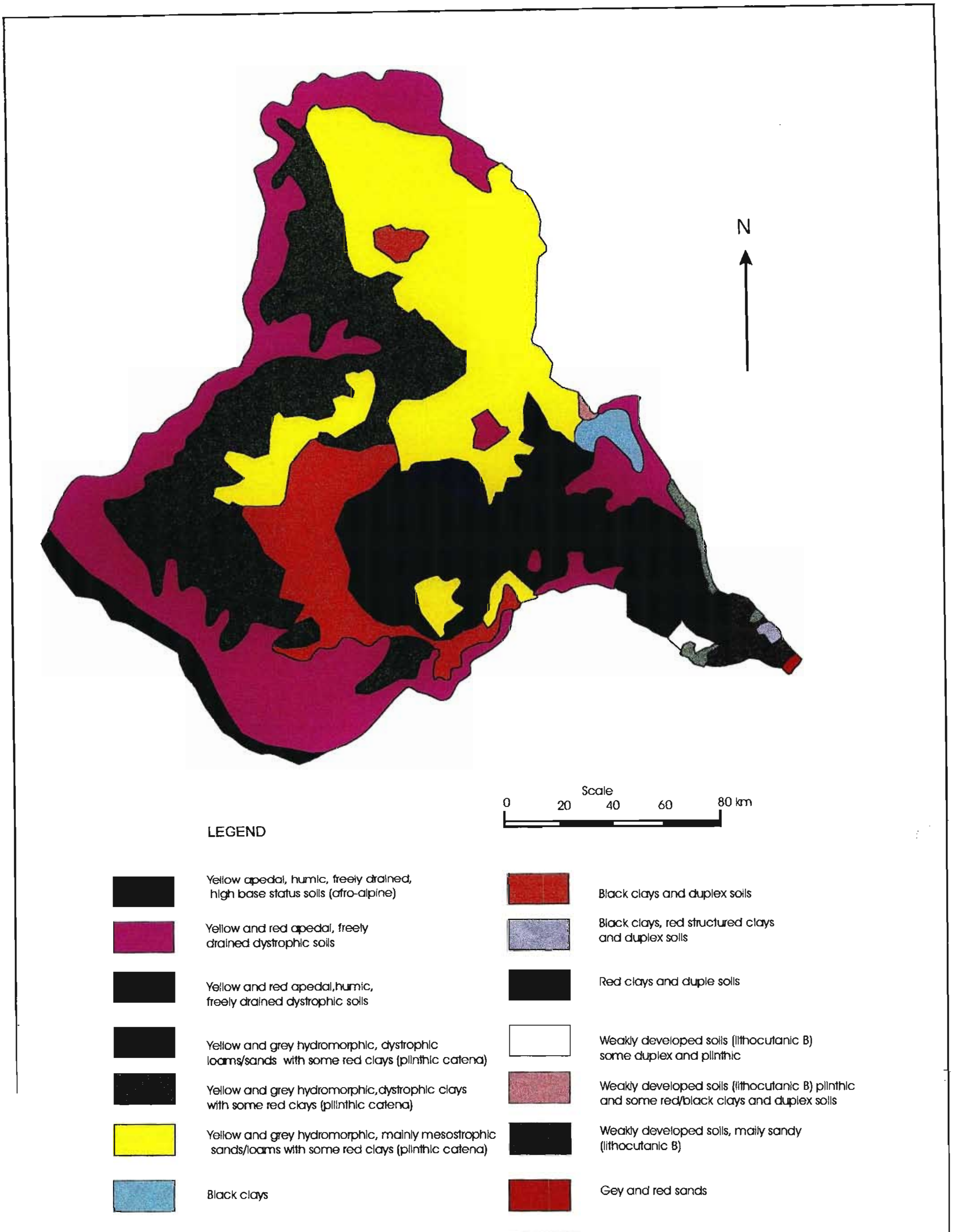


Figure 3.12 Fitzpatrick's (1978) soil types in the Tugela Basin (after Broderick, 1987).

CHAPTER 4.

RESEARCH METHODS

4.1. INTRODUCTION

In order to understand the dynamics of coastal dune formation, a knowledge of the sedimentological, geomorphological and biological processes involved is essential. Similar approaches to studying dune formation have been employed by Hesp (1982, 1989) Sarre (1989b) and Carter *et al.* (1992). Sediment characteristics reveal a great deal of information about the sources of the material and the transport mechanisms involved in their deposition (Pettijohn *et al.*, 1987). The transport of sediment in a fluid is controlled partly by the size, shape and density of the grains and partly by the physical properties of the fluid. When grains are transported they are sorted in relation to size, shape and density, and have been noted to undergo changes in shape through inter-particle collisions or impact with the bed. It is for these reasons that Pye & Tsoar (1990) assert that an appreciation of the physical characteristics of sand grains and the way in which the characteristics of grain populations are altered during wind transport is crucial for the accurate palaeoenvironmental analysis of aeolian sediments.

The objective of tacheometric field surveying was to create time-sequenced 3-dimensional surfaces of changing dune topography, and from them to calculate cross-sections and volumetric variation with time. This would assist in understanding the nature and the rate of dune formation and destruction, and contribute to an assessment of the life cycle of certain dune types. The observation of seasonal trends in the growth of foredunes might allow for the correlation with sediment fluxes to the beach/dune budget and dominant wind-producing systems.

Biological modifications of foredunes are manifested through greater threshold velocities for sediment transport and by increased displacement heights. The range of effects is determined by the species present in the region and their densities (Sherman & Hotta, 1990). The vegetation structure and floristic composition of the study area would further enhance our understanding of foredune evolution.

4.2. SEDIMENT SAMPLING

Sediment samples were collected along transect lines corresponding to fixed station numbers (Fig. 4.1). Samples were placed in plastic bags, sealed and transported to the laboratory for analysis. Only the top 3 cm of the beach and dune surfaces was sampled, except when comparing variation in grain size in a vertical profile, within a dune. Up to 8 samples were collected along each transect line depending on the foredune dimensions: i) the mid-beach; ii) the berm; iii) the base of the foredune ; iv) half-way up the seaward face; v) the dune crest; vi) the dune slack; viii) the base of the retention ridge. Sample size was approximately 1000 g.

4.3. SEDIMENT ANALYSIS

Since the sediment of the Tugela river is very similar in size and content to that of the adjacent dunes (Olivier, 1994) it was decided to follow a sediment analysis technique developed by Cooper (1986a), specifically for the estuaries of Natal (Fig. 4.2). The aim of the laboratory analysis was to ascertain the relative proportions of mud, sand and gravel, the grainsize distributions of the individual sand and mud fractions, and the carbon content.

Grain size characteristics can be obtained through sieving, settling tube analysis, electro-optical methods (Coulter counter and laser granulometry) and by computerized image analysis. The relevant procedures have been extensively documented (Folk, 1964, 1974; Anan, 1971; King, 1972; Goudie, 1981; Smith, 1992). Smith (1992) warns against the use of standard sieving and settling tube techniques, as measures of particle size can produce significant error. He questions the traditional view that particle size should be used as a beach sediment descriptor and suggests the use of specific surface. Specific surface is denoted by F and comprises the total particle surface area, divided by its mass to provide the units of mm^2 $gram^{-1}$. Although this method has its merits it is tedious and time

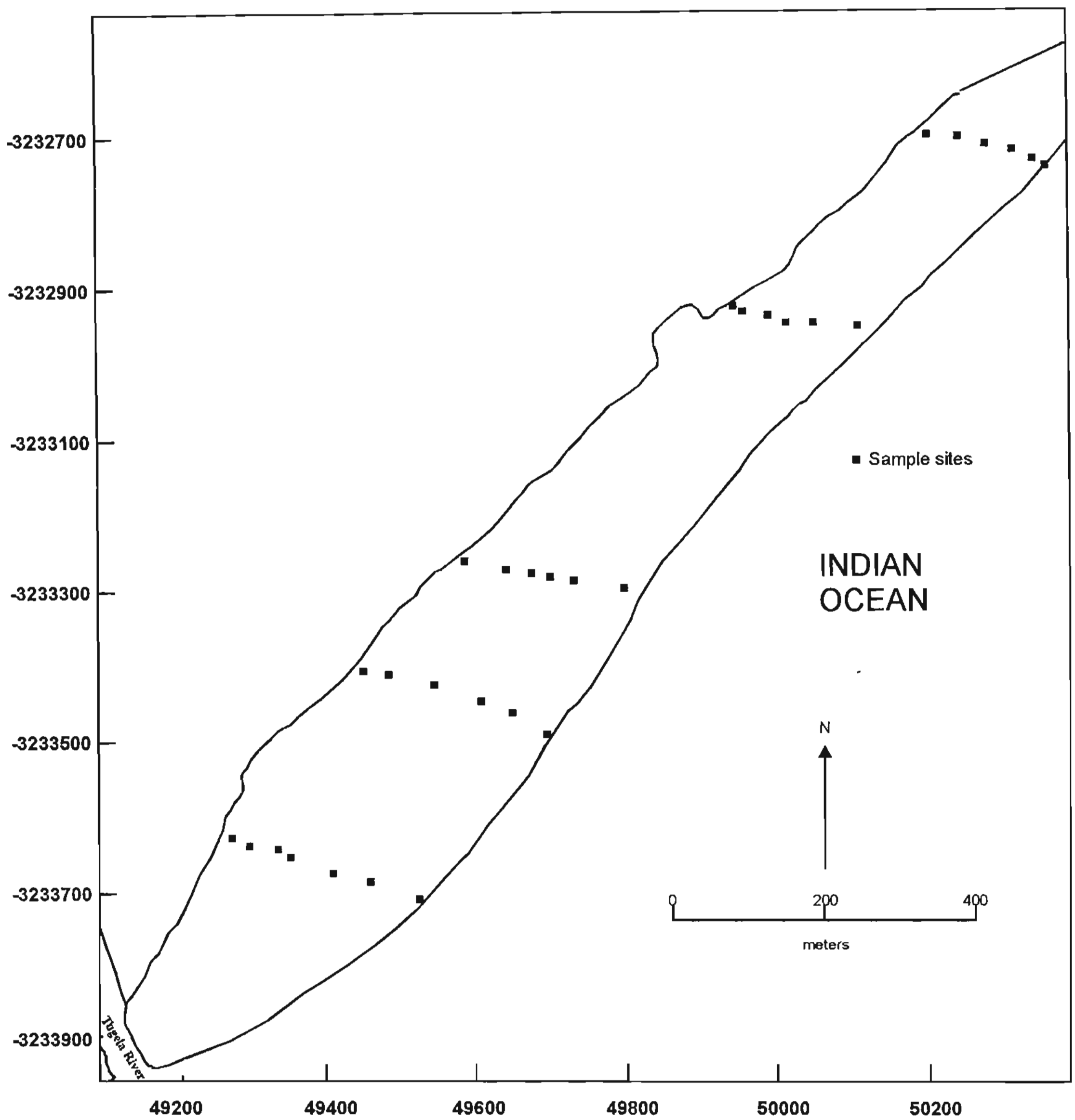


Figure 4.1 Sediment sample locations in the study area. The grid lines refer to the South African Co-ordinate System at intervals of 200 m.

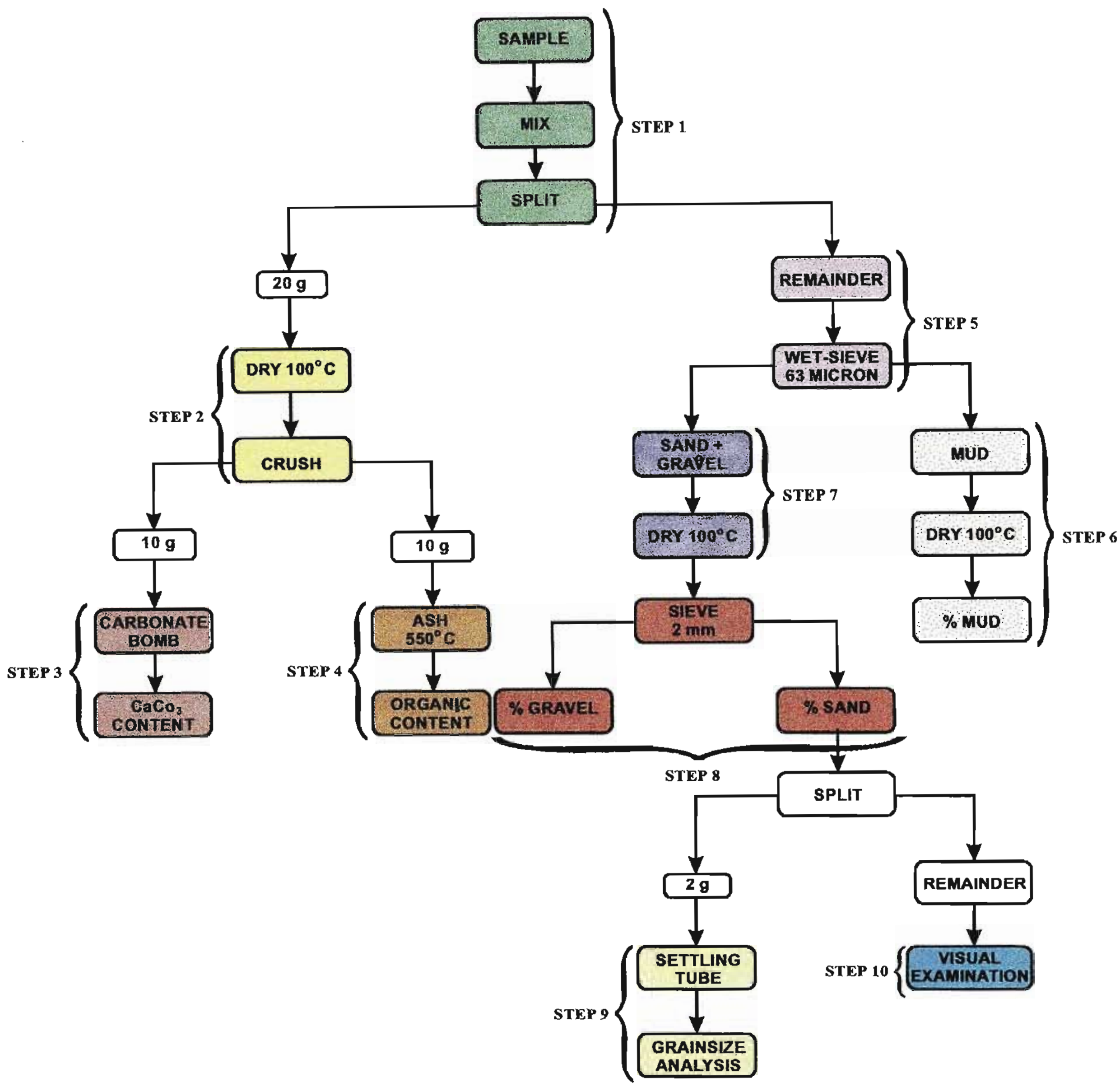


Figure 4.2 Laboratory procedure for analyzing sediment (modified after Cooper, 1986).

consuming and to date there lacks a simple mechanical test of specific surface other than visual microscopic determination. Since most of the sediment in the study area consists of quartz, the sand statistical parameters were calculated using a computer-linked settling tube. The accuracy of the tube was tested by Esterhuysen and Reddering (1985) and found to yield results comparable to standard sieving techniques. This method has been used successfully in a number of studies examining estuarine, beach and dune environments (Cooper, 1986, 1991b; Grobler, 1987; Wright, 1990; Illenberger, 1986,1993; Pillay, 1996).

Carbon content was established using a modified version of a carbonate bomb (Schink *et. al.*, 1978). This technique has been used successfully with favourable results in a number of estuarine studies (Reddering & Esterhuysen, 1981; Cooper, 1986a, 1991b; Grobbler, 1987; Wright, 1990). Furthermore Seisser & Rogers (1971) argue that in terms of accuracy, expense, analytical knowledge and time available, gasometry is the most appropriate method for carbonate analysis of large numbers of sediment samples.

Each sample was completely mixed (step 1) in the laboratory and subsamples (20 g) were extracted and dried at 105°C (step 2). These were then ground to a powder using an electric agate pestle and mortar for subsequent calculation of carbon content (step 3 and 4).

The remainder of each sample was wet-sieved (step 5) to remove the mud component, which was recorded as a percentage of dry weight of the total sample (step 6). The remaining sand and gravel proportions were dried at 105°C (step 7) and dry-sieved (step 8) to remove the gravel fraction. The grainsize distribution of the residual sand fraction was analyzed using a computer linked settling tube (step 9), where the Inman statistical parameters (median, mean, sorting and skewness) were calculated (Lewis, 1984) using both graphical and moment statistics (McBride, 1971; Buller and McManus, 1979).

The remaining sand and gravel was stored for visual analyses under a binocular microscope and the scanning electron microscope. Many researchers have sought to acquire information regarding the origin and transport history of a quartz sand grain by analysing their surface textures using a scanning electron microscope (Leeder, 1982; Pye & Tsoar, 1990). Some authors (Blackwelder & Pilkey, 1972; Nordstrom and Margolis, 1972; Krinsley *et al.*, 1973; Ly, 1978) have reported a reasonable success when relating certain relief features to depositional environments. Manker & Barker (1978) observed a high degree of similarity between quartz grain features from both fluvial and beach/dune environments, and warns that investigators should be wary of using such features alone as environmental indicators. The binocular microscope was used to identify mineral types.

4.4. CALCULATING SAND TRANSPORT RATES

Several theoretical, empirical and experimental attempts have been made to estimate sand transport rates (Bagnold, 1941; Kawamura, 1951; Zing, 1953; Chepil, 1945; Hsu, 1971; Letau & Letau, 1977; Horikawa *et al.*, 1986). Burkinshaw (1998) notes that many of these equations were simply variations of Bagnold's model and it was not until the mid-1980's that technological advances paved the way for a new understanding of sand transport (Sarre, 1987; McEwan and Willets, 1993). Notwithstanding, the association between grain transport rates and the shear velocity (V*) is still not well understood, and while the model proposed by McEwan & Willets (1993) is a refinement of Bagnold's (1941) theory, the results generated by both equations are similar (Burkinshaw, 1998). Sherman *et al.* (1998) evaluated five major models of aeolian sand transport (Bagnold, 1936; Kawamura, 1951; Zingg, 1953; Kadib, 1965; Lettau & Lettau, 1977) based on empirical data obtained from field measurements. The study revealed a low correlation between measured and predicted sand transport rates, the Bagnold and Zingg models were considered the most reliable. Bagnold's equation has been used in a number of studies examining sediment transport in coastal dunes of South Africa (Illenberger, 1986; Illenberger & Rust, 1988; Burkinshaw, 1998). Illenberger & Rust (1988: in Burkinshaw, 1998, p204) established that the Bagnold equation yielded results 'with a moderate degree of accuracy within the error limits inherent in sediment budget calculations'. In this study sand mobility was calculated using Bagnolds's (1941) formulae:

$$q = C(d/D)^{1/2}(p/g)(V^*)^3$$

where, q is the sand transport; C is an empirical co-efficient (1.8 for well-sorted sand); d is the grain diameter, D is the diameter of the standard grain (0.25 mm); p is the density of the air (~1.2 x 10^6); g is the gravitational acceleration (9.81); V* is the shear velocity.

Shear velocity is obtained from the Karman-Prandtl velocity law:

$$V^* = (V_z - V_t)/5.75\log(z/k)$$

where V_z is the wind velocity measured at z m above the surface; k is the surface roughness factor, considered to be 10 mm for a rippled sand surface; V_t is the threshold wind velocity for wind measurements at height k, taken as 4 ms^{-1} (Burkinshaw, 1998).

Wind speed frequency and sandrose tables (Appendix 1) were computed, following a techniques developed by Fryberger (1979). Wind energy is expressed in terms of the drift potential (DP). DP is a measure of the potential maximum volume of sand that can be eroded by wind in a year. The magnitude of the resultant vector is referred to as the resultant drift potential (RDP). The ratio of RDP /DP is a measure of the directionality of the wind (Tsoar & Illenberger, 1998). An increase in the directional variability of wind at a station will result in a reduction of the RDP/DP.

4.5. TACHEOMETRIC FIELD SURVEYS

4.5.1. Data Collection

Pye and Tsoar (1990) claim that the most detailed information concerning dune form can be secured through repeated theodelite and plain table surveys (eg. Sharp, 1966; Hastenrath, 1967; Tsoar, 1978; Reid, 1986; Warren, 1988; Carter and Wilson, 1990; Ritchie and Penland, 1990). An alternative approach to monitoring dune formation and movement is to conduct regular measurements relative to fixed pegs (Cooper, 1958; Inman *et al.*, 1966; Pye, 1980, Warren and Kay, 1987; Sarre, 1989b; Jungerius and van der Meulen, 1989;

Livingstone, 1989a). Although the use of pegs is relatively rapid and inexpensive, it proved to be unsuccessful in the study area due to theft and damage by vehicles.

Initially it was decided to survey the first 10 km of the coastline to the north of the Tugela River, using a number of fixed stations at 500 m intervals. A reconnaissance survey of cross-sections normal to the ridge, using a graduated staff and dumpy level, proved extremely time consuming and failed adequately to record the shifting dunes. The results were discarded as the accuracy of the data was questionable, due to the lack of experience in field surveying techniques. It was decided to limit the survey of the dunes to the dune hummocks and embryonic dune ridges within the first 2 km north of the Tugela River mouth, as it is during this zone where the next coastal dune ridge was likely to develop.

Where three-dimensional co-ordinates of many points have to be established it is necessary to use a tacheometric method. After considering the nature of the task, tacheometric surveys were undertaken by the use of a total station, consisting of a theodelite and electronic distance measuring equipment combined in one unit.

The dunes at the Tugela mouth were surveyed on seven occasions between July 1993 and February 1996 every six months, corresponding to the wet (September-March) and dry (April-August) periods. The aim was to determine how the variations in sediment inputs affected the initiation and evolution of foredunes. In order to repeat the survey over time a controlled survey was employed. A closed traverse technique was used, to accurately fix four strategically placed stations on the dune ridge crests, which were linked to the South African survey grid system, based on Lo 31. Trigonometrical beacons number 20 and 140 were used to calculate station positions (Table 4.1).

Table 4.1 Trigonometrical stations used in the dune survey (Chief Directorate, Surveys and Land Information, 1991).

Number	Station	Y	X	Height
20	Mangete	-50383.95	3229977.94	118.8
140	Red Hill	-48270.86	323285.19	88.4

The instrument was set up over one of the control points (stations 1-4); where the station name, observation code and instrument height were recorded. Once the instrument is referenced, a manual survey of the subaerial dunes was performed using a standard 1.5 m survey rod. The survey rod had a 15 cm plate attached to its base to prevent penetration of the sand surface with the rod. Where required, an extension pole was added for an overall length of 4.5 m. The rod was placed at a variety of points that best displayed the major morphologic features. Output data from the total station was stored on a Psion Organiser II. The data was processed on a Personal Computer (PC) using the software package ALICE, developed in the Department of Surveying and Mapping at the University of Natal, Durban, this allows for the editing of misread data.

Two instruments were tested for the recording and storing of data in the field:

(1) Data was measured using a Nikon D-50 total station. For the first four surveys, all observations were recorded by hand. On returning from a survey the observations were manually entered into a edit programme on a PC. This method took a month for each survey and was later abandoned when access to a Psion Organiser (PO) was obtained. Observations were stored in the PO under the control of Booker 5.1 applications software, where no attempts were made to calculate joins and polars in the field (dumb recording). Information was downloaded to a PC using CL.EXE software.

(2) Data was recorded using a Leica TC 500 total station. Readings were stored in the PO the Organiser Programme Language (OPL). This requires that a programme SETPC be written. Similarly information is downloaded from the PO the PC, using the software CL.EXE.

The Nikon proved to be the more suitable of the instruments, as the optical sight had a superior design and allowed for the rapid location of the prism. Secondly, the battery of the Nikon charged at five times the speed of the Leica, although one could have used an external 12 Volt battery. Despite the Leica having and increased measuring range of 500 m as compared to 300 m of the Nikon, it took longer to calculate distance measurements, over shorter distances. Although the Leica had a greater accuracy of 5 seconds as opposed to the 20 seconds of the Nikon, the project did not require such accuracy.

4.5.2. Data Processing

Initially, digital mapping encountered a number of difficulties associated with contouring (Davis, 1973; Quick, 1983; Devereux, 1985; Reid, 1986). However, advances in computer technology have greatly enhanced the ability for accurate 3-dimensional digital terrain maps. Two different approaches were tested to process the data and represent it in a three-dimensional format:

(1) The raw data file on the PC was checked and corrected using MSDOS EDIT. The corrected data file was imported into ALICE applications software. ALICE, essentially makes joins and polar calculations using existing co-ordinates of beacons, occupied and sighted points, which allows for the calculation of spot heights. Files in ALICE exist in ASCII format and consists of 4 columns separated by spaces. The ALICE files were then imported into SURFER for WINDOWS. SURFER is a grid-based contouring and three dimensional plotting and graphics package. SURFER interpolates irregularly spaced x, y, z data, onto a regularly spaced grid to produce grid files. The grid files are used to produce contour maps and surface plots. SURFER allows for great flexibility, representing three-dimensional plots and cross-sectional profiles, and even allows for calculating the volume between two surfaces (dune surfaces).

(2) The corrected data files were imported into STARDUST for WINDOWS. STARDUST provides all the facilities of the Surfer package but is able to make joins and polar calculations, thus eliminating the need to process the data using ALICE.

For future work it was decided to use STARDUST for calculating joins and polars and SURFER for WINDOWS to edit and display the data in map form, as it proved to be an extremely powerful and versatile editing and graphics package. Volume calculations for the whole study area was conducted for those surveys where data sets were complete (Table 7.2).

Volumes were calculated in SURFER using the Tripezoidal Rule, Simpsons Rule and Simpsons 3/8 Rule and the results averaged. The base datum level was defined as -3 m below sea level and the boundaries of the dune maps were standardised.

4.6. VEGETATION SURVEYS

In September 1994 six transects running from the foreshore to the dune forest were sampled (Fig. 4.3). The transects were positioned to pass through the most vegetated area of the dunefield. Plot sizes were determined by the type of community and to conform to the plot size limits suggested by Mueller-Dombois and Ellenberg (1974). Plots were spaced at 50m intervals along the transect lines. In the dune pioneer community on the incipient foredune, 5 m x 5 m plots were used. In the open dune scrub community, 10 m x 10m plots were laid out. In the closed dune scrub plot size was 15m x 15m. The releves were sampled recording the following information: date, transect number, plot number, plot size, structure of vegetation, floristics and general notes. The following structural and floristic parameters were recorded, total percentage aerial cover, plant height, dominant growth form and all species of trees, shrubs, creepers, herbs. The results are shown in the form of a profile diagrams (Fig. 6.6 - 6.11).

In June 98 five vegetation plots measuring 5 m x 5 m, were laid out in different size foredunes in attempt to establish a relationship between plant density and foredune dimensions. Shoot densities and average shoot heights were recorded together with stem widths.

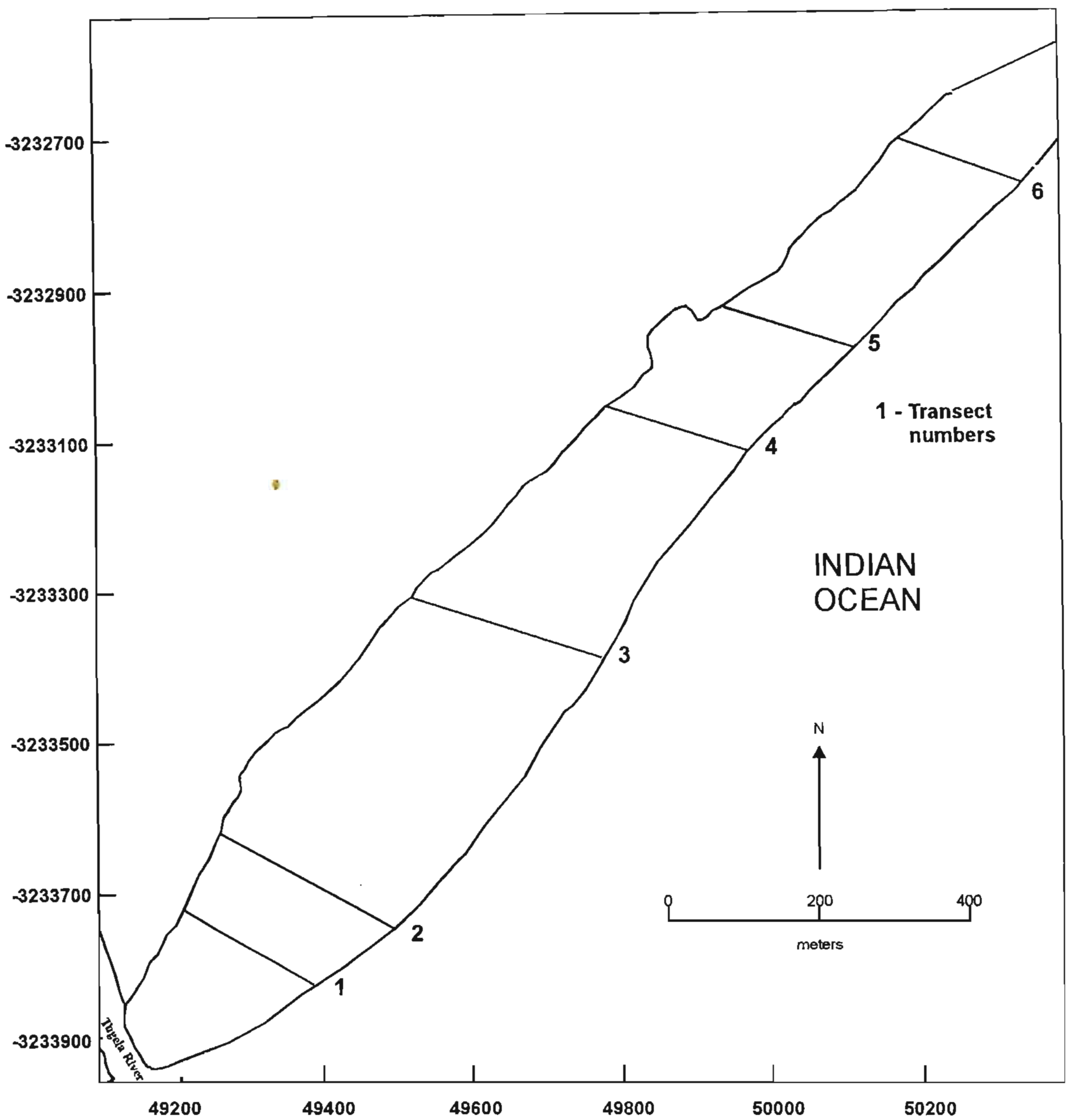


Figure 4.3 Vegetation transect locations. The grid lines refer to the South African Co-ordinate System at intervals of 200 m.

CHAPTER 5.

SEDIMENT COMPOSITION, TEXTURE AND DISTRIBUTION OF THE TUGELA MOUTH DUNES

The aim this chapter is to determine the composition, texture and distribution of sediments on the foredunes and beaches adjacent to the Tugela River mouth. The sediments were analyzed using the techniques described in Chapter 4.

5.1. GRAVEL FRACTION

Gravel (>2 mm) is the coarsest sediment fraction found in the dune/beach environment. The gravel fraction accounts for less than 0,1 % of the material. The gravel composition is diverse and comprises marine and estuarine shell fragments, feldspathic and calcareous sandstone, igneous fragments and quartz. Gravel is located in the dune slacks and on the beach.

5.2. SAND FRACTION

The sand fraction (2 mm to 0.063 mm) is the dominant sediment type in both the dune and beach environments and accounts for over 99 % of the total sediment. It is predominantly composed of quartz and feldspar, with the heavy minerals ilmenite, rutile, magnetite, pyroxene and hornblend present in varying quantities. Small amounts of lithic fragments and biogenic material are also present.

The shape and surface textures of sand grains were examined under the scanning electron microscope. The beach and dune sand is subangular to well rounded, with the majority being subrounded (Plate 5.1). The quartz grains from the beach display mechanical v-shaped pits as well as straight or curved grooves (Plate 5.2) and to a lesser extent conchoidal fracture

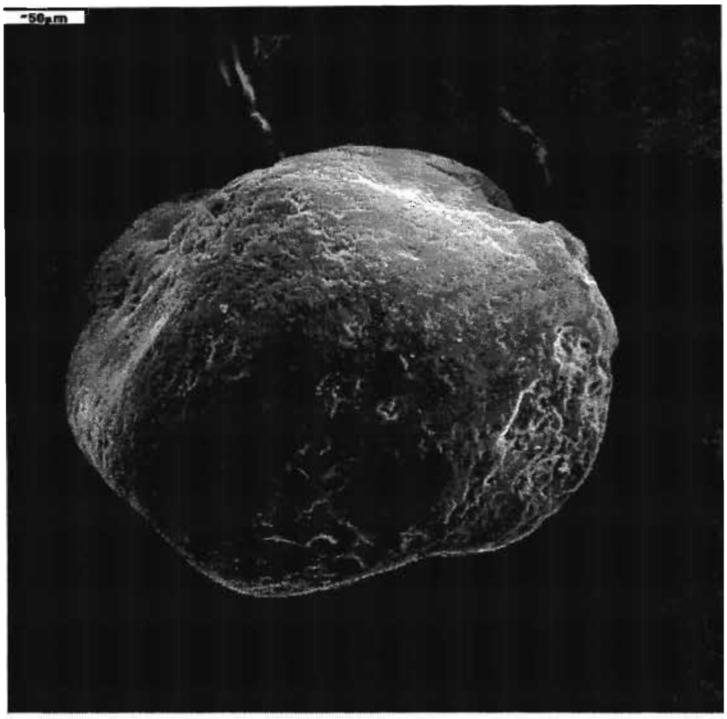


Plate 5.1 Rounded quartz grain observed on the beach.

Plate 5.2 V-shaped pits and curved grooves observed in dune sand.

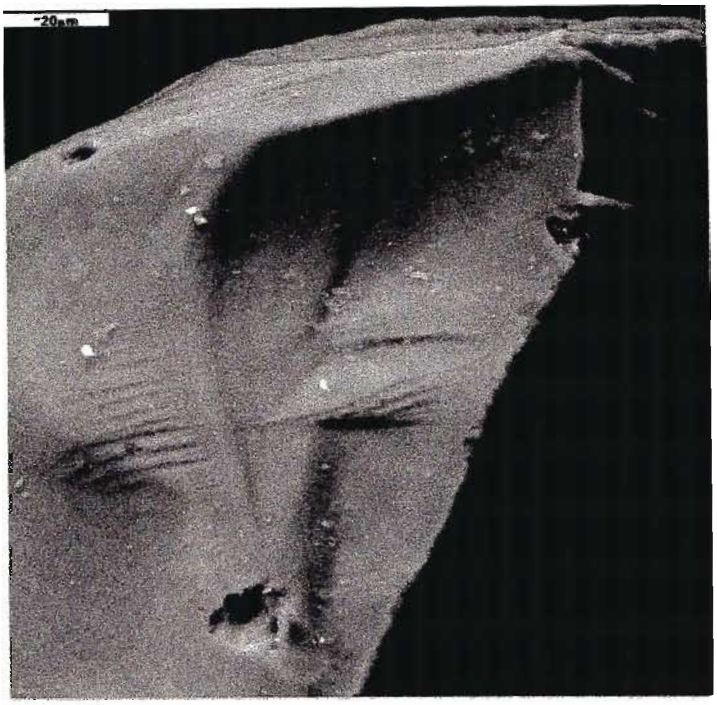


Plate 5.3 Large conchoidal fracture of a quartz grain from the beach.

Plate 5.4 Dark bands represent the concentration of heavy minerals at the base of the relict foredune ridge.

patterns (Plate 5.3). The dune sands are also characterized by mechanical v-shaped pits and straight or curved grooves. No major distinction was observed between the dune and beach quartz grain surface features.

Heavy minerals tend to concentrate near the base of the dune ridges. Sediment size only increases towards the base of a ridge when it is devoid of heavy minerals (Plate 5.4).

5.3. SAND STATISTICAL PARAMETERS

The average value of the mean grain size of all samples is 1.66 ϕ (0.319 mm) (Table 5.1). The sand is well sorted (0.38), with a slight negative skewness (- 0.03). The average of the mean grain sizes of the dune sand is 1.62 ϕ (0.308 mm) or 14 % finer than the average of the mean sizes of the beach samples (Table 5.1). Dune sand is on average fractionally better sorted (0.36) than beach sand (0.41), and the average skewness value for beach sand (0.06) is slightly more negative. The average mean grain size of sand on the crest of the ridge is 1.82 ϕ (0.283 mm) as compared to the mean sand size in the dune slack of 1.57 ϕ (0.357 mm).

5.4. MUD FRACTION

Mud includes both the silt and clay fractions. The silt is composed predominantly of fine quartz grains and finely disseminated organic matter, while the clay component consists of clay minerals. Mud accounts for less than 1 % of the total sediment, but increases to 4 % in backshore lagoons. Higher mud concentrations are found in the dunes (0.34 %) compared to the beach (0.01 %) for the May 1994 survey. However, the August 1997 survey revealed that the beaches (0.34 %) have a slightly higher mud concentration than the dunes (0.23 %).

Table 5.1. Average values of grain size parameters for the Tugela dunefield and beach for both surveys combined. Size parameters in phi units (ϕ) [phi unit = - $\log_2$ (diameter in mm)]; (n) refers to sample total; median and mean sizes also given in mm in parenthesis.

	All analysis n = 70	Beach n = 21	Dune n = 49
median grain size	1.66 (0.319)	1.53 (0.346)	1.72 (0.305)
mean grain size	1.64 (0.332)	1.50 (0.359)	1.62 (0.308)
sorting	0.38	0.41	0.36
skewness	-0.03	-0.06	-0.02

Table 5.2 Average values of grain size parameters for the Tugela dunefield and beach as sampled in May 1994 (survey 1) and August 1997 (survey 2). Size parameters in phi units (ϕ) [phi unit = - $\log_2$ (diameter in mm)]; (s) refers to survey number; (n) refers to sample total; median and mean sizes also given in mm in parenthesis.

	All analysis		Beach		Dune	
survey number	s 1 n = 30	s 2 n = 40	s 1 n = 11	s 2 n = 10	s 1 n = 19	s 2 n = 30
median grain size	1.62 (0.325)	1.68 (0.312)	1.49 (0.353)	1.57 (0.339)	1.71 (0.305)	1.72 (0.304)
mean grain size	1.61 (0.341)	1.66 (0.323)	1.46 (0.373)	1.546 (0.344)	1.70 (0.323)	1.72 (0.313)
sorting	0.39	0.37	0.40	0.42	0.38	0.34
skewness	- 0.05	- 0.02	- 0.07	- 0.06	- 0.01	-0.03

5.5. CARBONATE

The sediments in the beach and dune environment are generally carbonate poor (< 1 %). Since no carbonate rocks occur in the catchment the carbonate found must be of marine origin. Microscopic investigations of the beach and dune sediment reveals that the majority of the detectable carbonate is of skeletal origin, comprising of forams, bivalves, gastropods and ostracods.

A greater concentration of carbonate exists in the dune sediment (1,55 %) compared to the beach sediment (0.44 %). There appears no variation in carbonate content along the beach profile or between the beach and dune environment for the May 1994 samples. However, there is a slight reduction in carbonate concentrations for August 1997 between the beach (0.2 %) and the dune (1.83 %).

5.6. DISCUSSION

Variations between the beach and dune sediments can change notably over short distances. Anan (1971) argues that these differences may be related to sampling procedures. The time of sampling has also been shown to significantly alter grain parameters. The small amount of terrigenous gravel which occurs at the mouth of the estuary and the adjacent beach is diagnostic of the mature sediment that exists in the lower Tugela system. The gravel that does occur in the dune slack is typical of a coastal dune environment (Goldsmith, 1972). Larger particles have a greater tendency to roll down, or less of a tendency to be transported up the dune by wind. The mean grain size between the dune slack and crest is greater than between the dune and adjacent beach, which is consistent with the findings of Goldsmith (1972).

Gutman (1977: in Goldsmith, 1985) asserts that the density of dune vegetation and the most recent winds affect grain characteristics. This is an important point to consider when analyzing grain size parameters, as when wind lag deposits are formed, the fine sediments are differentially shifted, leaving a coarse lag deposit on the surface of the dune.

The mean grain size of the dune sands (1.62 ϕ) is slightly coarser than typical dune sands (2 to 3 ϕ; Ahlbrandt, 1979). The dune sands are well sorted which compares favourably with other studies (Ahlbrandt, 1979; Illenberger, 1986). However, the dune sands are slightly negatively skewed which is uncharacteristic of coastal dune sand which is typically positively skewed (+ 0.2; Blatt *et al.*, 1972; Ahlbrandt, 1979). Illenberger's (1986) study of the Alexandria coastal dunefield revealed similar results for skewness (0.08). This is possibly because the dune sand is essentially beach sand which has been transported over a short distance by wind, hence the aeolian sorting processes have not had sufficient time to operate. Dune sand is finer than beach sand which indicates the winnowing action of the wind as it shifts the sand off the beach.

The shape of the sand grains are slightly more angular than one would expect of a beach and dune environment. This is possibly due to the proximity of the study area to the Tugela River mouth, where the sand grains have not been subjected to subaqueous action, such as waves, associated with this high energy coastline. The quartz grain surface features observed in the study area, such as v-shaped percussion marks, straight and curved grooves and conchoidal fracture patterns indicate both a fluvial and marine influence on the sediment (Krinsley & Donahue, 1968; Krinsley & Margolis, 1971; Ly, 1978; Moral-Cordona *et al.*, 1996).

The beach and dune sediment contains very little mud suggesting that a high proportion of the finer material that is transported by the Tugela River is deposited offshore. Felhaber's (1985) study corroborates this assertion as large deposits of very fine sand and mud (Fig. 3.6b,c) are located on the inner shelf. This would account for the low concentrations of very fine sand (0.84 %) and mud (0.41 %) that occurs in the study area. A characteristic of marine sand is the absence of mud, suggesting that marine derived mud is negligible (Wright, 1990). The small amount of mud found in the intertidal zone, is due to the winnowing effect of fluctuating water levels.

The low carbonate values of the sand in the beach and dune sediments, indicates a strong fluvial influence in the study area, as the catchment-derived sediments lack carbonate. The low concentrations of carbonate are in contrast to the high calcium carbonate content (35 %) that is typical of South African coastal sands (Illenberger, 1993; 1996). The low concentrations of carbonate could be related to the lack of biogenic activity in the study area.

CHAPTER 6.

DUNE VEGETATION

6.1. INTRODUCTION

Coastal foredunes most commonly form in the presence of vegetation. In partly vegetated dunes the patterns of sand transport are influenced by surface topography as in fields of bare dunes, but with the added complication introduced by the plant cover. The plant canopy retards the wind flow up to roughly its own height, and further physically blocks the flight of moving grains (Willetts, 1989). To the north of the Tugela River mouth, extending from the backshore to the dunes are a number of distinctive plant communities.

The aim of this chapter is to record the vegetation structure and floristic composition of the study area in order to gain an understanding of the role of vegetation in foredune development. This would aid in determining which species are most important in establishing an accreting coastline. A range of factors influencing foredune morphology and evolution, including plant canopy density, height and distribution, wind velocity and a variety of ecological and environmental processes are examined.

6.2. DUNE VEGETATION SUCCESSION

Weisser and Backer (1983) conducted a preliminary survey of dune vegetation-succession chronology in the Mtunzini and Siyayi region and noted a distinctive increase in maturity of vegetation, inferring relative stability of the older ridges and long term beach accretion. Similarly, a number of zones of vegetation were recognized to the north of the Tugela river and were classified following the scheme of Weisser & Backer (1983). The results are the vegetation surveys are presented in Figures 6.1- 6.6.

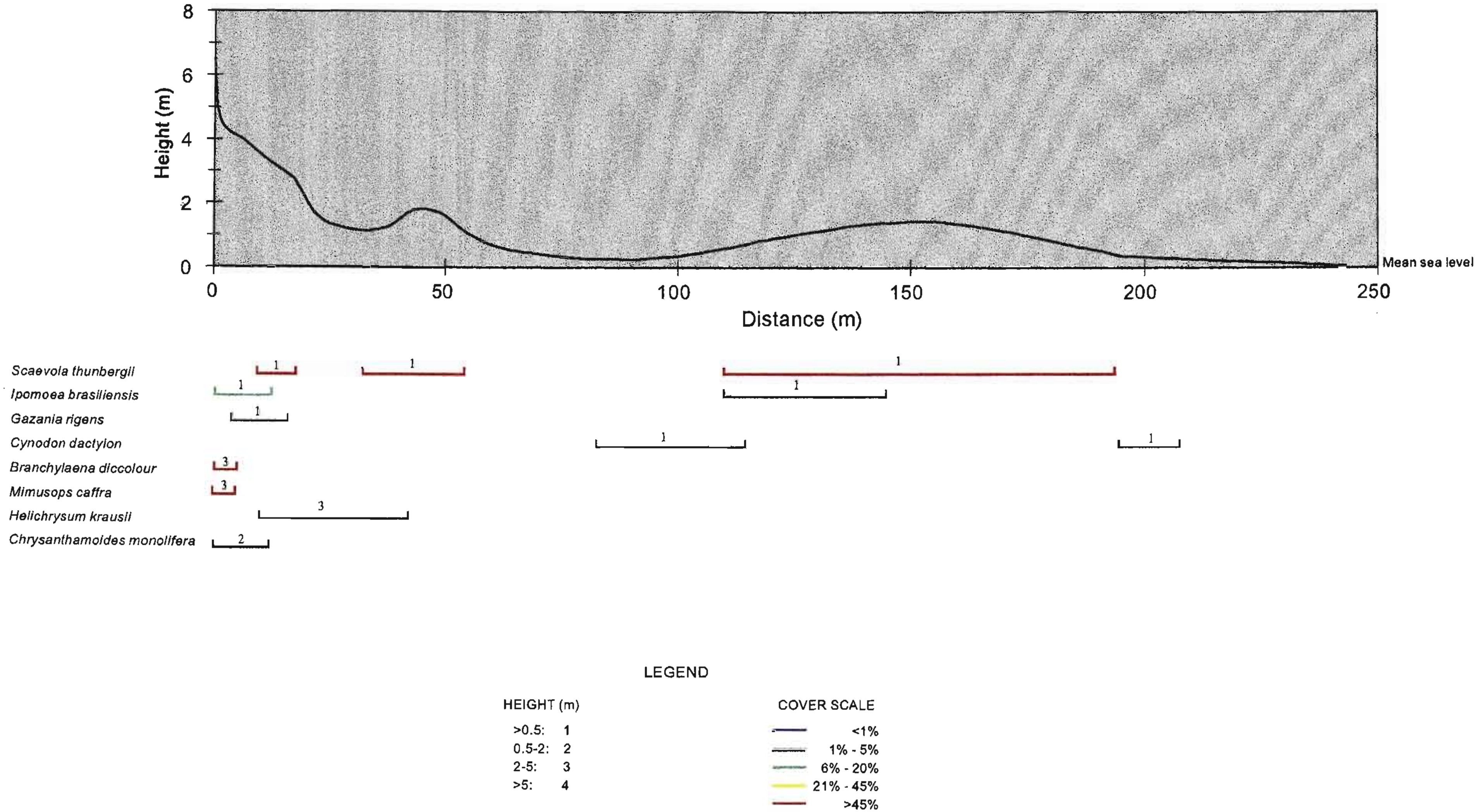


Figure 6.1 Profile 1 of the vegetation of the Tugela dunefield in September 1994. Species abundance is indicated in the lower part of the diagram as aerial cover in each quadrant along the cross section.

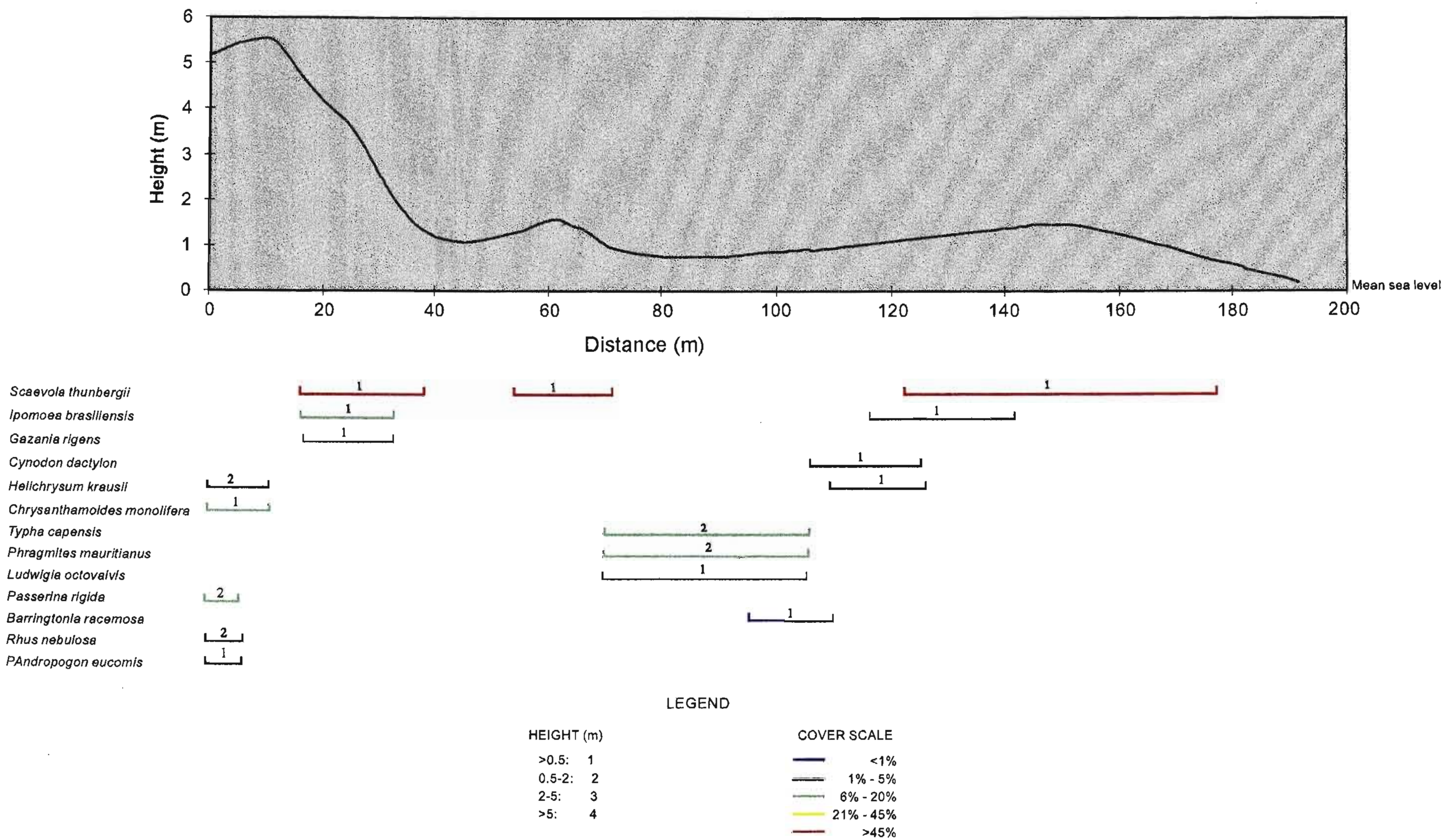


Figure 6.2 **Profile 2 of the vegetation of the Tugela dunefield in September 1994. Species abundance is indicated in the lower part of the diagram as aerial cover in each quadrant along the cross-section.**

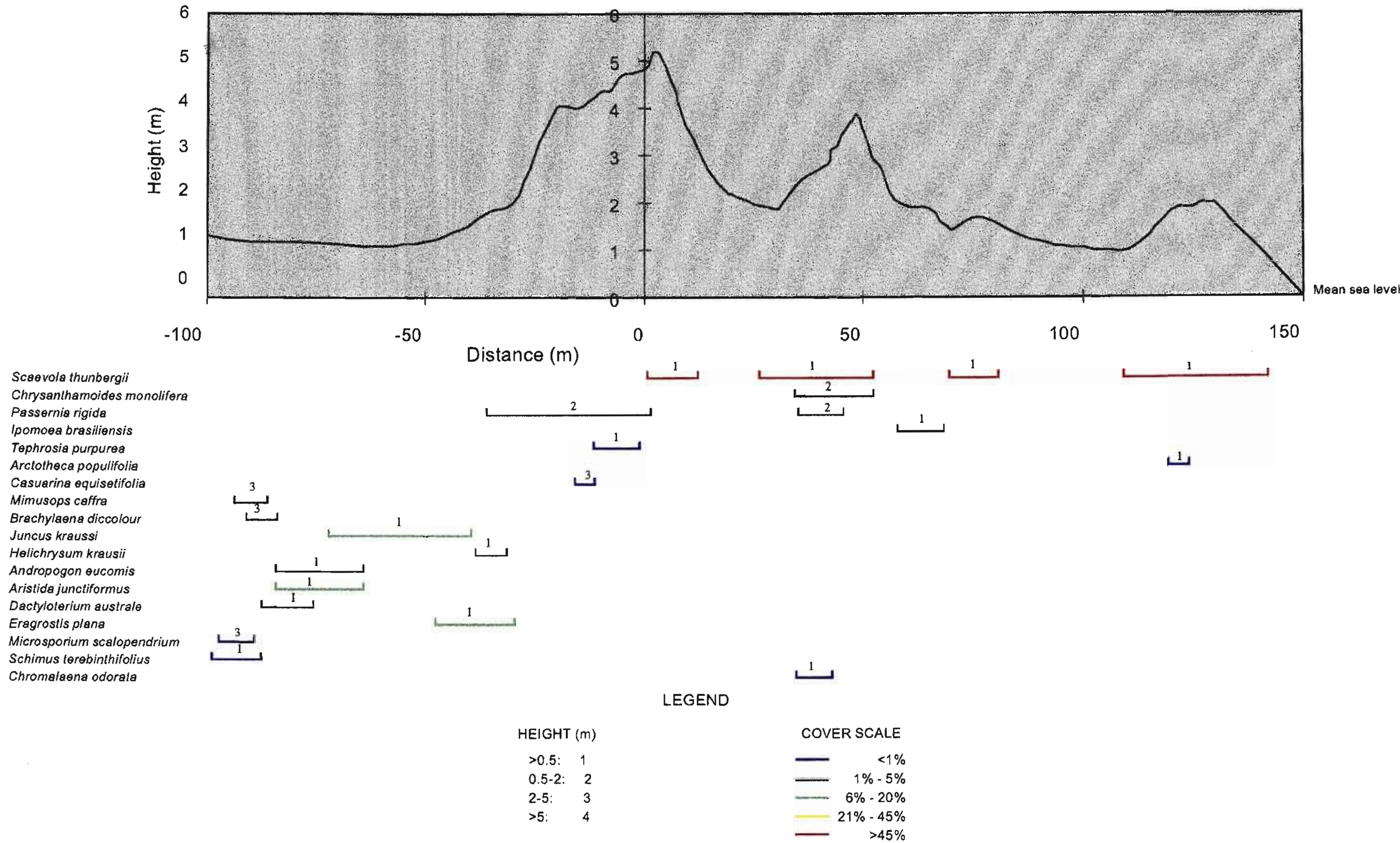


Figure 6.4 Profile 4 of the vegetation of the Tugela dunefield in September 1994. Species abundance is indicated in the lower part of the diagram as aerial cover in each quadrant along the cross-section. Negative distance refers to the extent inland of the fossil dune ridge.

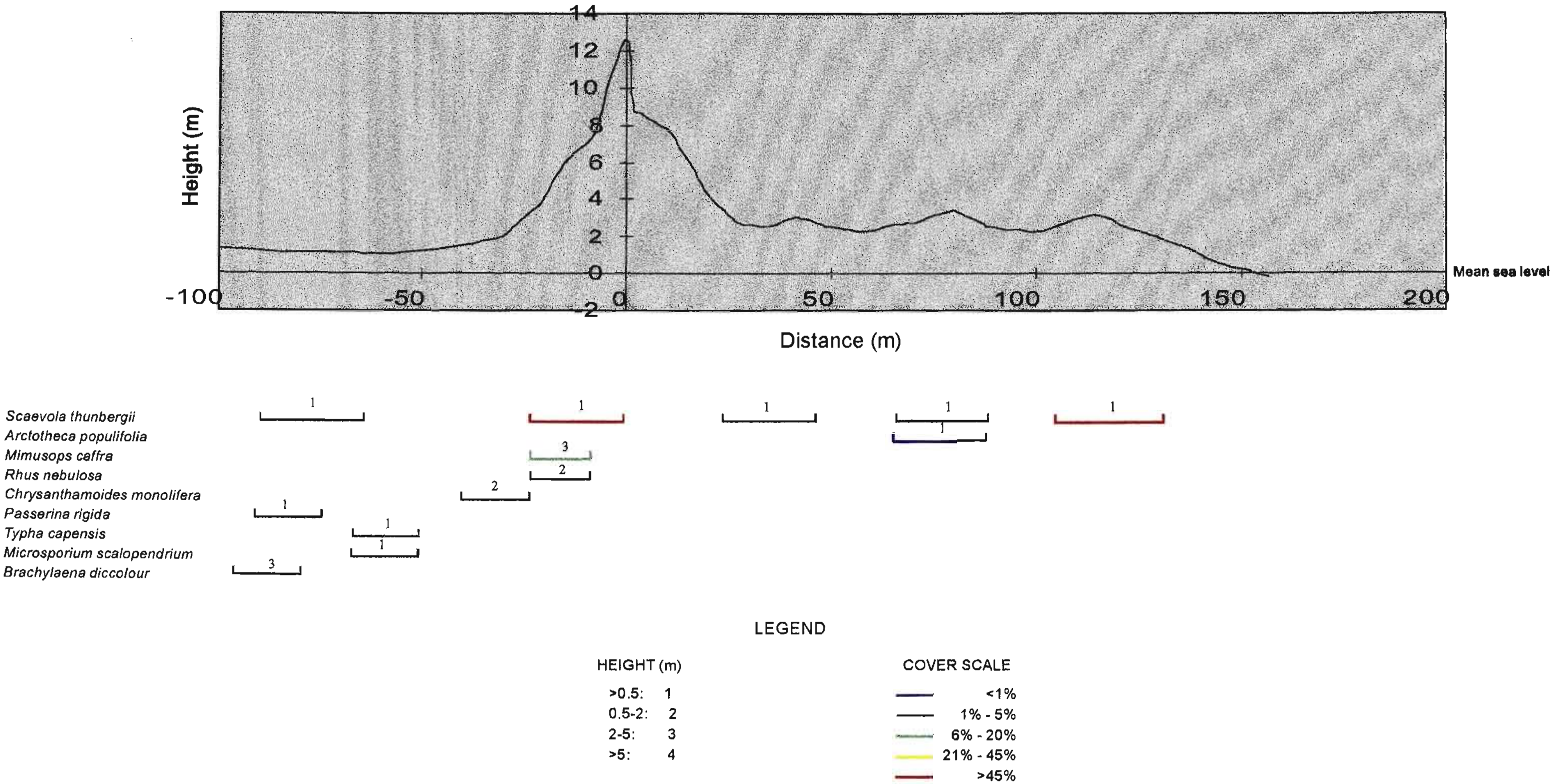


Figure 6.5 Profile 5 of the vegetation of the Tugela dunefield in September 1994. Species abundance is indicated in the lower part of the diagram as aerial cover in each quadrant along the cross-section. Negative distance refers to the extent inland the fossil dune ridge.

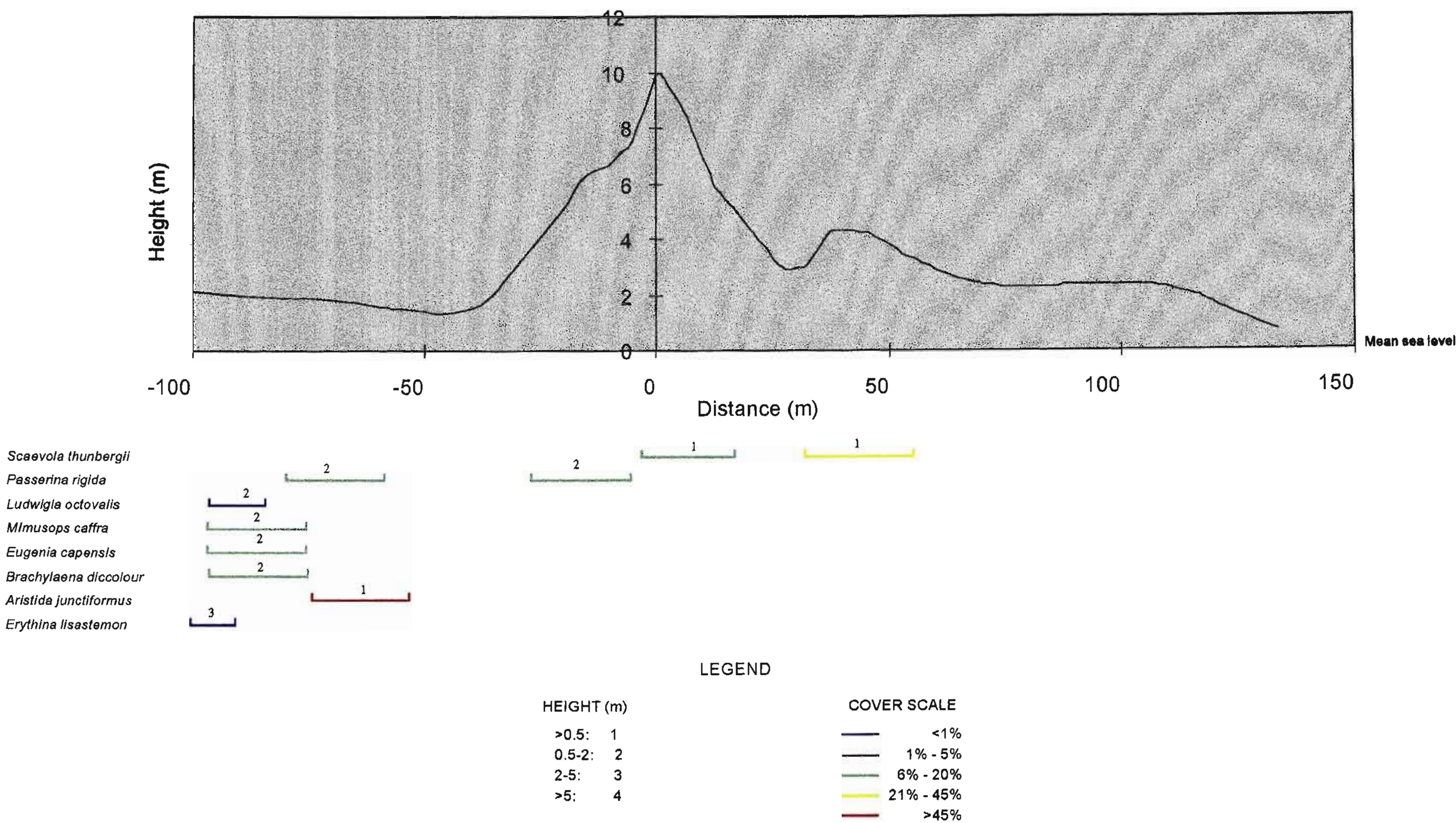


Figure 6.6 Profile 6 of the vegetation of the Tugela dunefield in September 1994. Species abundance is indicated in the lower part of the diagram as aerial cover in each quadrant along the cross-section. Negative distance refers to the extent inland of the fossil dune ridge.

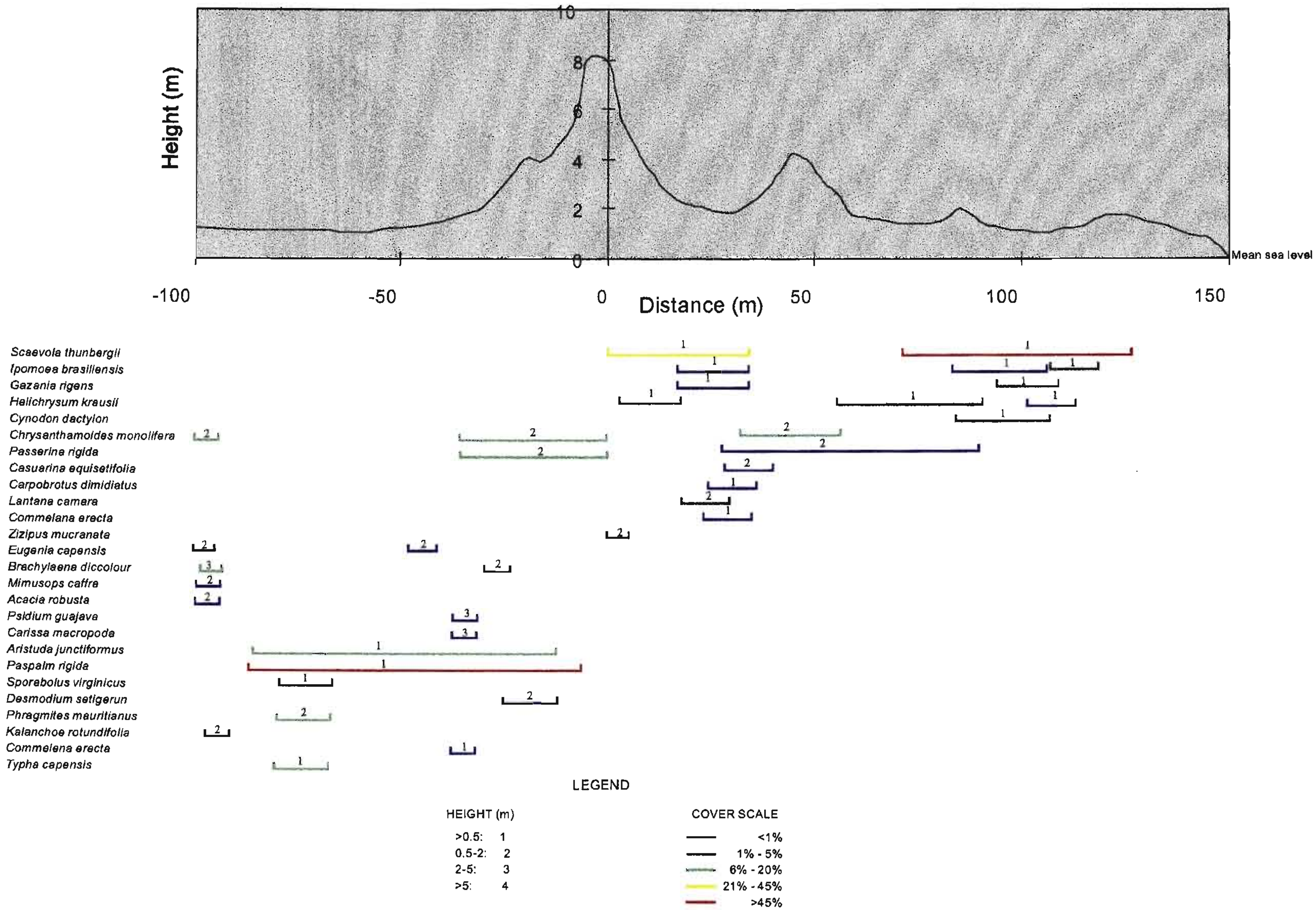


Figure 6.3 Profile 3 of the vegetation of the Tugela dunefield in September 1994. Species abundance is indicated in the lower part of the diagram as aerial cover in each quadrant along the cross-section. Negative distance refers to the extent inland of the fossil dune ridge .

This community is approximately 50 -100 m wide and is dominated by *Scaevola thunbergii* (Plate 6.1). Common species include *Ipomoea brasiliensis, Gazania rigens, Helichrysum ericaefolium, Phylohydrax carnosa*. The community structure is simple, with a field layer 0-0.5 m high. Total cover values range from 5 to 90 %. Small patches of the grasses *Stenotaphrum secundatum* and *Cynodon dactylon* occur. A small wetland community is developed on a flat plain before the first dune ridge, approximately 200 m to the north of the Tugela River mouth where, *Typha capensis, Ludwigia octovalvis, Phragmites mauritianus, Paspalum* sp. and *Dactyloctenium australe* are dominant.

6.2.2. Open Dune Scrub

As one moves landwards there is a notable increase in species diversity. The most abundant species in this community are the shrub *Passerina rigida* and the forb *Helichrysum ericaefolium* (Plate 6.2). This zone is also characterized by *Tephrosia purpurea, Chrysanthemoides monilifera*, with seedlings and young plants of the Closed Dune Scrub community/vegetation type may also be found, including *Eugenia capensis* and *Mimusops caffra*. A number of alien invasives such as *Lantana camara* and *Chromalaena odorata* occur in sheltered enclaves on the lee face of the incipient dunes.

Two layers were recognised in this community. The field layer is 0-0,5 m high and the scrub layer 0-2 m high. Average cover values range form 10-50 % for the field layer and 5-80 % for the scrub layer.

6.2.3. Closed Dune Scrub

There is a gradual shift from Open to Closed Dune Scrub. This vegetation type occurs on

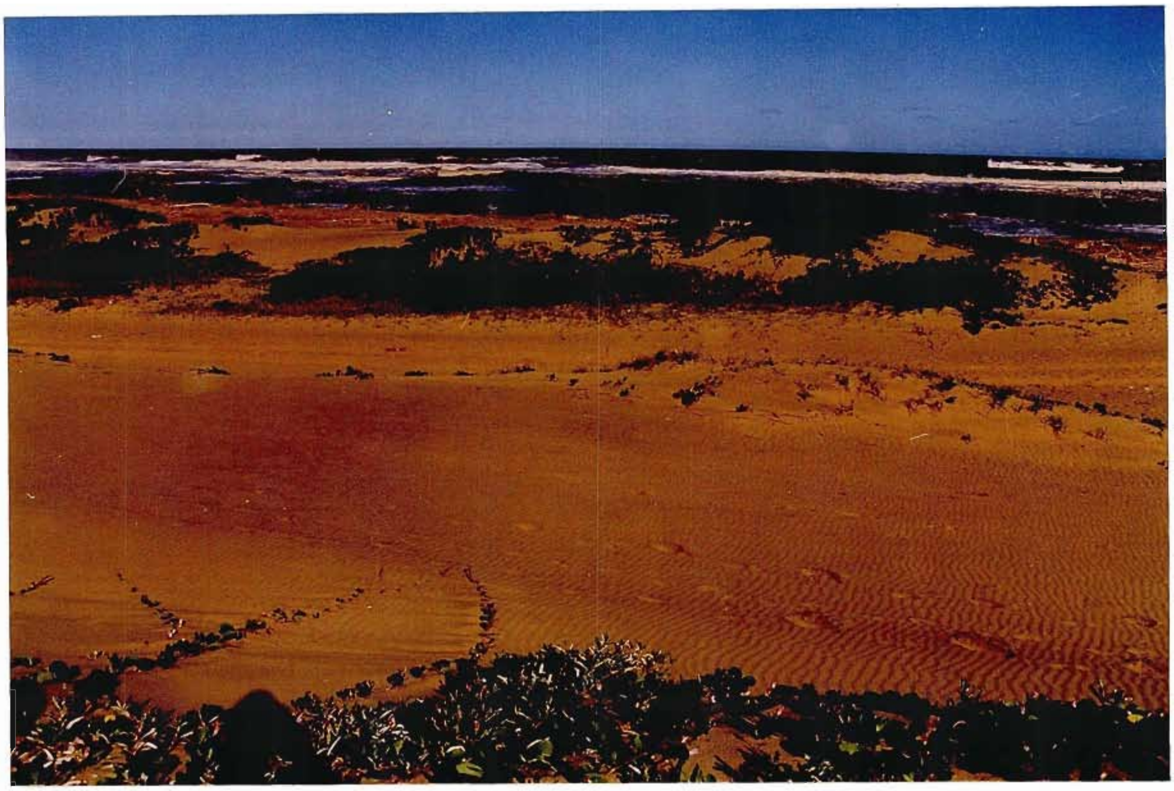


Plate 6.1 Embryonic foredunes colonised by *Scaevoli thunbergii*. *Ipomoea brasiliensis* and *Gazania rigens* are growing in the foreground.

Plate 6.2 Open dune scrub community dominated by *Passerina rigida* on the crest of the relict foredune.

the landward side of the first dune ridge and in parts of the large dune slack. Species present are *Eugenia capensis, Brachyleana discolour, Rhus nebulosa, Mimusops caffra, Carissa macropoda* and *Maytenus nemorosa.* This is a dense, unistratal community and typically displays a thicket-type structure. Total cover values range from 80 to a 100 % with heights varying from 1 to 5 m.

6.2.4. Dune Forest

This community was not surveyed in sample plots as it was not considered important in the evolution of the foredunes in the study area . However, Edwards (1967) provides a detailed description of the structure and floristic composition of the Hlogwene forest situated just south of the Tugela mouth. Unpublished observations by Olivier & Patrick (1994) note that approximately 85 % of the species that occur in the Hlogwene forest may be found in the dune forest landward of the study area.

6.3. DISCUSSION

The vegetation structure and floristic composition at Tugela Mouth is very similar to the dune vegetation, recorded between Mtunzini and Richards Bay (Weisser, 1978; Weisser *et* al, 1982; Weisser & Backer, 1983; van Daalen *et al.*, 1986; Weisser, 1987). The sampled area and the stretch of coastline to the north as far as the Siyayi River (38km) provides an excellent example of dune vegetation succession. The plant communities which characterize the dunes represent different stages of a successional sequence.

An early coloniser, *Scaevola thunbergii*, is dominant on the backshore environment. It is a hardy species, destroyed under marine erosion and apparently thriving with pulses of accretion. Once established it responds to burial by increasing the rate of elongation of its stems in relation to the dune surface (Ward, 1980). Continuous stem elongation and the development of a strong adventitious root system leads to the obstruction and restraining of sand particles (Edwards, 1967). Small patches of *Artotheca populifola* may also be found in the littoral zone and together with *Scaevola thunbergii* are ephemeral species, being destroyed during periods of erosion and re-establishing with phases of aggradation. Even under ideal circumstances these species die back after two or three years (Tinley, 1985).

Once a dune is stabilized it is colonised by *Gazania rigens* and *Ipomea pes-caprae* where soil conditions are more appropriate. Although these species may tolerate salt-spray to a degree, they do not appear to survive the harsh conditions to which *Scaevola thunbergii* is subjected (Ward, 1980). On the leeward side of the first dune ridge herbs such as *Tephrosia purpurea* proliferate as they are afforded protection under reduced wind velocities.

Over time woody species, typically *Passerina rigida* become more dominant, whereas under shaded conditions the *Scaevola thunbergii* declines in abundance. Under improved soil conditions and increased protection *Chrysanthamoides monolifera* and *Eugenia capensis* are able to establish (Ward, 1980). These plants are used as perch sites by birds which drop more seeds of shrub species around existing wood species thus creating bush clump nuclei, which coalesce through lateral or outward growth (Tinley, 1985).

On the leeward side of the first dune ridge and in the dune slack *Scaevola thunbergii* and *Passerina rigida* are outcompeted by a mixed scrub community, characterised by bush clumps. The bushclumps are dominated by *Brachylaena discolour*, *Mimusops caffra*, *Eugenia capensis*, *Chrysanthamoides monolifera* and *Passerina rigida*. van Daalen *et al.* (1986) suggest that the development of bushclumps represents an important step in the progression to dune forest. They act as regeneration sites for forest species and form forest cores which expand until the canopy is closed (van Daalen *et al.*, 1986). This may be observed in the northern part of the study area behind the first dune ridge. However, this pattern is discontinuous in the large dune slacks as the water table is high and the area is often inundated with water from the Tugela river under flood conditions or spring tides. Islands of bushclumps are interspersed by a grassland/wetland community, consisting of species such as *Aristida junciformis, Dactyloctenium australe, Helichrysum spp., Phragmites mauritianus* and *Typha capensis.*

As one moves north along the first dune ridge, it is broken by transgressive blowouts to form an interdigitated pattern. The tongues of sand are aligned in an east-west direction at right angles to the main dune ridge. The blowout is backed by the grassland/wetland community, parts of which have been inundated by aeolian sand. The development of a blowout at this particular locality could be related to the use of this section as a pathway for cattle to graze on the poor grass species present in the dunefield.

The occurrence of fire is sporadic and the development of the first dune ridge and large dune slacks towards a more fire tolerant species like grassland does not appear to occur.

6.4. BIOLOGICAL AND ECOLOGICAL PROCESSES

The density of both individual shoots and pioneer plant canopies have been observed to have a strong influence on sand deposition and foredune morphology (Olson, 1958a; Hesp, 1989). In order to examine this contention four hummock dunes and four foredunes were examined in the study area.

The shoot densities recorded on the foredunes at Tugela are relatively low when compared to shoot densities reported by Hesp (1989) for *Spinifex sericeus*, a common grass which is 25-30 cm in height (700-800 plant shoots m^{-2}) and *Ammophila arenaria*, an erect tufted grass of up to 1 m that grows in clumps (Table 6.1). Although the stem width of the *Scaevola thunbergii* (12-32 mm) is comparatively wide, the spacing between each shoot is large (0.15-0.3 m). Thus under moderate to strong winds the large spacing between each shoot allows the sand particles to pass relatively unhindered. However, *Scaevola thunbergii* has been shown to be effective in encouraging rapid sand accumulation, and growth rates of up to 180 mm per month have been observed (Olivier, 1996). The success rate of *Scaevola thunbergii* in increasing sand deposition in incipient foredunes can perhaps be attributed to aerial cover of up to 90%.

Table 6.1 The relationship between dune dimensions and plant shoot density, stem widths and vegetation structure in the study area; S refers to seaward facing; C refers to crest; L refers to landward facing.

Dune Description	Dune Height (m)	Dune Length (m)	Dune Width (m)	Shoot Density(m^2)	Basal Stem Widths (mm)	Vegetation Height (m)
Hummock Dunes 1	1	3	4	7.04	S: 12 C: 11 L: 13	S: 0.36 C: 0.41 L: 0.55
2	1.4	9	7.4	17.71	S: 11 C: 13 L: 12	S: 0.65 C: 0.85 L: 0.65
3	2.6	8.6	9.3	15.24	S: 14 C: 12 L: 13	S: 0.44 C: 0.55 L: 0.47
4	3.1	12.4	11.6	16.8	S: 14 C: 15 L: 12	S: 0.61 C: 0.78 L: 0.63
Foredune 1	1.1	20	10.7	13	S: 13 C: 12 L: 12	S: 0.38 C: 0.4 L: 0.44
2	1.5	17.2	9.3	17	S: 13 C: 12 L: 13	S: 0.45 C: 0.52 L: 0.47
3	3	18.8	15.4	13.68	S: 15 C: 17 L: 11	S: 0.55 C: 0.74 L: 0.75
4	5	50	19	19.12	S: 13 C: 14 L: 15	S: 0.67 C: 0.46 L: 0.79

Plant distribution alongshore and within plant canopies was not measured and could perhaps account for foredune shape in the study area. Hesp (1989) revealed that flow adjusts rapidly to changes in surface roughness. Creep and saltation was observed in small areas within canopies, resulting in particular areas that erode and others that accrete. Hesp (1983) contends that the processes described above may account for downwind and alongshore variations in dune morphology

6.5. CONCLUSION

The sand dunes to the north of Tugela mouth provides an excellent example of vegetation-succession. Since most of the South African coastline is eroding, the four plant communities observed in the study area are rarely complete. Weisser *et* al. (1982) claims that this is typical of an accreting coastline. The study area represents a catena of parallel phytogenic dune ridges, which forms a progressive gradation in age, size and complexity of dunes and plant communities from the backshore landwards.

Pioneer plant species contrast in mode of beach colonisation (eg. seedlings, shoot production, rhyzome development), in morphology (eg. low, prostate, open herbs vs. tall, erect, dense tufted grasses), in growth rates, survival rates and as a consequence of a number of environmental factors (eg. rate of sand inundation, surface erosion, salt spray deposition, swash inundation, seasonal variations in precipitation, nutrient levels and temperature regime (Hesp, 1989). The variation in the findings of Hesp (1983, 1989) and that observed in the study area could be ascribed to any one or a combination of these variables. A more detailed study examining the effect of wind flow over a vegetated foredunes and the relationship vegetation and dune relief is required.

CHAPTER 7.

FOREDUNE DYNAMICS AT TUGELA RIVER MOUTH

7.1. INTRODUCTION

The ensuing chapter focuses on the development of foredunes and beach ridges. Results of the tacheometric field surveys are presented and related to sediment availability and the wind regime in the study period. A range of factors influencing foredune morphology and evolution are examined. A variety of models of foredune evolution are examined in an attempt to explain the foredune-ridge formation adjacent to the Tugela River mouth.

7.2. TACHEOMETRIC FIELD SURVEYS

7.2.1. Dunefield Topography and Shoreline Changes

Dune types include hummock dunes, foredunes, parabolic dunes and fossil dune ridges (retention ridges). The study site has a surface area of between 2.59 km^2 and 4.27 km^2, depending on the shoreline position. Slopes range from 25° -32° from the horizontal, but angles of 32° -35° were found on the avalanching slip faces.

The western boundary of the study area includes the first fossil dune ridge, up to 14 m in height. Seaward of the first dune ridge is a number of hummock dunes and foredunes. During the rainy months the dune slacks can fill with water. Occasionally a small lagoon 1000 m in length and 50 m in width forms behind the first foredune. It generally results from overwash during spring tides and is supplemented with rainfall. A large blowout occurs on the first fossil dune ridge in the north western part of the study area.

Table 7.1 reveals that between June 1993 and February 1996 the coastline regressed at 14 of the 16 cross-sections by an average of 113.97 m. Higher rates of coastal erosion were recorded near

Table 7.1 Shoreline widths as measured (m) from the first fossil dune ridge on the western boundary of the study area.

Cross-section	July 1993	December 1993	February 1994	July 1994	May 1995	February 1997
1	191.65			191.65	151.30	136.17
2	245.09	192.93	290.13	243.38	139.08	93.57
3	302.28	225.86	265.13	273.41	202.09	118.87
4	327.19	245.39	181.34	276.07	235.17	173.82
5	307.21	233.26	130.29	256.62	227.01	148.44
6	310.34	215.10	124.99	235.58	235.58	157.87
7	320.92	196.63	109.94	220.32	232.17	149.99
8	292.0		97.54	201.77	212.25	151.33
9	261.53		205.34	147.95	200.46	161.79
10	256.32		234	177.72	224.31	177.58
11	275.28		220.15	193.27	207.92	170.75
12	232.65		229.32	166.18	232.65	172.83
13	233.41		228.43	156.63	225.73	171.99
14	193.74		191.3	190.92	240.41	219.20
15	184.60		218.17	142.65	201.38	170.34
16	161.96		191.0	133.36	164.23	173.52

Erosion **Accretion** **No Information**

the mouth, reducing in a northward direction. Marine erosion generally occurred over the wet period (October - April), with minimal accretion recorded in the dry months (May-September). Although an incomplete data set exists for December 1993, the available cross-sections indicate that the shoreline regressed between July 1993 and December 1993. Average erosion for this period was 83.98 m.

Between December 1993 and February 1994 minimal coastline progradation occurred, with a general retreat ranging from 4.98 m to 194.46 m. The average erosion was 62.07 m at 11 of the 15 cross-sections. Two cross-sections close to the river mouth and a further two in the northern section of the study area experienced coastal accretion averaging 49.77 m.

From February 1994 to July 1994 shoreline aggradation of 92.42 m at six locations, while 9 cross-sections experienced erosion averaging 50.61 m. Coastline accretion occurred in the central areas with erosion in the northern section of the study area.

The results of the tacheometric survey conducted in December 1994 was lost, thus the coastal positions are averaged over the whole year (July 1994- May 1995). Coastal progradation occurred at 11 of the cross-sections at an average of 40.04 m. Erosion of the shoreline was recorded at 4 of the locations averaging 64.22 m. Erosion occurred near the mouth with accretion in the northern section of the study area.

Between May 1995 to February 1996 the coastline regressed at 15 of the 16 cross-sections, averaging 53.97 m.

7.2.2. Volume Calculations

Volume computations for the whole study area were conducted for those surveys where data sets were complete (Table 7.1). The results reveal that the study area has experienced a large amount of erosion from July 1993 to February 1996 (29.17%). A small amount of accretion occurred between July 1994 and May 1995. River.

Table 7.2 Volume computations for the study area calculated on the -3m base datum level.

Survey date	Total volume (m^3)	% erosion (-) /accretion (+)
July 1993	2 223 976.67	
July 1994	1 802 736.67	- 18.94
May 1995	1 850 226.67	+ 2.57
February 1996	1 575 323.33	-14.86

7.2.3. Cross-sections

Cross-section locations are indicated in Fig 7.1.

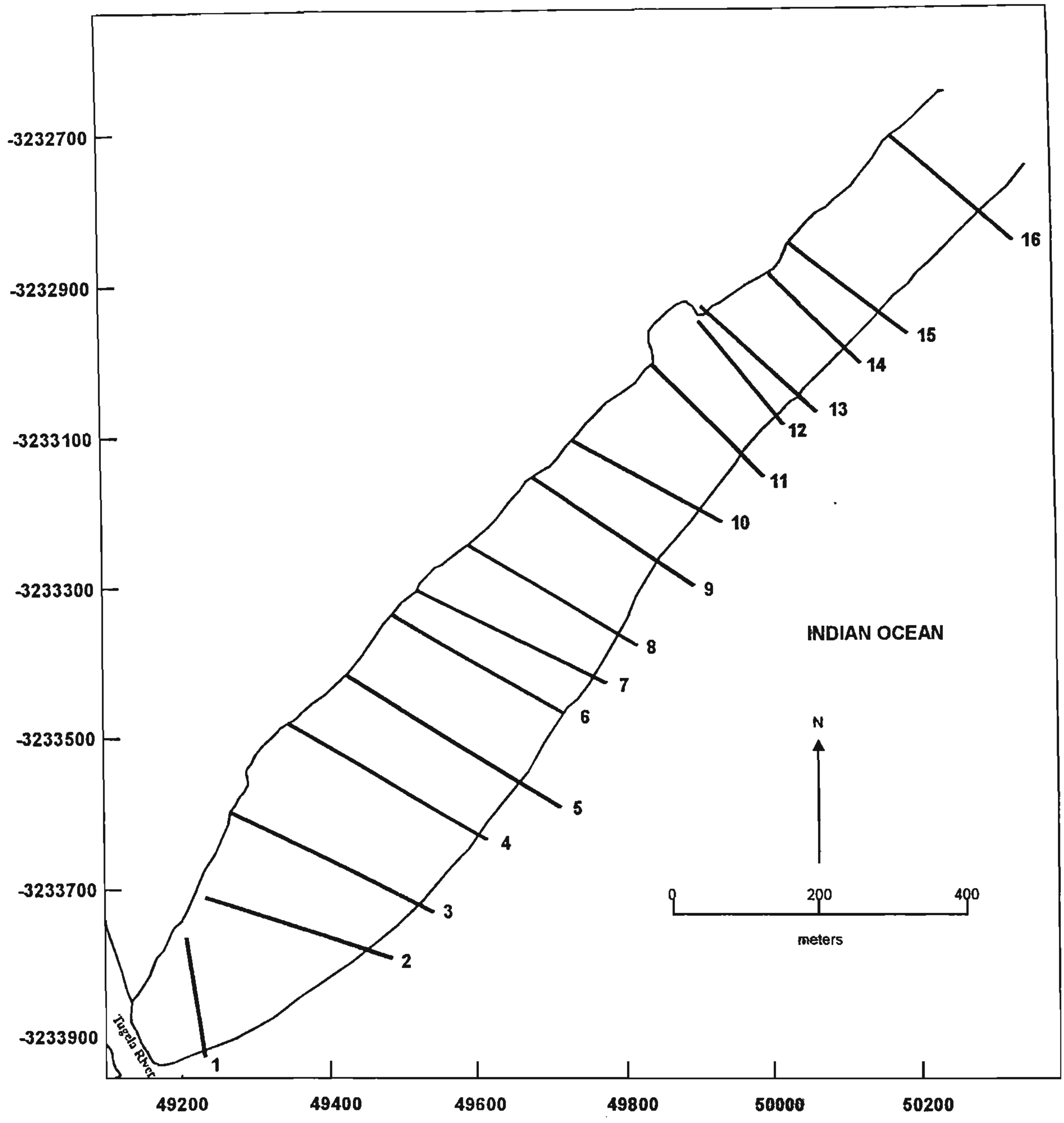


Figure 7.1 Cross-section locations. The grid is based on the South African Co-ordinate System.

7.2.3.1. *Cross-section 1*

Cross-section 1 is located in the southern end of the study area adjacent to the Tugela River mouth (Fig. 7.2). Between July 1993 and May 1995 the crest of foredune 1 steadily increased in height by 0.89 m (Table 7.3). However, by February 1996 the crest had declined by 0.54 m, with a corresponding increase in the basal width. Foredune growth occurred when the beaches were relatively wide (100 m).

Table 7.3 Variation in the foredune crest heights (m) for cross-section 1 between July 1993 and February 1996.

Foredune number	July 1993	December 1993	July 1994	May 1995	February 1996
1	2.47	2.64	3.26	3.36	2.82

7.2.3.2. *Cross-section 2*

Foredune 1 moved landward as the shoreline eroded (Fig. 7.3). Between July 1993 and December 1993 the foredune crest increased in height by 0.34 m before eroding to 1.22 (Table 7.4). From February 1994 to May 1995 the foredune accreted vertically by 0.62 m, at a rate of 41 mm per month. However, by February 1996 the shoreline had regressed eroding the dune completely. Foredune 2 began forming between the reconnaissance field visit in February 1993 and July 1993. A small lagoon (500 m in length and 30 m in width) developed immediately seaward of foredune 2. The foredune crest increased in height by 1.08 m (36 mm per month) between July 1993 and February 1996.

Table 7.4 Variations in the foredune crest heights (m) for cross-section 2 between July 1993 and February 1996.

Foredune number	July 1993	December 1993	February 1994	July 1994	May 1995	February 1996
1	1.51	1.85	1.22	1.44	2.04	eroded
2	1.49	1.49	1.33	1.78	2.23	2.58

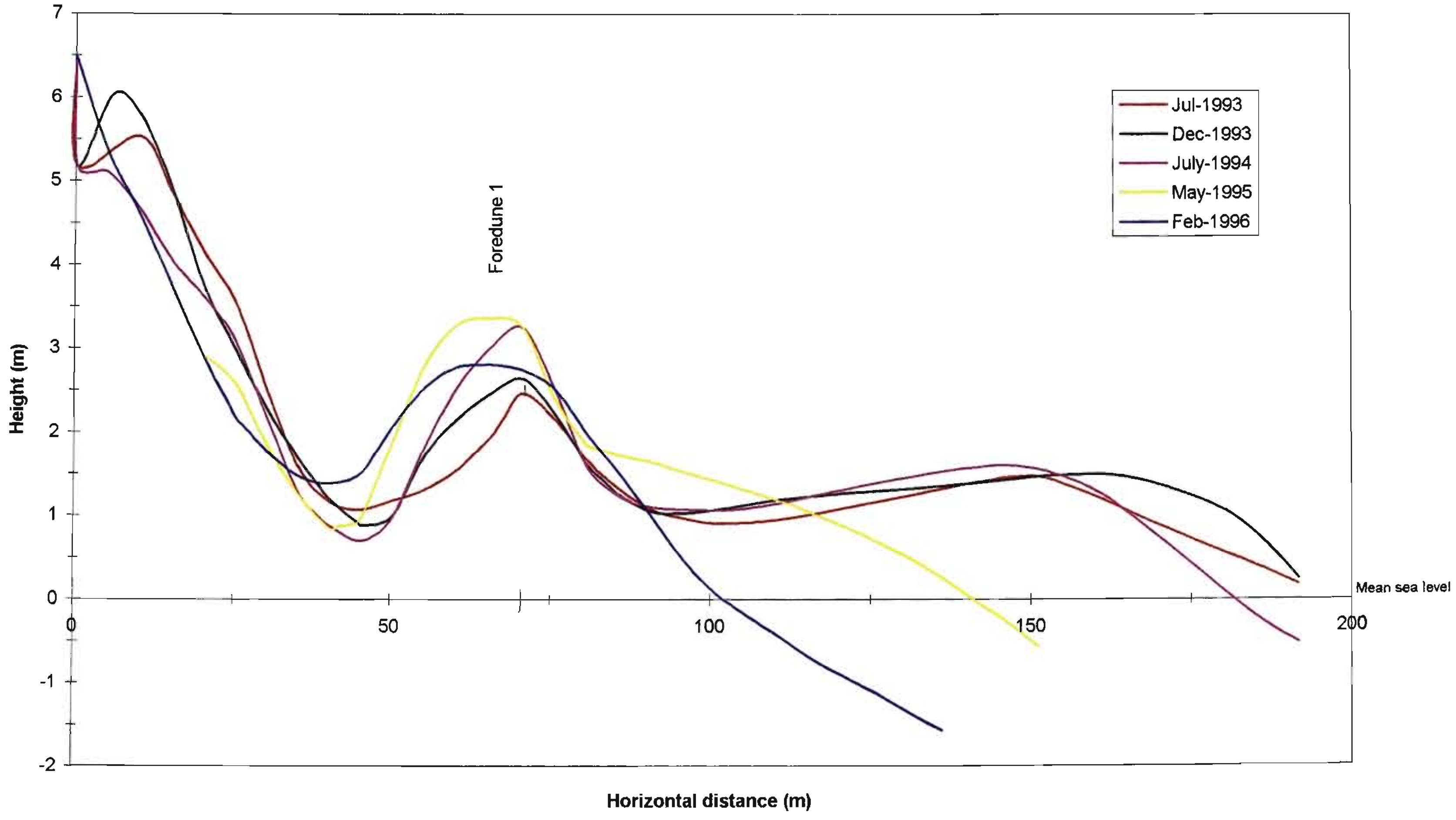
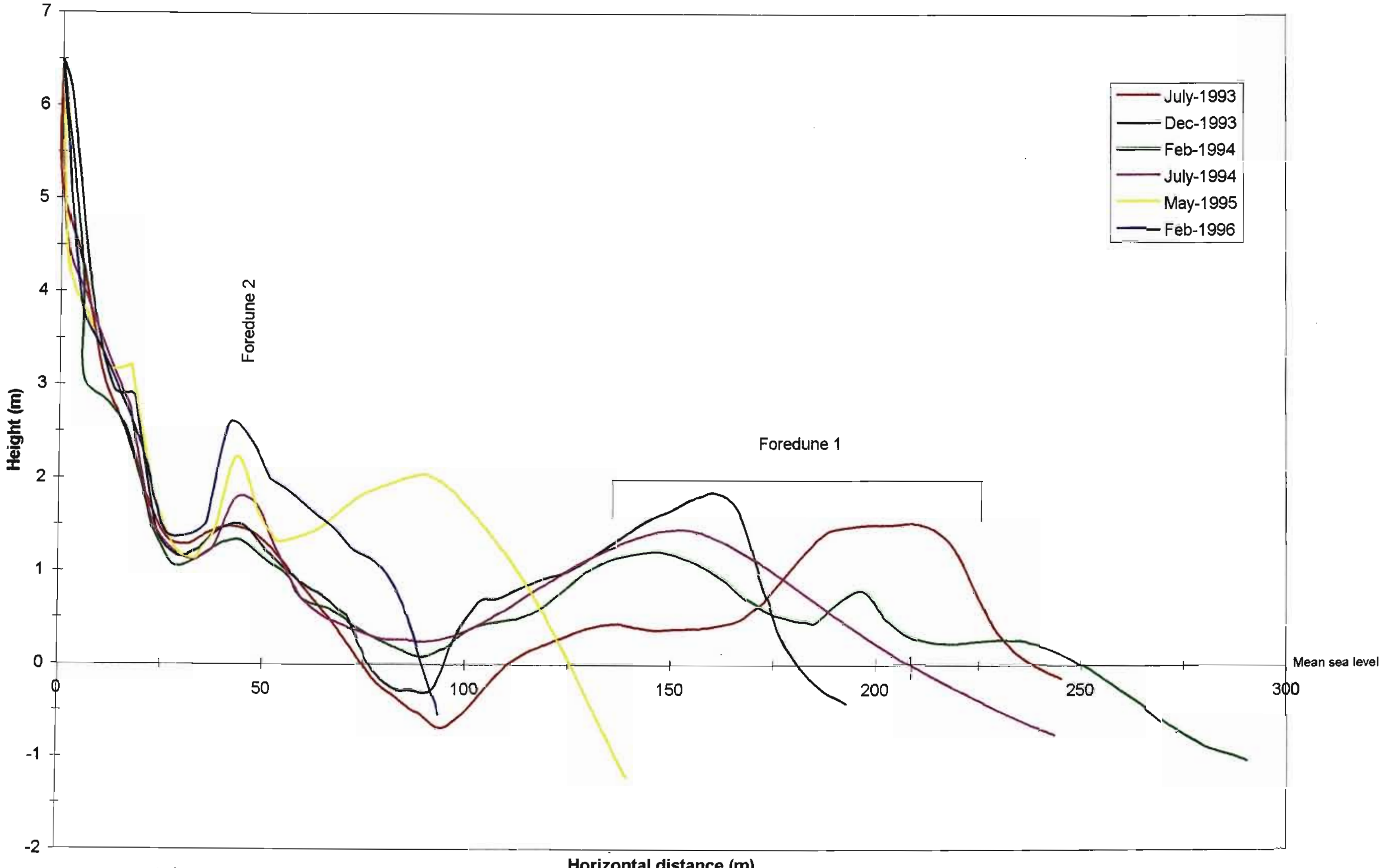


Figure 7.2 Cross-section 1



1m = 0,68 m

Fig7.3 Cross-section 2

7.2.3.3. *Cross-section 3*

A cursory examination of cross-section 3 shows a complex set of morphological changes (Fig. 7.4). However, a closer examination reveals a rollback effect of the seaward most foredune. Although the dune crest fluctuated marginally in height the dune migrated inland by 108 m from July 1993 to May 1995, as the shoreline regressed (Table 7.5). However, by February 1996 the whole foredune had eroded away. Although a number of small foredunes developed landward of this, there appeared no pattern in their formation and destruction.

Table 7.5 Variation in the foredune crest heights (m) for cross-section 3 between July 1993 and February 1996.

Foredune number	July 1993	December 1993	February 1994	July 1994	May 1995	February 1996
1	1.85	1.39	1.36	1.41	1.95	eroded

7.2.3.4. *Cross-section 4*

Foredune 1 moved inland as the shoreline regressed (Fig. 7.5). It decreased in height by 0.98 m between July 1993 and December 1993, before gradually accreting to former levels by February 1996 (Table 7.6). In July 1993 a small lagoon had formed behind foredune 1 and slowly became infilled with sediment.

Similarly, foredune 2 decreased in height by 0.41 m between July 1993 and December 1993, before rebuilding, eroding and accreting again. Foredune 3 slowly eroded away, possibly loosing sediment to foredune 2.

Table 7.6 Variation in the foredune crest heights (m) for cross-section 4 between July 1993 and February 1996.

Foredune number	July 1993	December 1993	February 1994	July 1994	May 1995	February 1996
1	2.67	1.69	eroded	1.88	1.89	2.68
2	2.08	1.67	2.34	2.36	1.25	2.67
3	1.61	1.82	1.77	1.32	0.75	lost data

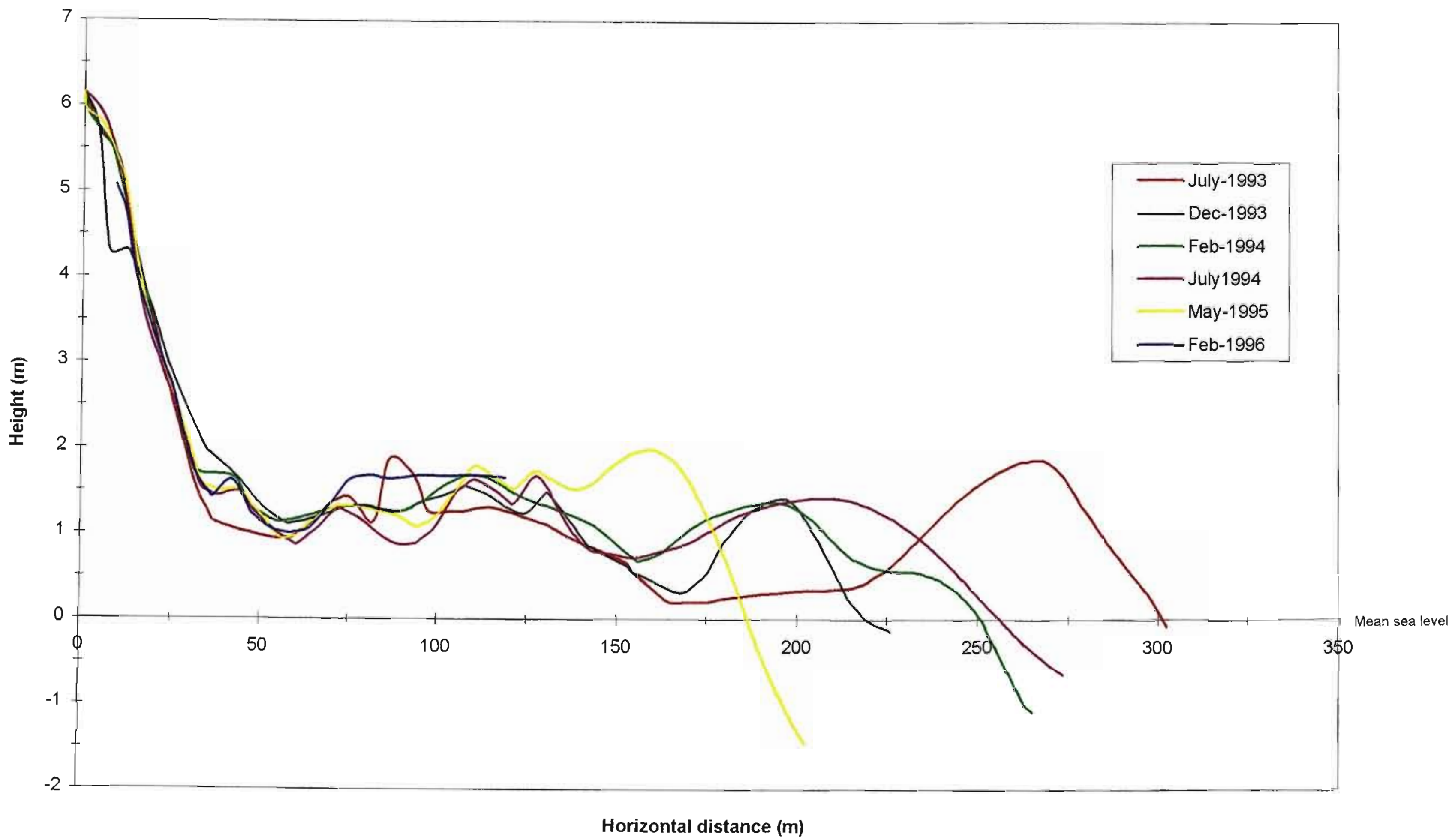
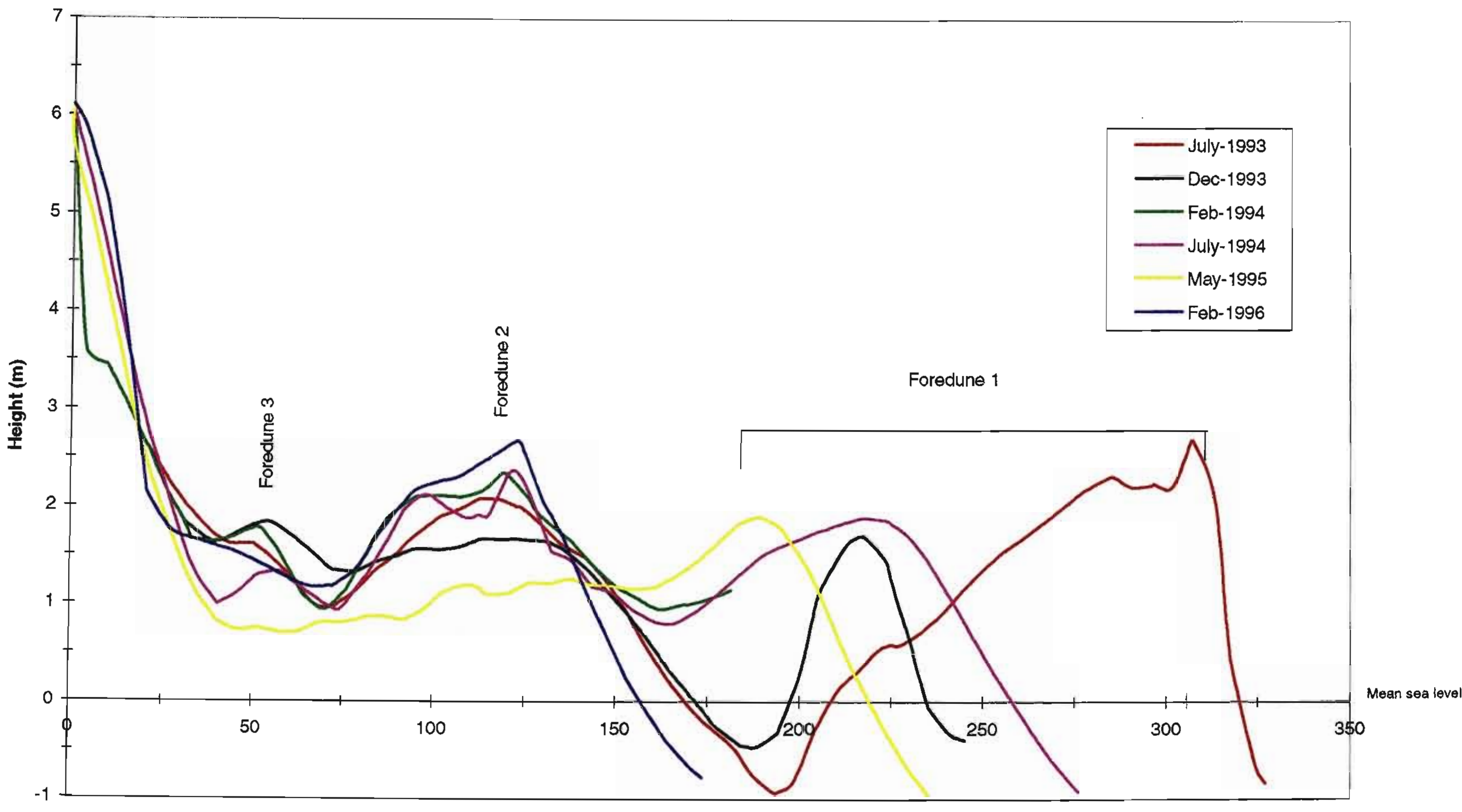


Figure 7.4 Cross-section 3



1 m = 1,85 m

Figure 7.5 Cross-section 4

7.2.3.5. <u>*Cross-section 5*</u>

Between July 1993 and December 1993 foredune 1 shifted shoreward by 61 m (Fig.7.6). Over the same period the dune crest decreased by 0.32 m (Table 7.7). By February 1994 the whole foredune had been eroded away only to have reformed 5 months later and accrete vertically to 2.41 m. However, by February 1996 the dune was completely eroded away.

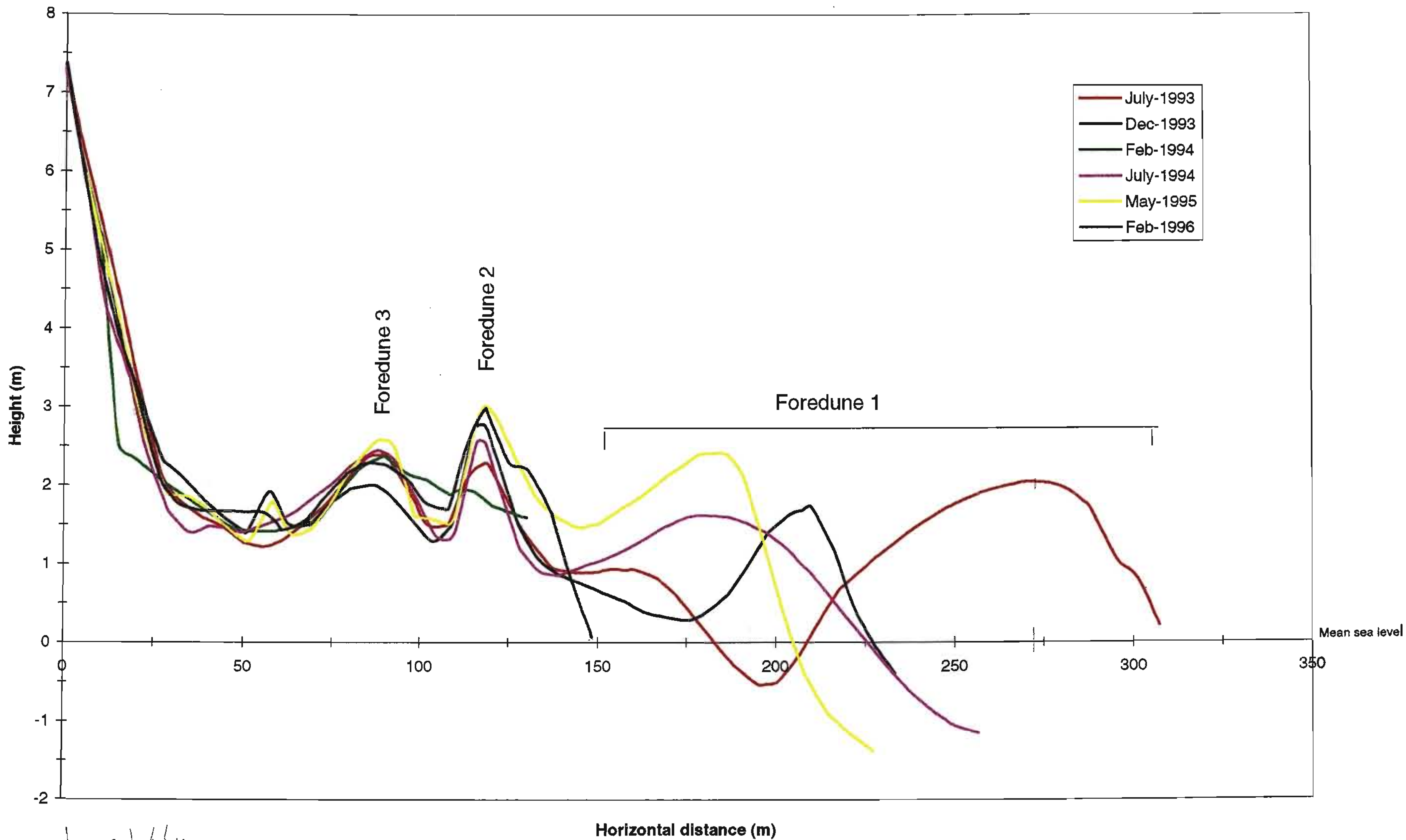
Foredune 2 was more stable and steadily increased in height by 0.69 m over the survey period. As the dune crest accreted the dune width increased. Foredune 3 remained stable throughout the survey period.

Table 7.7 Variation in the foredune crest heights (m) for cross-section 5 between July 1993 and February 1996.

Foredune number	July 1993	December 1993	February 1994	July 1994	May 1995	February 1996
1	2.05	1.73	eroded	1.62	2.41	eroded
2	2.29	2.77	eroded	2.56	3.02	2.98
3	2.39	2.01	2.38	2.44	2.58	2.30

7.2.3.6. <u>*Cross-section 6*</u>

Foredune 1 went through several cycles of formation, erosion and reconstruction (Fig 7.7). The foredune crest increased in height between July 1993 and December 1993 at 20 mm per month, before completely eroding by February 1994 (Table 7.8). Five months later the dune had re-established itself 50 m seaward at a marked accretion rate of 41.6 mm per month. Foredune 2 was generally more stable with a slight decrease in crest height of 0.24 m between July 1993 and February 1996. Dune 3 decreased by 0.23 m over the same period. In most cases the foreshore was steep and was characterised by narrow beaches.



1m = 1.66m

Figure 7.6 Cross-section 5

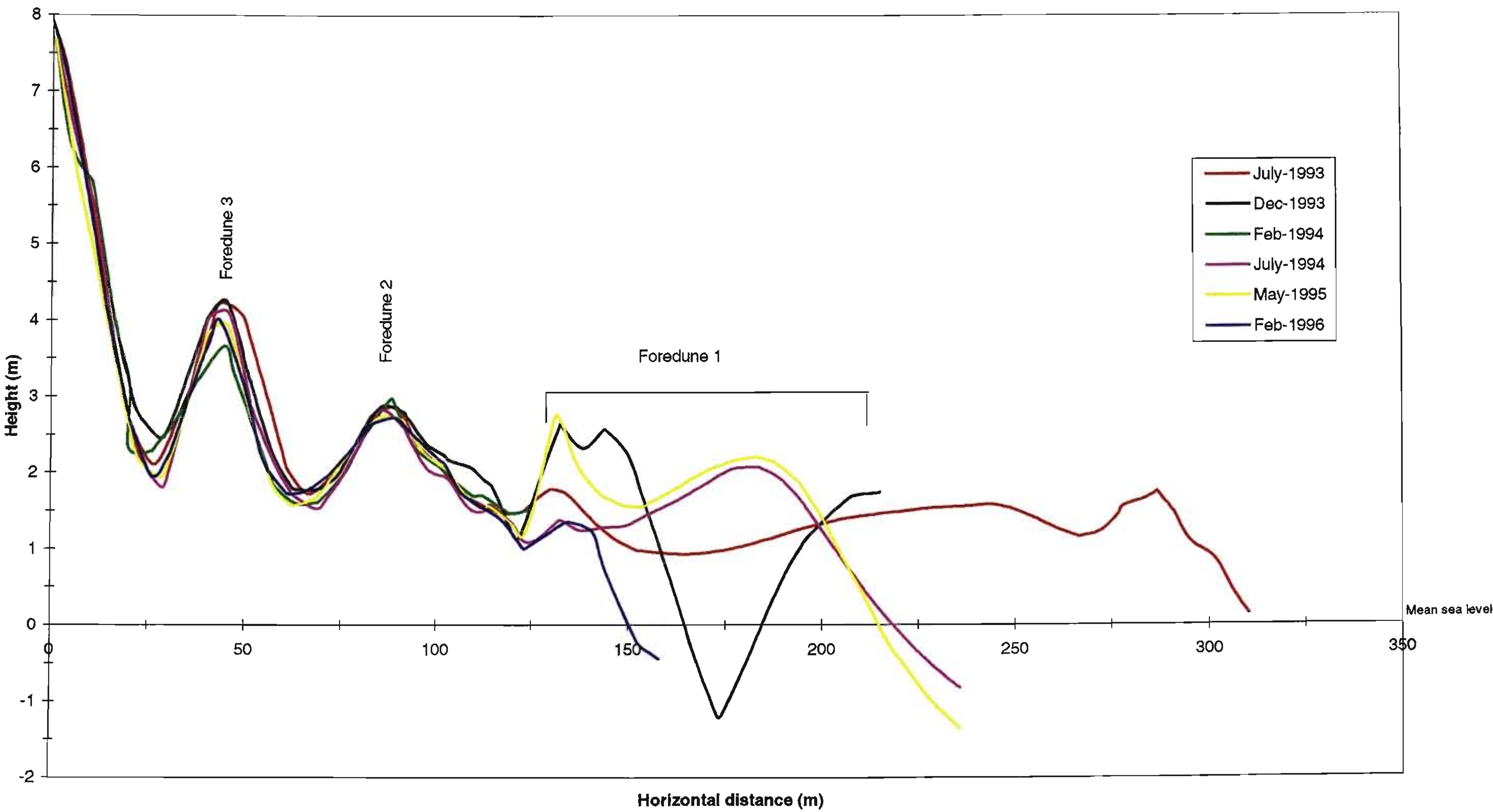


Figure 7.7 Cross-section 6

Table 7.8 Variation in the foredune crest heights (m) for cross-section 6 between July 1993 and February 1996.

Dune number	July 1993	December 1993	February 1994	July 1994	May 1995	February 1996
1	1.57	2.57	eroded	2.08	2.20	1.35
2	2.86	2.88	2.96	2.83	2.74	2.64
3	4.23	4.23	3.66	4.08	3.93	4.0

7.2.3.7. *Cross-section 7*

The change in the foredune height and shape is complex in cross-section 7 (Fig 7.8). Foredune 1 increased in height by 0.57 m (95 mm per month) between July and December 1993 (Table 7.9). From December to July 1994 the foredune had rolled back by 16 m and reduced in height by 0.71 m. In May 1995 the foredune reformed in its former position and enlarged to 2.5 m at a rate of 6.2 mm per month. However, by February 1996 the same dune was completely eroded as the shoreline receded.

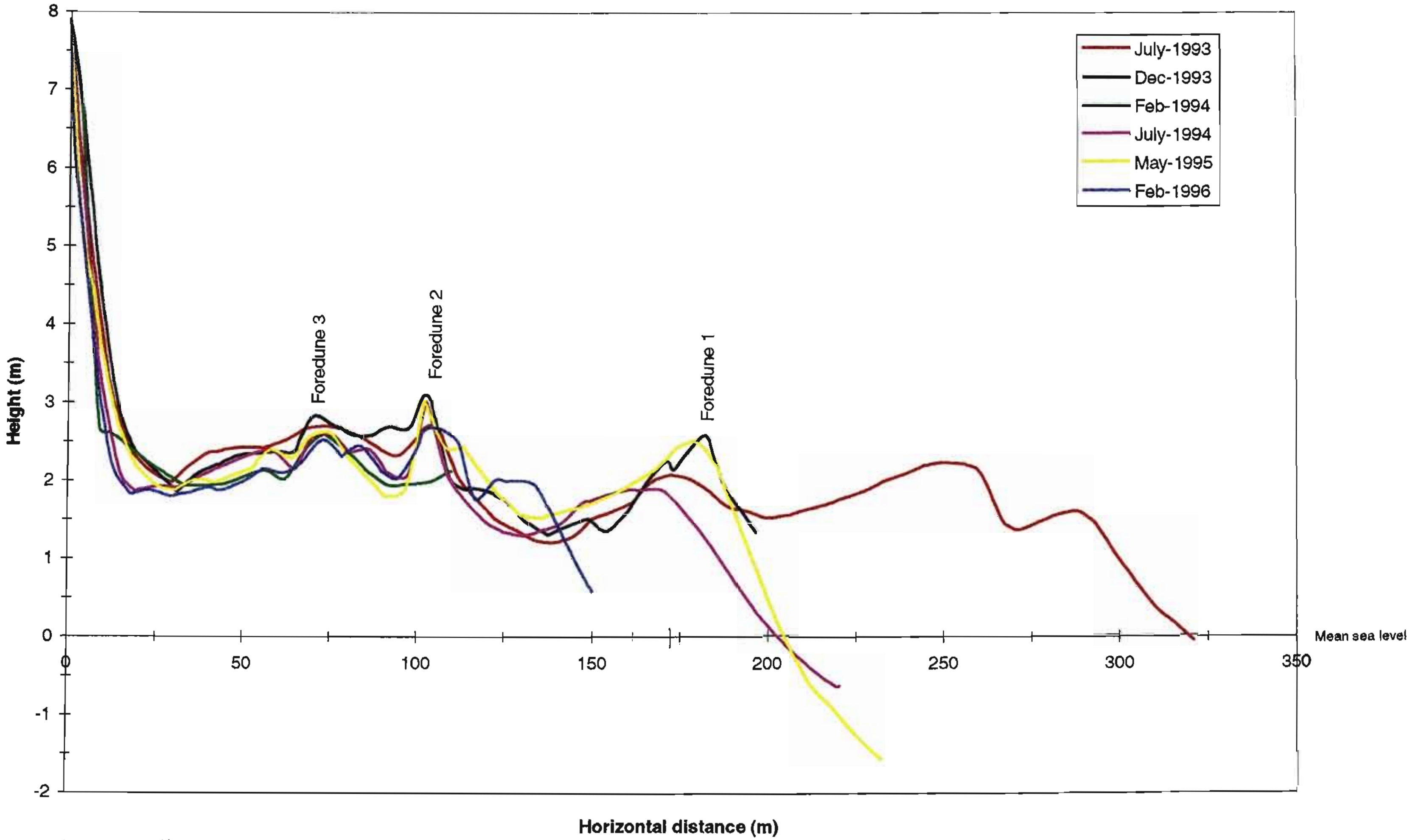
In comparison foredune 2 was more stable and increased in height by 0.39 m between July 1993 and December 1993. Between December 1993 and May 1995 the foredune was stable. However, from May 1995 to February 1996 the foredune decreased in height by 0.36 m. Foredune 3 remained generally stable over the survey period.

Table 7.9 Variation in the foredune crest heights (m) for cross-section 7 between July 1993 and February 1996.

Foredune number	July 1993	December 1993	February 1994	July 1994	May 1995	February 1996
1	2.02	2.59	lost data	1.88	2.50	eroded
2	2.67	3.06	lost data	2.99	3.01	2.64
3	2.70	2.71	2.58	2.58	2.62	2.53

7.2.3.8. *Cross-section 8*

Like many establishing foredunes, foredune 1 was completely eroded away and later reformed and grew to its former dimensions (Fig. 7.9). Dune 2 began to form in July 1994 and accreted



1m = 1,85

Figure 7.8 Cross-section 7

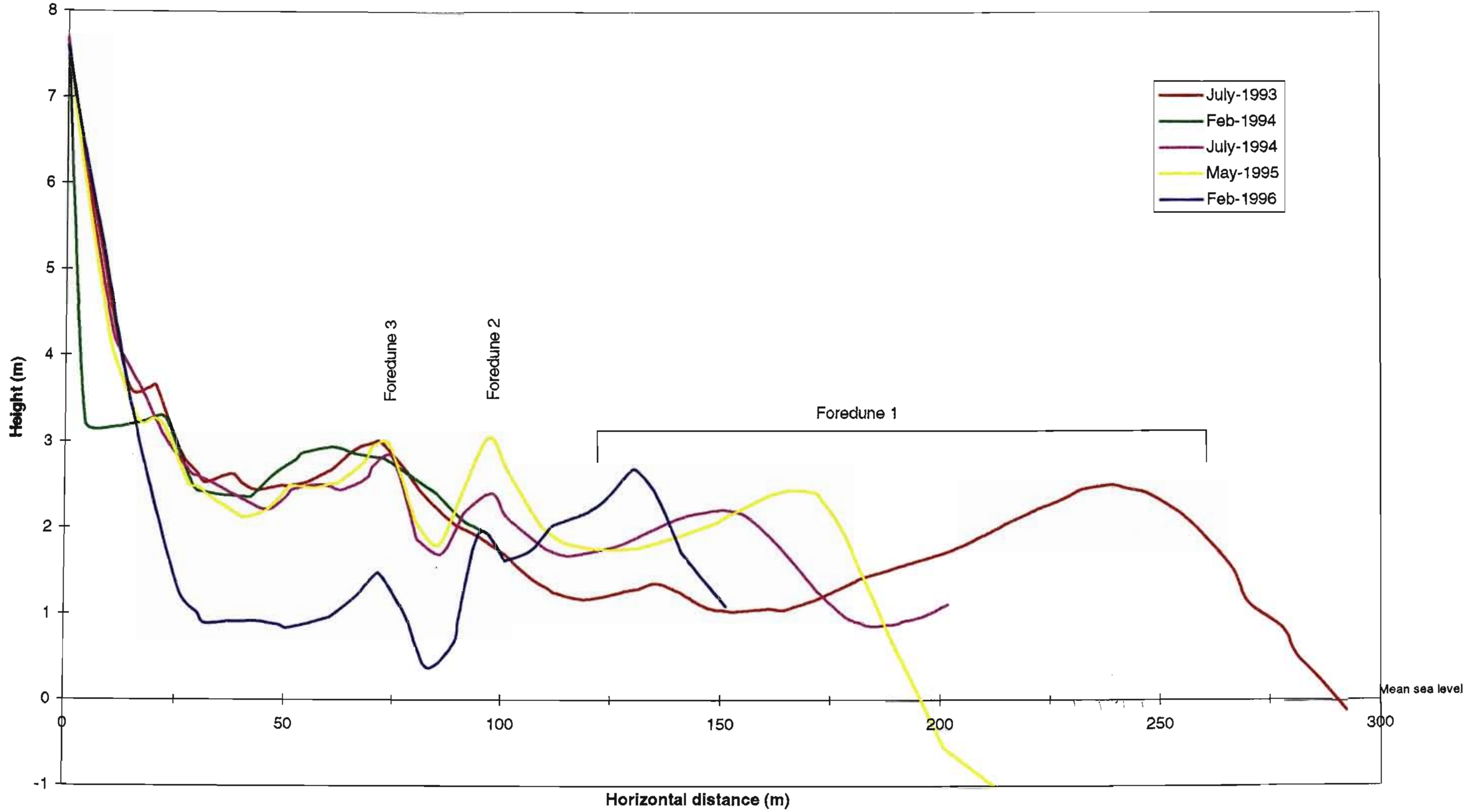


Figure 7.9 Cross-section 8

by 0.64 m from July 1994 to May 1995, before eroding markedly between May 1995 and February 1996 (Table 7.10). Similarly foredune 3 displayed high erosion rates from May 1995 to February 1996 and decreased by 1.50 m (50 mm per month).

Table 7.10 Variation in the foredune crest heights (m) for cross-section 8 between July 1993 and February 1996.

Foredune number	July 1993	February 1994	July 1994	May 1995	February 1996
1	2.51	eroded	2.22	2.44	2.68
2	not yet formed	lost data	2.41	3.05	1.95
3	3.0	2.94	2.82	2.97	1.47

7.2.3.9. <u>*Cross-section 9*</u>

Foredune 1 increased in height by 0.81 m from July 1993 to February 1994 from 3.70 m to 4.51 m before at a rate of 105 mm per month for the remainder of the survey period (Fig. 7.11 and Table 7.10). The increase in dune height between July 1994 and May 1995 occurred during a phase of slight shoreline progradation. The foreshore was typically steep resulting in narrow beaches. Foredune 2 decreased in height between July 1993 and February 1994 by 1.58 m (226 mm per month). The dune started to accrete between May 1995 to February 1996.

Table 7.11 Variation in the foredune crest heights (m) for cross-section 9 between July 1993 and February 1996.

Foredune number	July 1993	February 1994	July 1994	May 1995	February 1996
1	3.70	4.51	3.58	3.76	1.99
2	6.31	4.73	4.81	4.80	5.34

7.2.3.10. <u>*Cross-section 10*</u>

Foredune 1 has undergone a phase of erosion between July 1993 and February 1994 followed by a period of accretion until May 1995 (Fig. 7.11). Between May 1995 and February 1996 the dune crest decreased by 2.49 m, probably linked to coastal recession of 25m (Table 7.12). Approximately 48 m landward of foredune 1 a new dune started forming in May 1995 and had

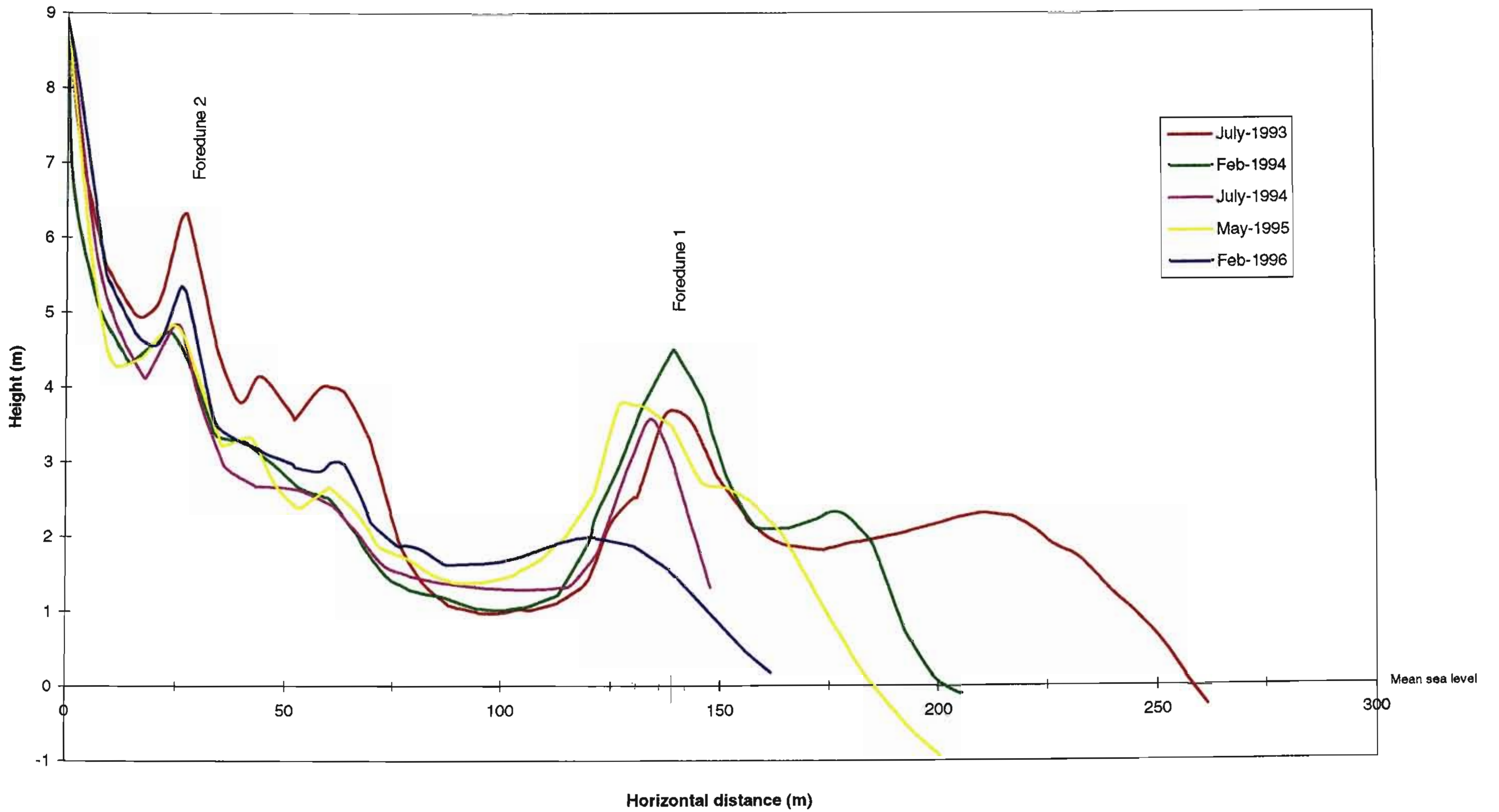


Figure 7.10 Cross-section 9

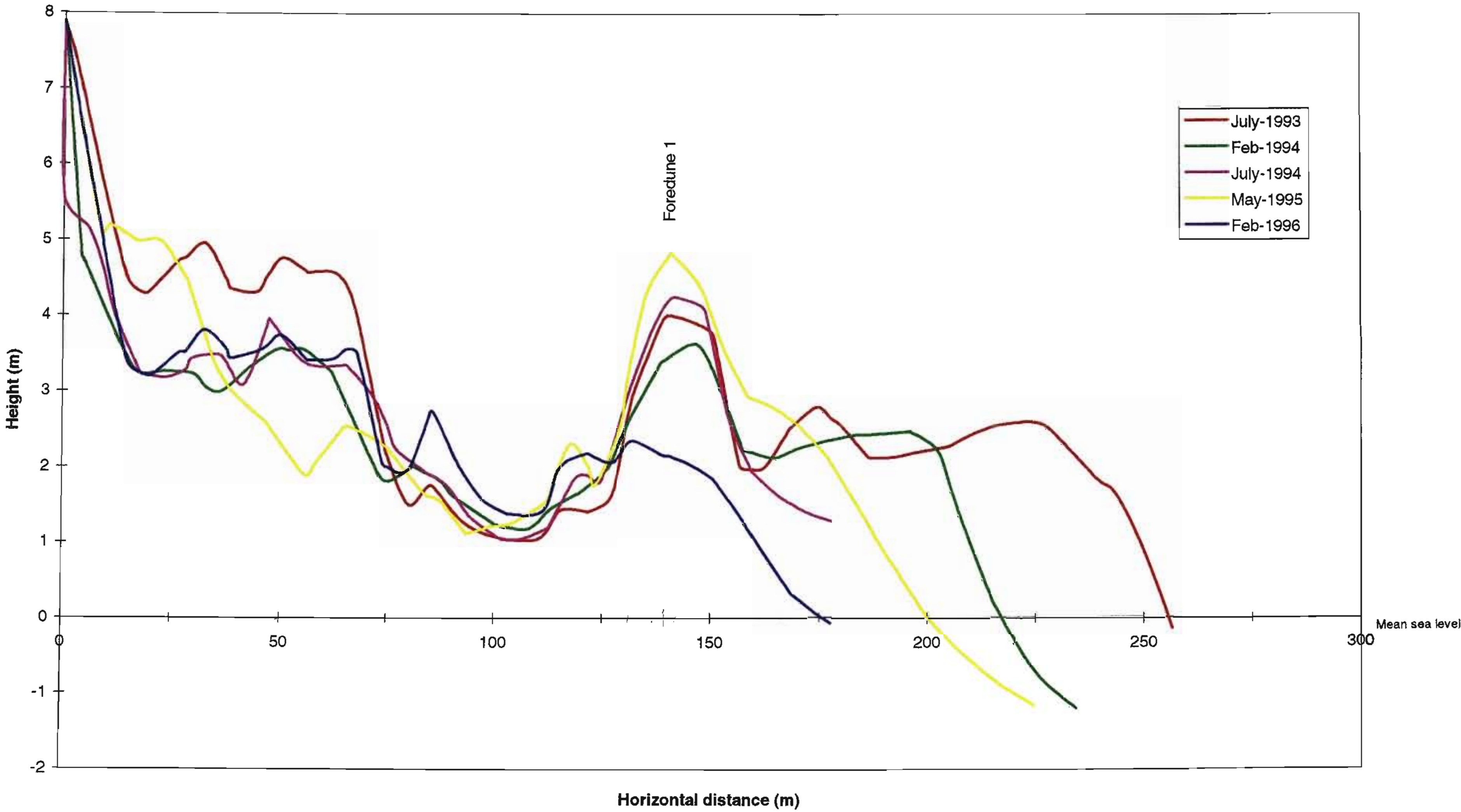


Figure 7.11 Cross-section 10

accreted to 2.72 by February 1996. Over the whole survey period there were a complex set of erosion and accretion phases as well as a landward and shoreward movement of foredune crest positions between 50 to 100m from the western boundary of the study area.

Table 7.12 Variation in the foredune crest heights (m) for cross-section 10 between July 1993 and February 1996.

Foredune number	July 1993	February 1994	July 1994	May 1995	February 1996
1	3.99	3.61	4.24	4.81	2.32

7.2.3.11. *Cross-section 11*

Foredune 1 eroded between July 1993 to February 1994 before increasing in size to its former dimensions by February 1996 (Fig. 7.12 and Table 7.13). The foredune was generally stable with the dune crest migrating 13 m seaward over the survey period.

Table 7.13 Variation in the foredune crest heights (m) for cross-section 11 between July 1993 and February 1996.

Foredune number	July 1993	February 1994	July 1994	May 1995	February 1996
1	4.50	3.22	3.46	4.04	4.52

7.2.3.12. *Cross-section 12*

From season to season both foredune 1 and 2 experienced phases of erosion and accretion (Fig 7.13 and Table 7.14). When one dune increased in size the other decreased in size, which due to their close proximity to one another would suggest dune scavenging. Although the crest heights fluctuated from season to season their dimensions remained more or less the same over the survey period. The shoreline position did not appear to influence foredune evolution.

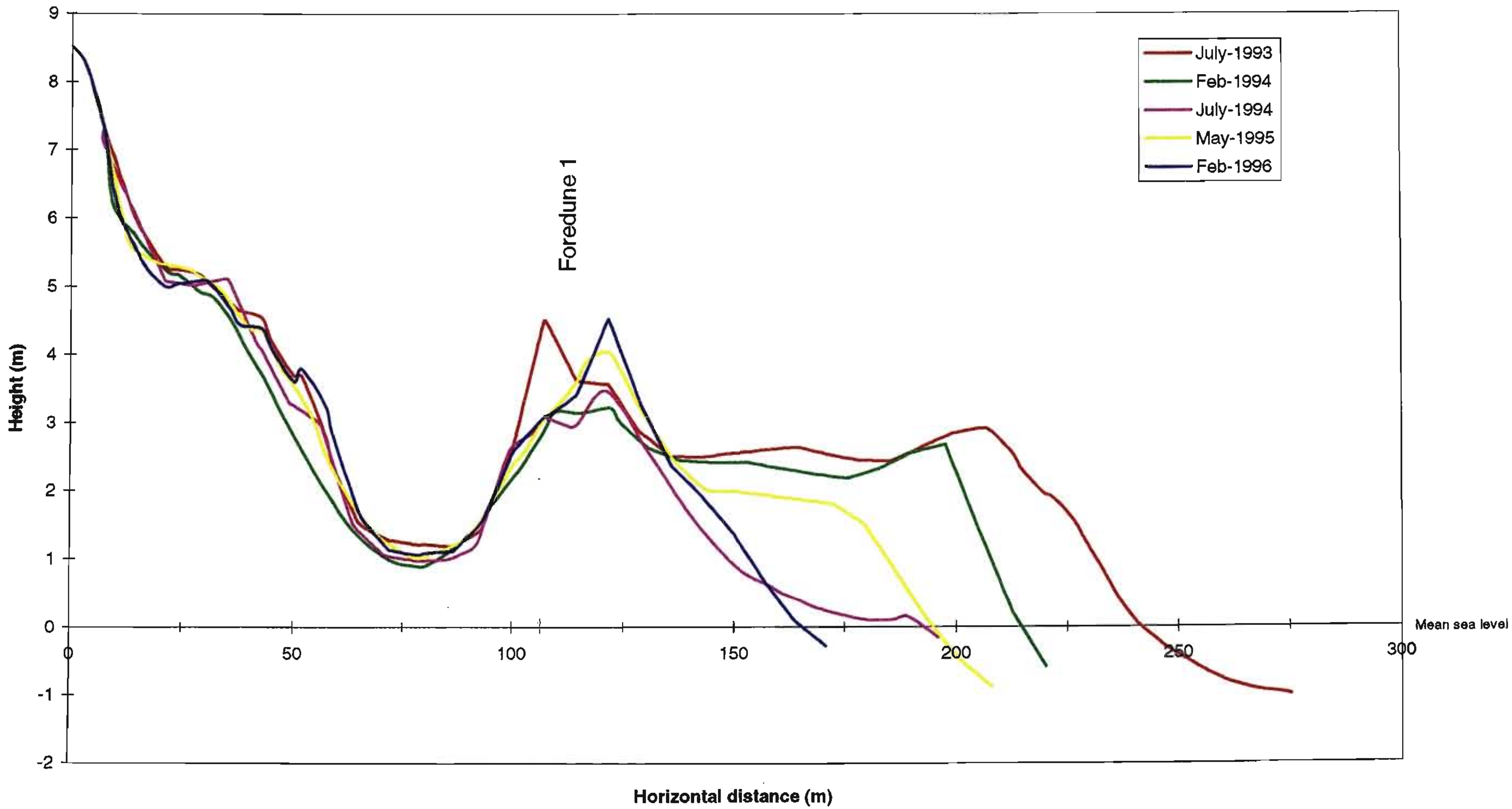


Figure 7.12 Cross-section 11

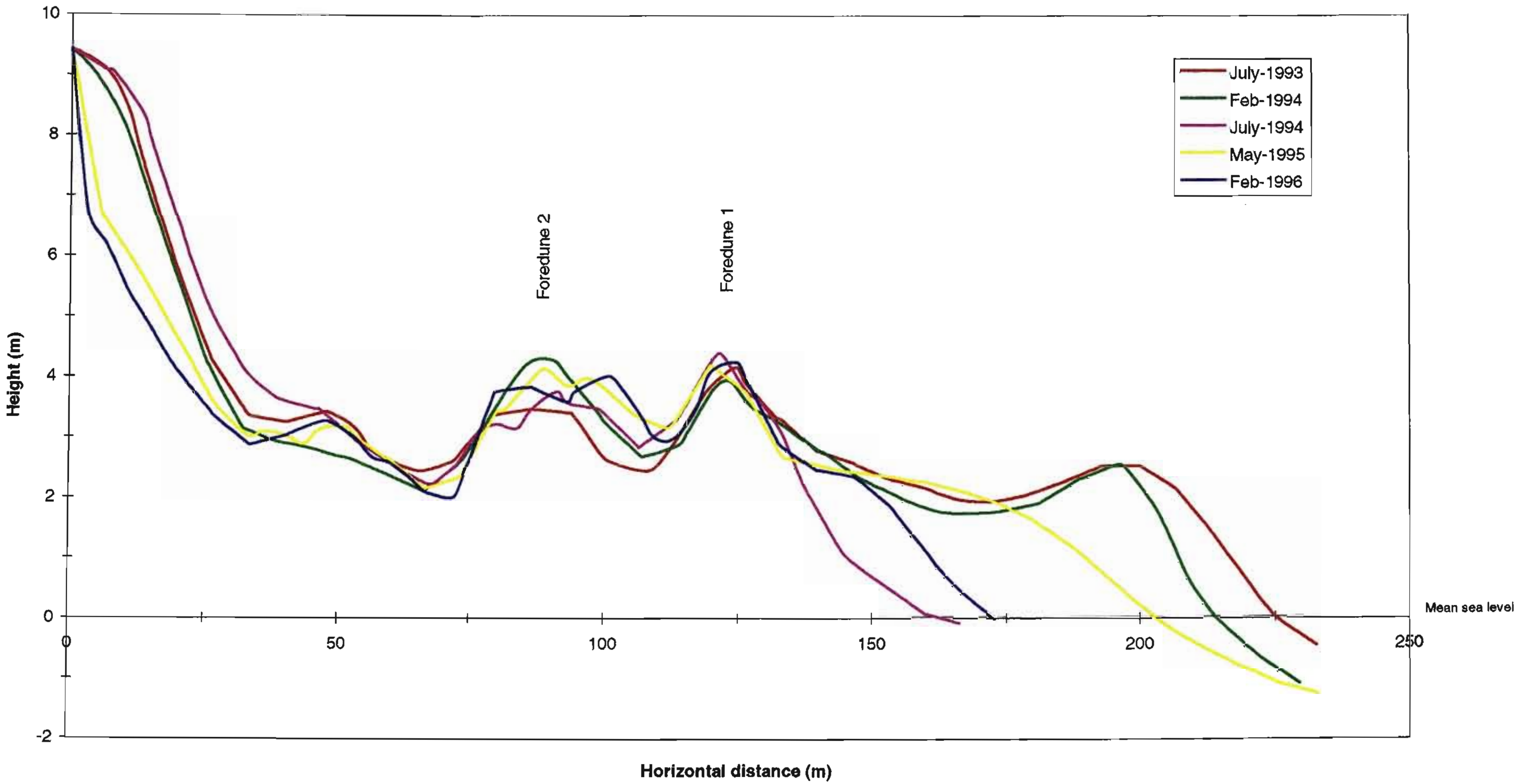


Figure 7.13 Cross-section 12

Table 7.14 Variation in the foredune crest heights (m) for cross-section 12 between July 1993 and February 1996.

Foredune number	July 1993	February 1994	July 1994	May 1995	February 1996
1	4.15	3.94	4.39	4.20	4.25
2	3.47	4.28	3.76	4.14	3.99

7.2.3.13. *Cross-section 13*

Foredune 1 was fronted by a large beach of up to 120 m during the survey period (Fig. 7.14). The foredune showed a steady increase in height of 1.7 m over 30 months (56 mm per month). The greatest increase occurred from July 1994 to May 1995 by 1.14 m (Table 7.15).

In comparison foredune 2 showed a lower growth rate of 0.38 m between July 1993 and February 1996. There was a marked decrease in height of 0.62 m between July 1993 and February 1994, reform to its previous dimensions. Foredune 3 was generally stable over the survey period.

Table 7.15 Variation in the foredune crest heights (m) for cross-section 13 between July 1993 and February 1996.

Foredune number	July 1993	February 1994	July 1994	May 1995	February 1996
1	2.76	3.08	3.16	4.30	4.46
2	3.13	2.41	3.39	3.59	3.51
3	3.13	2.89	3.06	3.14	2.96

7.2.3.14. *Cross-section 14*

Compared to previous cross-sections the foreshore was a lot wider (Fig 7.15). Foredune 1 experienced 0.63 m of erosion between July 1993 and July 1994 before accreting towards the end of the survey period (Table 7.16). From May 1995 to February 1996 the dune accreted at a marked rate of 100 mm per month.

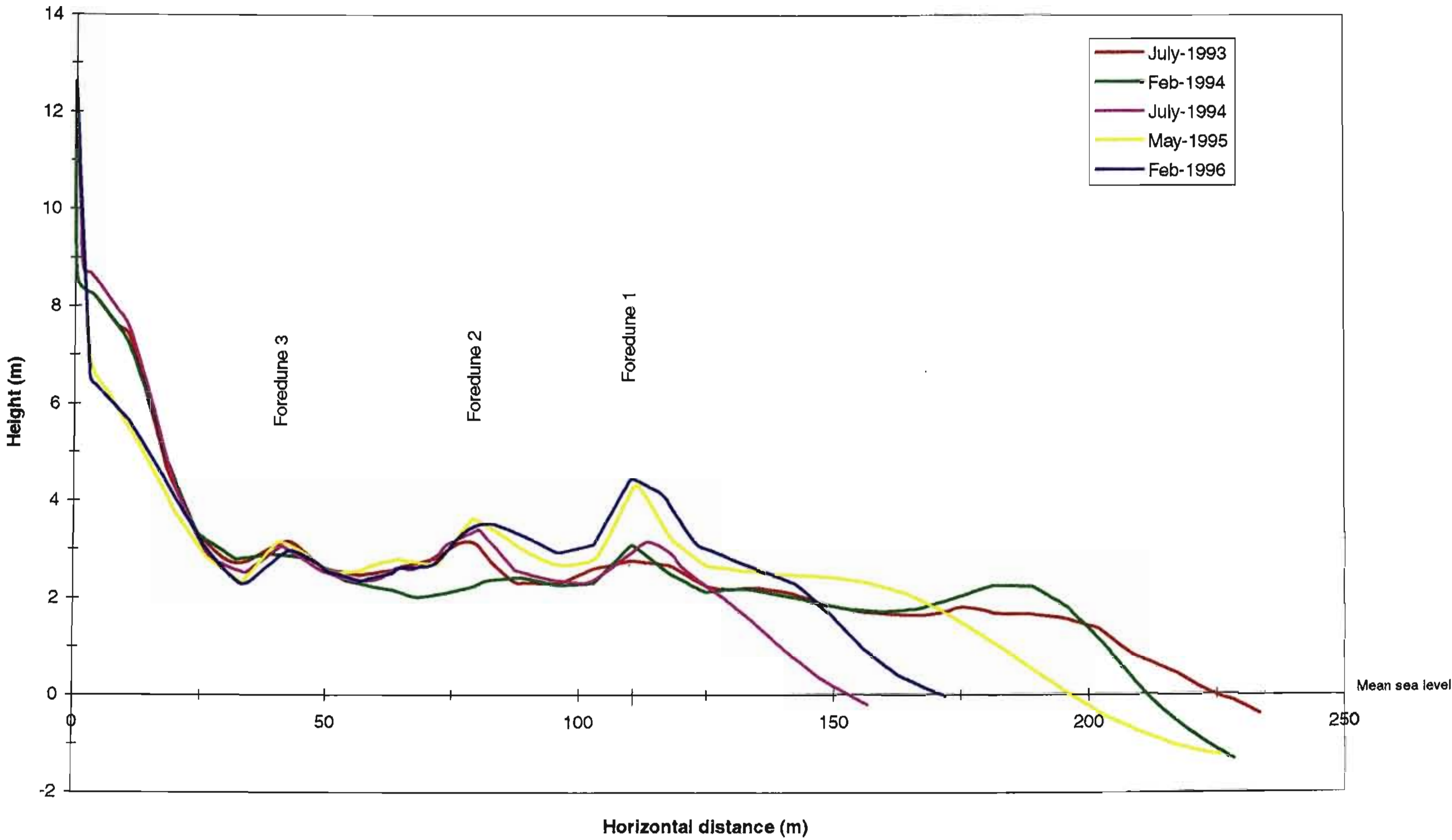


Figure 7.14 Cross-section 13

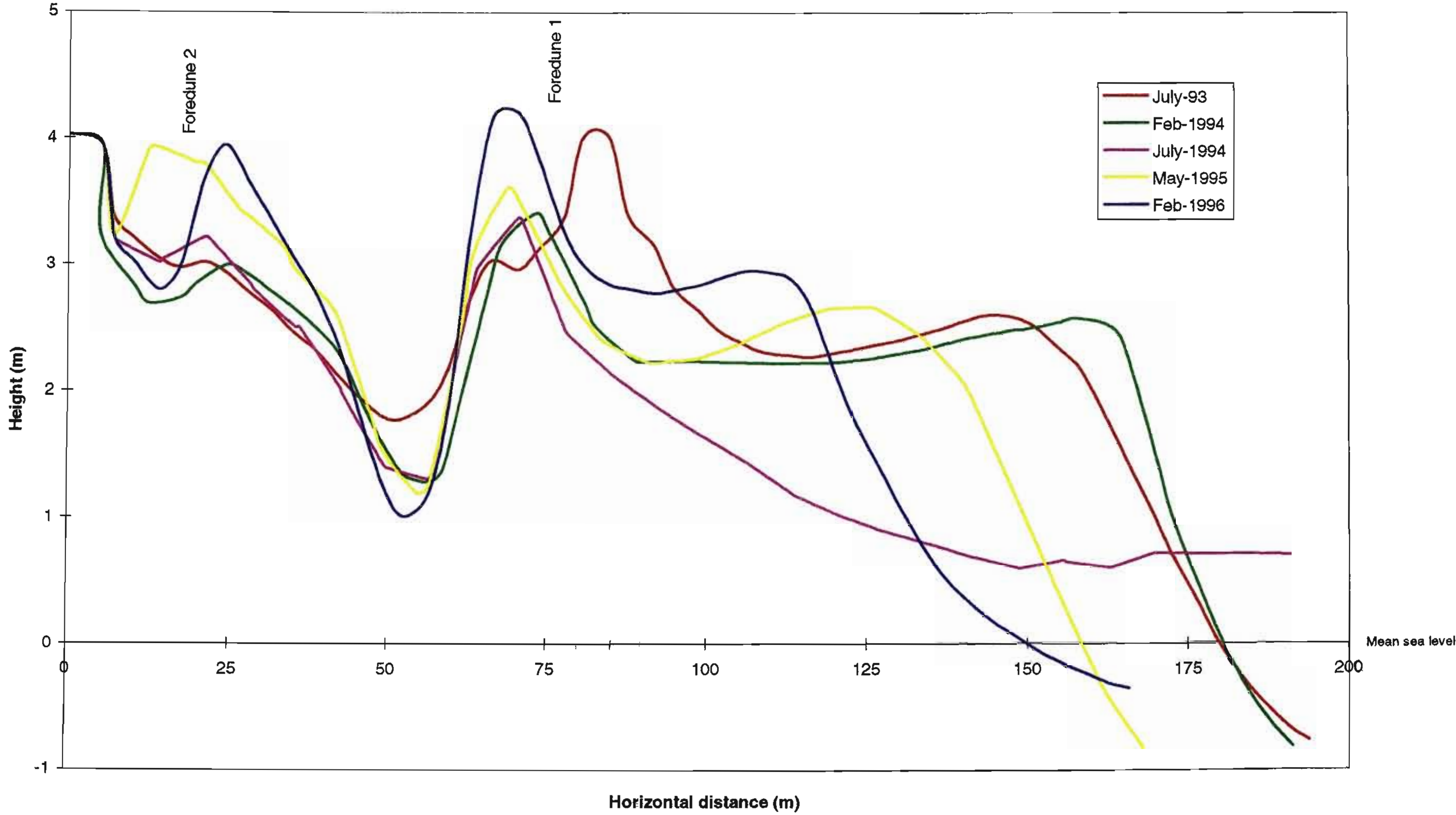


Figure 7.15 Cross-section 14

Foredune 2 enlarged throughout the survey period. The most notable increase in crest height occurred between July 1994 and May 1995 at a rate of 77 mm per month.

Table 7.16 Variation in the foredune crest heights (m) for cross-section 14 between July 1993 and February 1996.

Foredune number	July 1993	February 1994	July 1994	May 1995	February 1996
1	4.00	3.41	3.37	3.51	4.21
2	3.02	3.00	3.22	3.91	3.95

7.2.3.15. *Cross-section 15*

A small lagoon frequently forms seaward of foredune 1 through overwash (Fig. 7.16). Foredune 1 experienced rapid erosion between July 1993 and February 1994 before accreting at significant rate of 200 mm per month by July 1994 (Table 7.17). The dune continued to accrete until February 1996 but at a lower rate of 3 mm per month.

Table 7.17 Variation in the foredune crest heights (m) for cross-section 15 between July 1993 and February 1996.

Foredune number	July 1993	February 1994	July 1994	May 1995	February 1996
1	3.72	3.00	4.04	4.3	4.68

7.2.3.16. *Cross-section 16*

Over the whole survey period foredune 1 increased in height by 2.05 m at 68 mm per month (Fig. 7.17 and Table 7.18). A notable increase occurred between July 1994 and February 1996. Growth rates do not appear to be related to beach width, scavenging or deflation of dune slacks.

Table 7.18 Variation in the foredune crest heights (m) for cross-section 16 between July 1993 and February 1996.

Foredune number	July 1993	February 1994	July 1994	February 1996
1	3.71	3.68	4.35	5.76

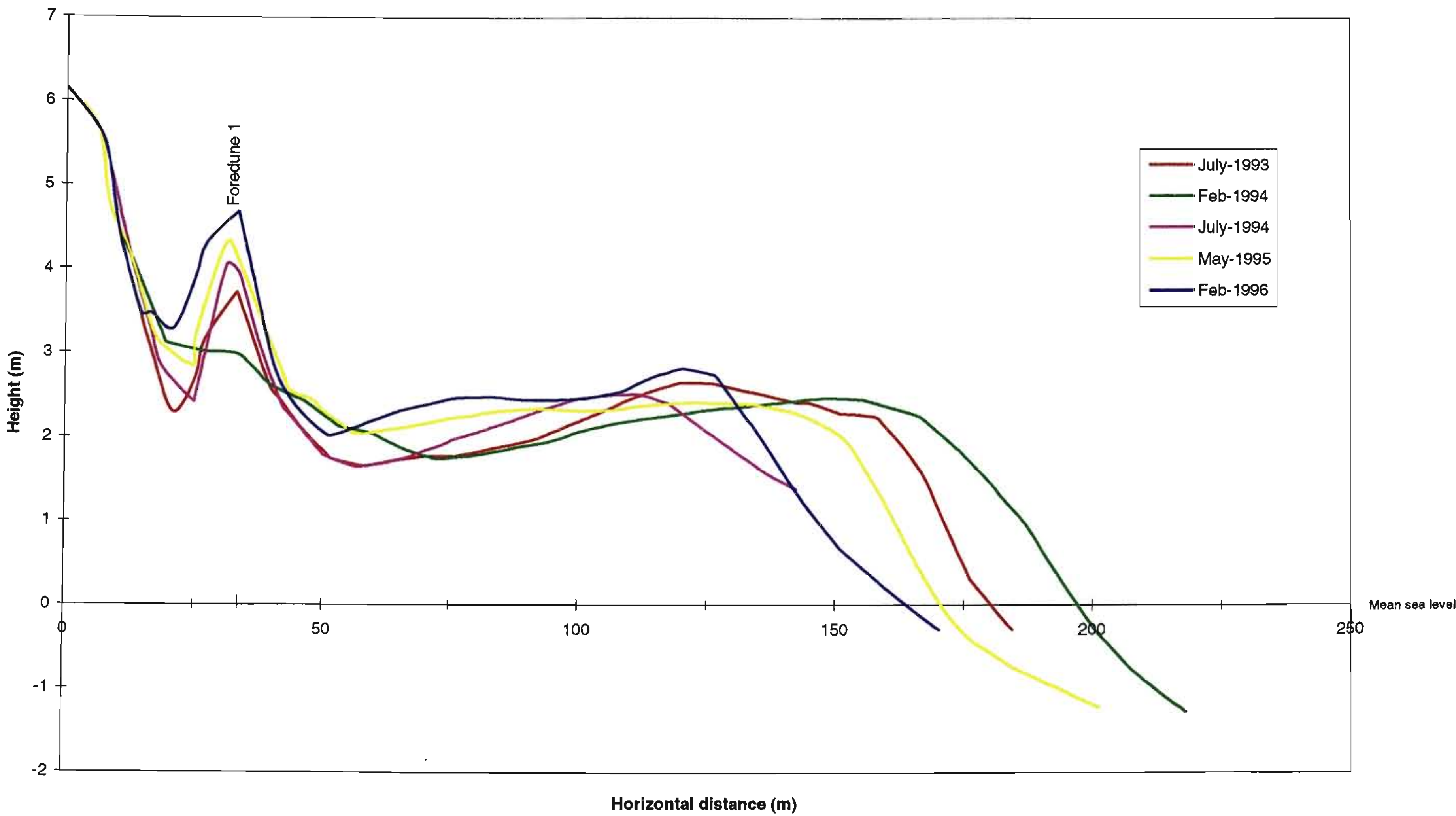


Figure 7.16 Cross-section 15

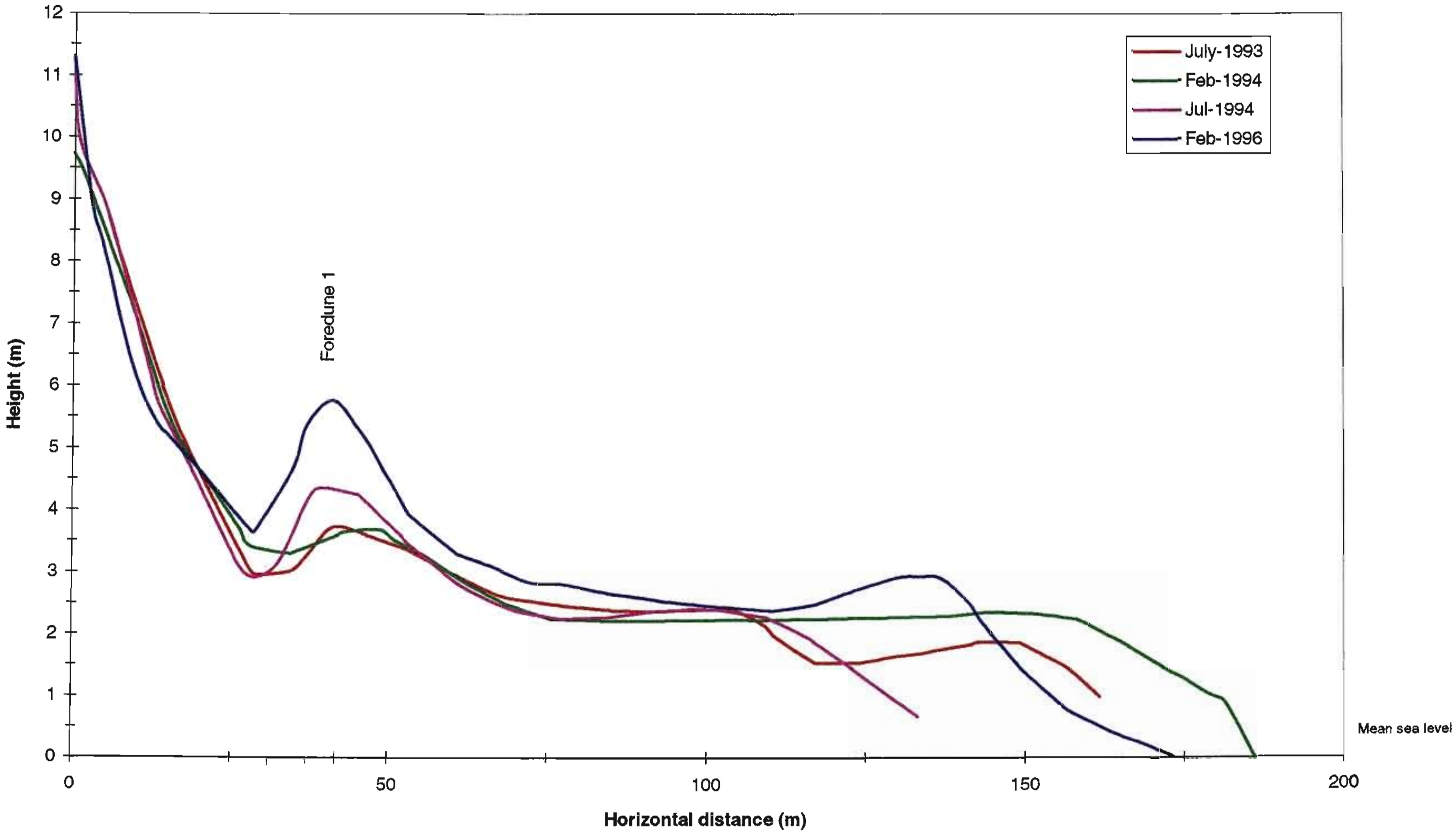


Figure 7.17 Cross-section 16

7.2.4. Crestline Shifts

A measure of the relative positioning of dune crestlines between surveys was undertaken in an attempt to understand the transfer of sediment between foredunes and beaches. Hummock dunes and unstable incipient foredunes were not included because of their ephemeral nature. Of the 23 dunes measured 14 remained stable while 6 shifted inland and 3 moved seaward (Appendix 2). Patterns of accretional or erosional displacements were not observed alongshore. Furthermore changes in crestline positions of the foredunes was not temporally related.

7.3. DISCHARGE DATA

The availability of sand to beaches in the study area is directly related to the Tugela River discharge. Since the first tacheometric field survey was conducted in July 1993 it is necessary to examine the discharge of the preceding year (Fig. 7.18). In the 12 months prior to July 93 the Tugela river discharged 1.042 x 10^9 m^3 of water, which is well below the annual average of 2.684 x 10^9 m^3 (1958-1995). Moreover, the mean discharge for the period 1991-1996 was 0.973 x 10^9 m^3. In fact the annual discharge for 1994/1995 and 1995/1996 are the lowest for two consecutive years on record (Fig. 7.19). The dry-spell from 1991-1996 does not fit into the cycle forecast by Preston-Whyte & Tyson (1988), who predicted a wet-spell for this period. However, anomalies do exist and have been noted by Preston-Whyte & Tyson (1988) and (Tyson, 1980).

Huizinga & van Niekerk (1997) claim that the Tugela River mouth can close when the river flows at 7.7 m^3s^{-1} and lower. An increase in mouth closure was noted over the dry months (June-October) from 1992 to 1995 (Appendix 3). The mouth was reported closed for 10 days in 1992, 0 days for 1993, 4 days for 1994 and 20 days for 1995 (Huizinga & van Niekerk, 1997). The increase in the incidence of mouth closure can be correlated to a general phase of erosion of the coastline over the measured period.

7.4. WIND DATA

The drift potential (DP) and resultant drift potential (RDP) were calculated according to a method developed by Fryberger (1978), described in Chapter 4. The seasonal DP and RDP for Richards Bay indicate the relative seasonal influences of the different wind directions on the Tugela coastal dunefield (Fig. 7.20 Appendix 1). Figure 7.20 shows an increase in the DP for winter and spring 1994 and a reduced influence over autumn. The annual average RDP for 1994 and 1995 (2.35 m^3 m^{-1} yr^{-1}) was relatively small when compared to Port Elizabeth with 20.4 m^3 m^{-1} yr^{-1} (Illenberger, 1986) and Cape Recife 36 m^3 m^{-1} yr^{-1} (Illenberger *et al.*, in prep.).

On average the RDP/DP ratio for 1994 and 1995 was 0.23, which is very similar to that of Durban airport of 0.19. According to Fryberger (1979) this falls into the class of low directional variability and is classified as an obtuse bimodal wind regime.

The dominant sand moving wind for the region is southwest to west-southwest of 10.7 to 13.8 m s^{-1} strength, with the secondary sand-moving wind of northeast to north-northeast of 10.8 to 13.8 m s^{-1}. This is in contrast to principal wind which blows north to north-northeast, with west to west southwest winds of secondary importance.

7.5. DISCUSSION

A comparison of the seasonal shoreline data indicates that there are no patterns of erosion or accretion. Over the study period the shoreline receded at all 16 cross-sections. This may be ascribed to the low amounts of sediment introduced to the littoral zone by the Tugela River. The survey was conducted during a drought period in the Tugela catchment. The decrease in discharge from the Tugela River, particularly over the winter months lead to an increase in the incidence of mouth closure. The reduced availability of sediment to the coast made it particularly vulnerable to marine erosion, which resulted in the narrowing of the beaches and the steepening of the foreshore. Despite increased marine erosion the foredunes continued to accrete vertically between July 1993 and February 1996.

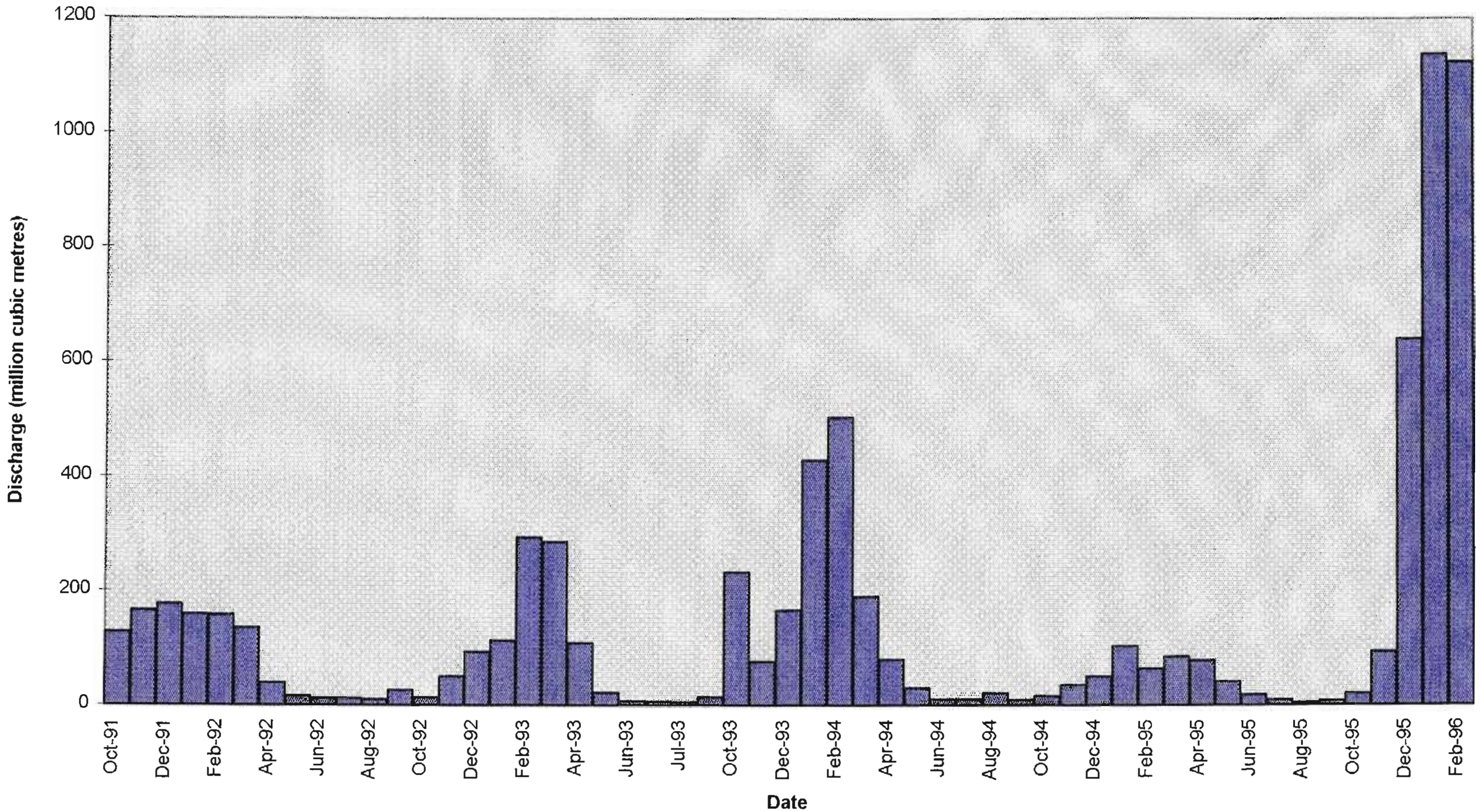


Figure 7.18 Monthly discharge values (October-Spetember rainfall year) for the Tugela River from October 1991 to February 1996 at Mandini gauging station (Department of Water Affairs and Forestry).

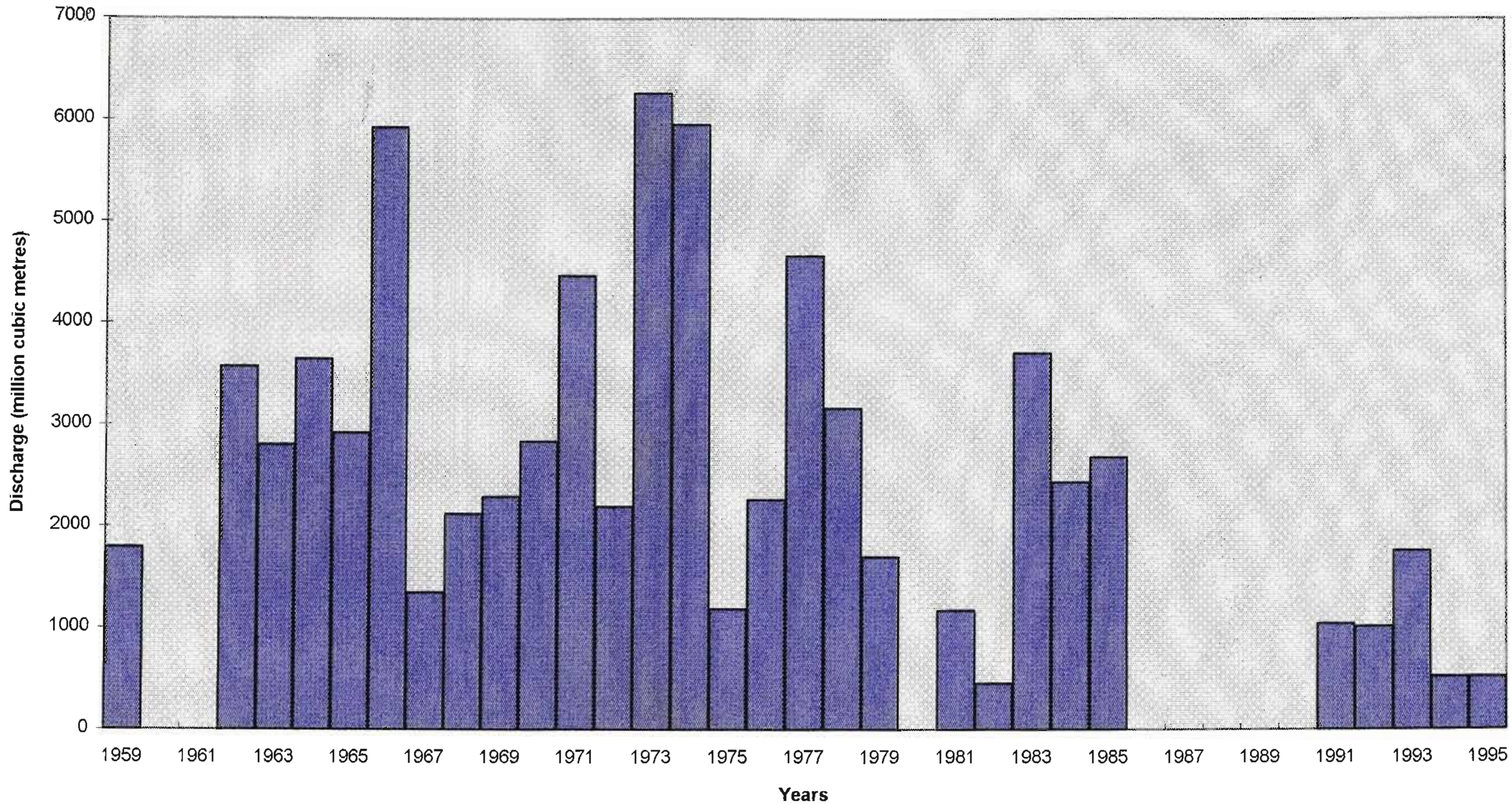


Figure 7.19 Annual discharge values (October-September rainfall year) for the Tugela River from 1959 to 1995 at Mandini gauging station (Departmnet of Water Affairs and Forestry)

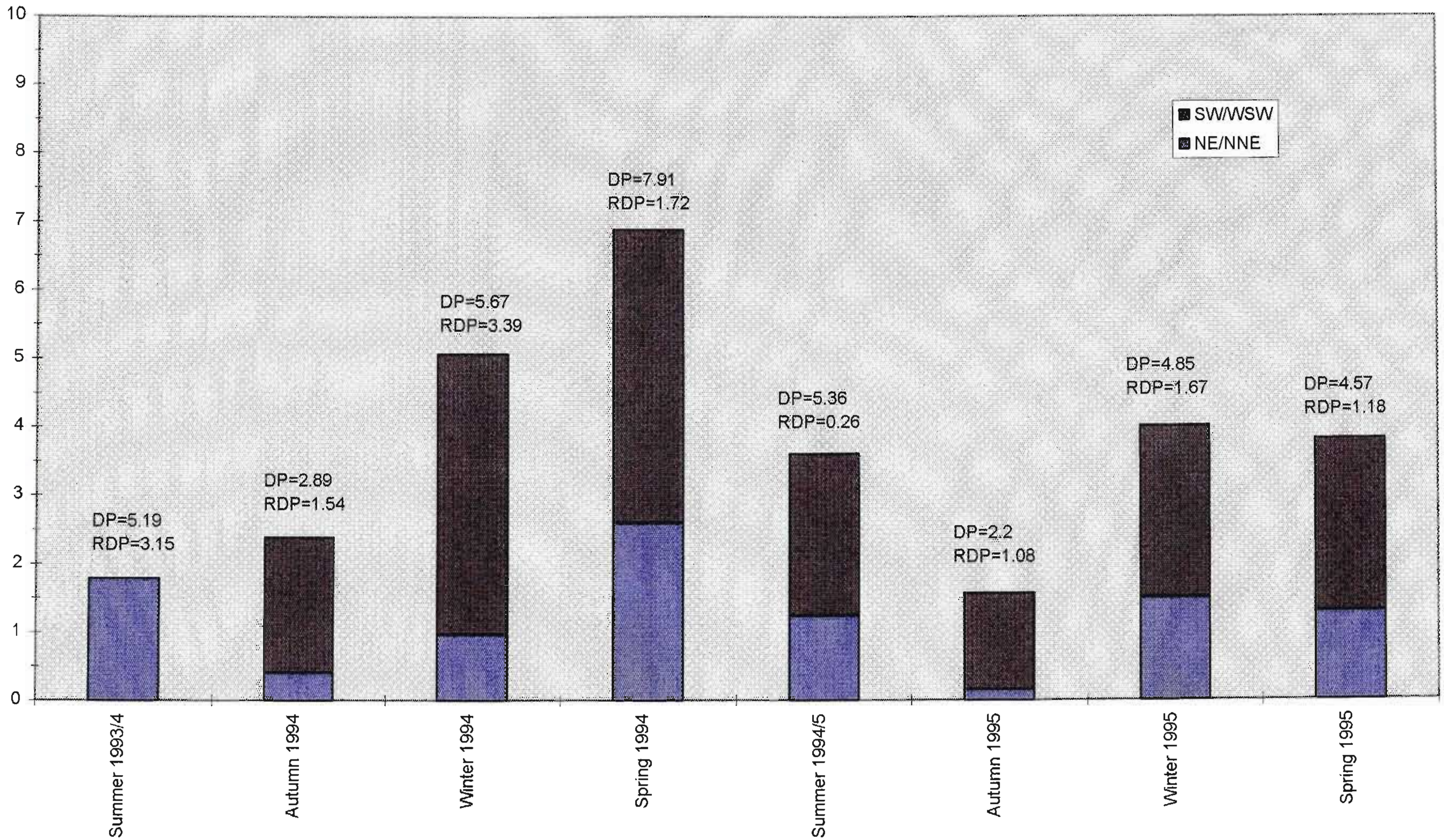


Figure 7.20 Bar chart showing the seasonal drift potential for each wind direction (units are $m^3\ m^{-1}\ yr^{-1}$)

An examination of the cross-sections shows that the largest sand level changes usually occur at or near the dune crests. The average accretion rate of the seaward most foredune is 90 mm per month. The highest accretion rates were recorded between February and July 1994 at cross-section 4 (376 mm per month) and cross-section 6 (376 mm per month). The abnormally high accumulation rates occurred following a large increase in the discharge of the Tugela River over January and February 1994 (Fig. 7.18). The increase in sediment discharge resulted in coastal accretion in the southern area of the dunefield. Incipient foredunes that were eroded between December 1993 and February 1994 frequently reformed in their previous positions (cross-sections 2, 4, 5, 6, 8). Over the same period there was an increase the amount of NE/NNE winds (Fig. 7.20) generated a swell approach from the same direction.

The average erosion rates of incipient dune crests was 216 mm per month. This figure could be misleading as it includes dunes that were totally removed by marine erosion. For example the average attenuation rate of the foredune crest between December 1993 and February 1994 at cross-section 5 was 563 mm per month. Five months later a new foredune had formed in the same position. A number of cycles of erosion and accretion were noted at 8 of the 16 cross-sections. Incipient foredunes in the southern section of the study area were subject to greater marine erosion and may be regarded as ephemeral features. The newly established foredunes in the northern section of dunefield were a lot more stable and generally displayed vertical accretion.

Some authors claim that dune erosion occurs primarily during storm episodes where high energy waves remove sediment from the seaward side of the offshore zone (Hughes & Chui, 1981; Vellinga, 1982: in Psuty, 1990). Scarping of the dune face effectively shifts the dune form inland. In this way sediment transfer is seen as an onshore-offshore movement of sand within a closed-system beach-dune profile. Psuty (1990) notes that previous authors regard offshore-onshore movement of coastal foredunes as two-dimensional.

In order to further elucidate the transfer of sediment along the beach-dune profile it is necessary to monitor crestline positions over time. Analysis of the crestline displacements reveal that the foredunes are not moving unidirectionally and that there are spatial variations in their movements. A correlation between crestline shifts and shoreline changes shows that seaward displacements occur even when the shoreline is eroding. For the most part crestline positions remained stable over the measured period. Psuty (1990) adds that foredunes retreat landward through erosion of the seaward margin of the dune and deposition on its lee side by aeolian activity. Analysis of the crestline positions could not substantiate this hypothesis. From this one could conclude that there is no simple pattern of sediment movement in an offshore-onshore direction in the study area. The wind data further substantiates this supposition in that very low RDP values were obtained for this section of the coast.

7.6. A MODEL OF FOREDUNE RIDGE TOPOGRAPHY

Before a theory of foredune-ridge topography can be proposed it is necessary to understand the hydrodynamics coastal characteristics prior to the dune surveys. Cooper (1991c) established that the coastline between the Tugela River and the Mlalazi River had accreted by up to 250 m between 1937-1978. The highest rate of progradation (6.1 m yr^{-1}) was recorded between 4.5 km and 6 km north of the Tugela River mouth. Landward of this section of coast the foredune plain reaches its greatest extent of 900 m. Cooper (1991c) notes that short-term fluctuations occur through the influence of episodic events.

The most recent flood was in 1987 with a peak discharge of 9440 cumecs. Cooper (1990) notes that barriers respond to fluvial floods in two ways. Where discharge is restricted within a narrow channel, prevailing inlets are extended through lateral and vertical erosion of the adjoining barrier. Wide flood plains allow channel migration and avulsion during floods, where a new mouth forms in a different position. Cooper (1990) found that large catchment rivers such as the Tugela are associated with extensive stream-mouth bars. He purports that stream-mouth bar volume is augmented by bedload sediment derived from fluvial floods.

Following the September 1987 floods stream-mouth bars developed seaward of the Tugela River mouth. Originally they were submerged following the high discharge event. As river discharge diminished wave energy became more important. In the case of the Tugela River dominant swells shifted the sediment landward. Stream-mouth bars were gradually exposed by wave action and reworked onto the adjacent beach, resulting in increased beach widths (Cooper, 1990). From available aerial photographs the estimated time for stream-mouth bars to be reworked and incorporated into the beach sediment budget takes 30 months. In order for a foredune-ridge topography to occur a positive beach budget is required over the long-term (Davidson-Arnott & Law, 1990). The transfer of sediment from the beach to the dunefield is a complex and not well understood phenomenon.

Psuty (1992) contends that most models of coastal dune development adopt a system-orientated classification. Foredunes have traditionally been regarded as evolving through a sequence of developmental stages with characteristic morphologies. Some authors regard vegetation as the most important factor controlling dune dimensions (Godfrey *et al.*, 1979; Hesp, 1984, 1989). The wind regime and the dune relief have also been suggested as important mechanisms of foredune formation (Pye, 1983, Sarre, 1989b). Psuty (1988, 1989) provides an alternative model that includes the concept of a sediment budget. He argues that it is essential to view foredunes as part of the beach/dune profile. He developed a basic matrix to explain the topographic/morphologic outcomes of beach/dune interactions (Fig. 7.21). The matrix shows a progression of forms as the sediment budget combinations move along the axes.

According to Psuty's model, extremely rapid coastal accretion (strong positive beach budget) leads to development of low foredunes (beach-ridge topography). The time available for foredune accumulation is limited by the formation of a new foredune as the beach is displaced seaward. Where there is a highly negative beach budget coastal recession results in the destruction of the incipient foredune and overwash may occur. Under conditions of moderate progradation, there is more time available for dune accretion leading to a foredune-ridge topography. Quadrant names are determined by relative budget proportions in the beach-dune profile. The different conditions shown in the model represent a continuum, which may be regarded temporally or spatially, or both. Although conditions may alter in either direction along the continuum, they must move through the phases as indicated in Figure 7.21.

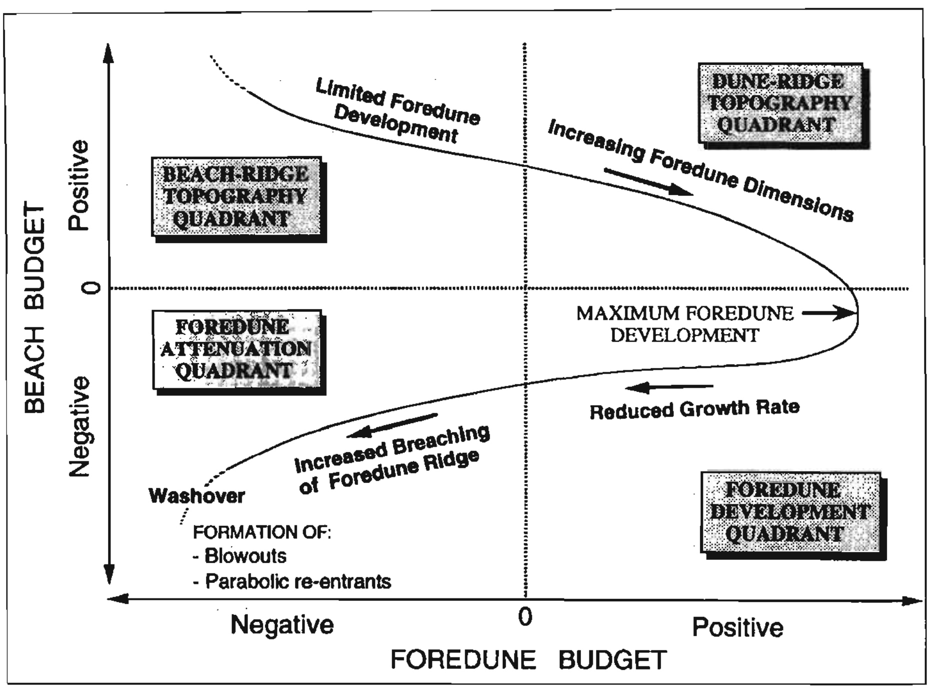


Figure 7.21 Sediment budget model of foredune development according to Psuty (1988).

The model presented by Psuty can be used to explain some of the conditions which occur adjacent to the Tugela River mouth. However, it would be a folly to apply this model to a whole dunefield as it is limited spatially. Longshore variations in the destruction and formation of incipient foredunes have been noted. Moreover shoreline displacements are not uniform over the study area.

The incipient foredunes at Tugela River mouth are similar to the Type 1b dunes observed by Hesp (1984) in Southeast Australia. Plants germinate from seed, or from seeds included in the swash-aligned driftwood. During periods of storm activity large amounts of driftwood and seeds are washed up (Plate 7.1). Plant material can act as foci for the establishment of embryonic dunes. Lenticular or shadow dunes develop in the lee of plants or other obstructions (Plate 7.2). Discrete sedimentary structures formed in association with these plants form hummock dunes. *Scaevola thunbergii* is the only plant associated with the development of the incipient dunes.

Incipient foredunes located close to river mouths are destroyed under flood events or strong wave attack. When the coastline recedes the beaches are narrow with steep foreshores. Wave action removes the toe of the dune and the sediment is moved offshore (Plate 7.3). Observations taken from local fishing boats as well as inspection of wave conditions suggest that the sediment is possibly stored in the nearshore zone in the form of a longshore bar approximately 50-100 m from the beach. Under calm conditions associated with shoreline accretion sediment is transported back the beach. Unfortunately the sediment movement between the beach and the dunes was not measured and remains a topic for future investigation.

Psuty (1990) asserts that enhanced foredune growth occurs in the early stages of a negative beach budget. Continued beach erosion eventually results in foredune erosion. Attenuation of the established foredune crests in the Tugela dunefield generally occurred under an extended erosive phase. Psuty (1990) notes that an increasing negative beach budget may result in the loss of the foredune ridge coherence. The end result is a series of dune hummocks interspersed with large washover fans that extend through the foredunes. Such a model concludes that the sequence of foredune development is a result of the changing combination of beach and foredune

Plate 7.1 Debris washed up on the foreshore after a small flood.

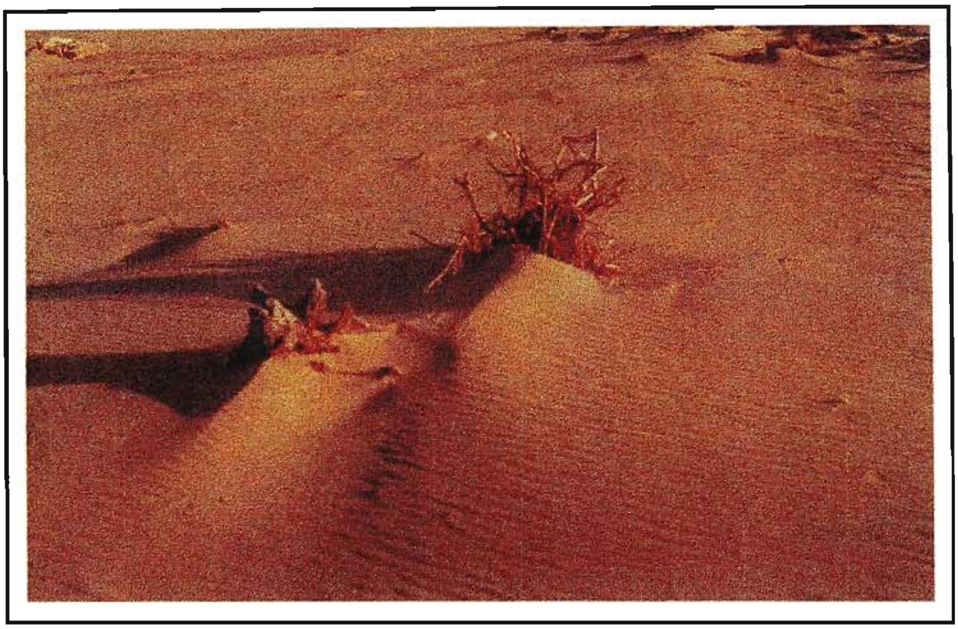


Plate7.2 Shadow dune formed in the lee of a piece of driftwood.

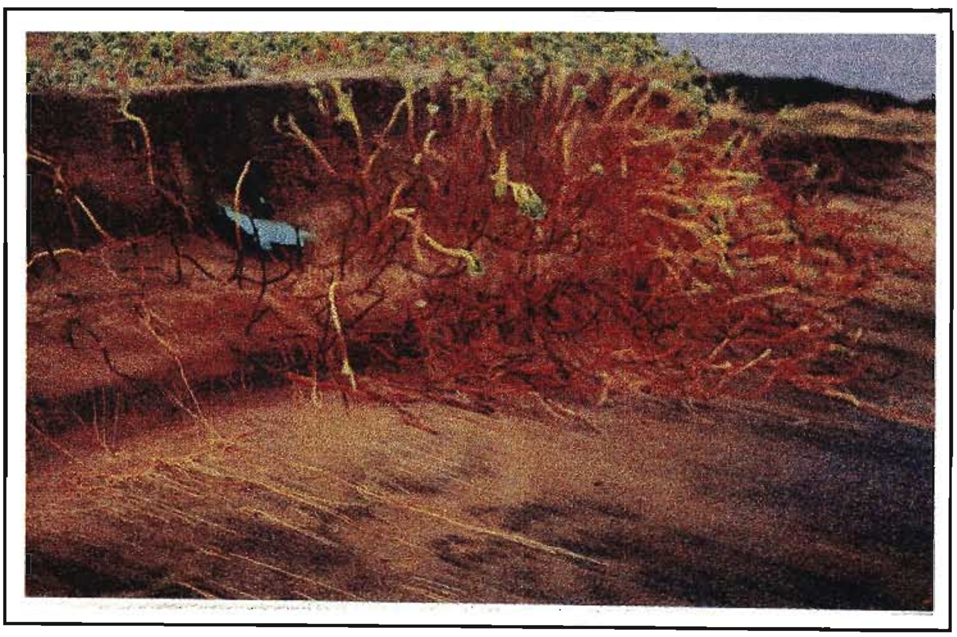


Plate7.3 Scarping of the embryonic foredune by storm waves.

sediment budgets. The foredune-ridge topography between the Tugela River and Mlalazi River is characterized by a number of dune blowouts. Although Psuty's model could perhaps account for some of the features observed, monitoring of a large section of the coastline is necessary in order to confirm this.

CHAPTER 8.

CONCLUSIONS

A review of the sediment characteristics of the foredunes and beaches in this study area represents the first phase in understanding the sediment dynamics of the Tugela River and adjacent coastline. The beaches and the dunes in the study area are devoid of marine shelly material which implies a strong fluvial influence. Only slight differences were noted between the beach and dune sediment. The sampling of sediment in the Tugela River and relating this to the adjacent coastline would refine our understanding of the development of a foredune-ridge topography.

Most fluvial sediment movement takes place during floods, where large amounts of the fine-grained material are deposited offshore. As flood waters subside coarse-grained material is deposited to form a stream-mouth bar (Cooper, 1990; Perry, 1990). The sediment is reworked by wave action landwards to produce wide beaches adjacent to the Tugela River mouth. Large amounts of sediment are transported in a northerly direction by longshore drift. In order for a beach-ridge plain to develop with low fordedunes a constant source of sediment is required, which allows for rapid coastal accretion. Drought in the Tugela catchment between 1991 and 1996 resulted in a decrease in the availability of sediment to the beaches north of the Tugela River. Although marine erosion resulted in the landward shift in the shoreline, the foredunes continued to accrete..

Relatively high rainfall experienced along this section of the coast encourages increased plant vigour. The ability of *Scaevola thunbergii* to withstand sediment encroachment allows for the rapid vertical accretion of foredunes. Foredune height and shape does not appear to be related to vegetation structure and shoot density. Preliminary findings suggest that vegetation cannot account for the changes in ridge and swale morphology of the coastal dunes.

Examination of the foredune crestlines and cross-sections revealed that the established dunes are relatively stable whereas the incipient foredune are ephemeral and more subject to marine and aeolian erosion. Changes in the foredune topography appear to be related to variations in the rate of sediment delivery, both temporally and spatially. Psuty's (1988, 1989) sediment budget model of foredunes appears to explain most of the conditions observed along the coastline. The present study corroborates Psuty's (1996) contention that the optimum condition for foredune development is a slightly negative beach budget.

Breaks in the dune crestline were observed under erosive conditions when marine and aeolian activity destroyed the dune integrity allowing for blowout and overwash fans to penetrate between the foredunes. Such breaks allow for the inland channelling of sediment to dunes that were formerly starved of sand. Under such conditions parabolic dunes are reactivated. This represents the last stage in the development of a fossil dune-ridge topography.

Although the aims of the thesis were achieved a complete model of fordune-ridge topography requires additional investigation. The study was limited spatially because of the time taken to complete each survey. The development of real-time GPS survey technology over the last few years has drastically improved the speed of three dimensional digital surveys. Monitoring of the coastline 2-4 km north of the study area, where the highest rates of coastal accretion were noted by Cooper (1991c) would improve our understanding of coastal progradation in the region.

The sequential evolution and location of the coastal foredune during periods of erosion and accretion remains an area for further study. The short-term rate of fordune growth is dependent on the amount of sand transported form the beach to the dunes (Davidson-Arnott & Law, 1990). Developing a model that could be used to predict sediment supply to coastal dunes could be employed by coastal zone managers and engineers when planning development projects.

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APPENDICES 1 - 4

APPENDIX 1

RICHARDS BAY STATION - 1994 (ANNUAL)

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0-1	3.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.90
-1.5	1.11	0.69	0.44	0.35	0.21	0.08	0.06	0.06	0.06	0.05	0.20	0.20	0.27	0.15	0.28	0.28	4.46
-3.3	5.01	4.67	2.61	1.46	1.31	0.60	0.86	0.60	1.05	0.94	1.08	1.69	4.41	1.19	0.59	1.04	29.09
-5.4	1.34	5.05	4.98	2.17	1.84	0.67	1.39	0.42	1.43	1.35	1.71	2.58	3.08	0.09	0.05	0.13	28.28
-7.9	0.96	4.36	5.35	1.61	2.67	0.47	0.40	0.07	0.23	1.17	2.97	3.18	0.74	0.03	0.01	0.08	24.31
-10.7	0.21	1.85	1.23	0.29	0.54	0.16	0.10	0.02	0.00	0.32	2.29	1.95	0.15	0.01	0.00	0.00	9.13
-13.8	0.00	0.00	0.00	0.03	0.00	0.00	0.01	0.00	0.00	0.02	0.36	0.34	0.00	0.00	0.00	0.00	0.76
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.03
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.02
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	12.5	16.6	14.6	5.91	6.57	1.99	2.82	1.17	2.77	3.85	8.61	9.98	8.64	1.48	0.92	1.53	%100

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
5.4																	
-7.9	0.17	0.77	0.94	0.28	0.47	0.08	0.07	0.01	0.04	0.21	0.52	0.56	0.13	0.01	0.00	0.01	4.29
-10.7	0.29	2.61	1.73	0.41	0.77	0.23	0.15	0.03	0.00	0.46	3.23	2.75	0.21	0.02	0.00	0.00	12.88
-13.8	0.00	0.00	0.00	0.17	0.00	0.00	0.06	0.00	0.00	0.11	1.77	1.65	0.00	0.00	0.00	0.00	3.76
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.30	0.00	0.00	0.00	0.00	0.45
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.00	0.00	0.00	0.00	0.65
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.46	3.38	2.67	0.86	1.24	0.31	0.28	0.04	0.04	0.78	5.67	5.92	0.34	0.02	0.00	0.01	22.02

Total northward component = 1.56   Total eastward component = 4.43

RDP = 4.70   DP =22.02   RDP/DP = 0.21

units: cubic metres per metre per year

[all in cubic metres per metre per year]
[calculated using Bagnold's equation]

RICHARDS BAY STATION - 1995 (ANNUAL)

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0-1	4.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.05
-1.5	1.16	0.61	0.42	0.41	0.29	0.03	0.08	0.05	0.10	0.07	0.21	0.11	0.40	0.28	0.17	0.32	4.71
-3.3	5.11	3.11	3.13	2.04	1.28	0.46	0.63	0.65	1.02	1.00	1.34	2.21	4.57	1.38	0.83	1.02	29.77
-5.4	1.24	3.23	6.50	2.62	1.42	0.76	1.18	0.48	1.76	1.73	2.25	4.00	3.75	0.09	0.05	0.11	31.17
-7.9	0.57	3.24	5.49	1.81	2.29	0.32	0.38	0.08	0.45	1.56	3.07	3.48	1.07	0.00	0.02	0.01	23.85
-10.7	0.09	0.93	0.50	0.21	0.62	0.00	0.00	0.00	0.01	0.29	1.39	1.65	0.14	0.01	0.00	0.00	5.83
-13.8	0.02	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.36	0.00	0.00	0.00	0.01	0.62
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	12.2	11.1	16.0	7.09	5.90	1.57	2.27	1.26	3.35	4.64	8.45	11.8	9.92	1.75	1.07	1.48	%100

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
5.4																	
-7.9	0.10	0.58	0.98	0.32	0.41	0.06	0.07	0.01	0.08	0.28	0.55	0.62	0.19	0.00	0.00	0.00	4.24
-10.7	0.13	1.32	0.72	0.29	0.88	0.00	0.00	0.00	0.02	0.41	1.97	2.35	0.20	0.02	0.00	0.00	8.30
-13.8	0.11	0.11	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.97	1.77	0.00	0.00	0.00	0.06	3.08
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.35	2.01	1.75	0.62	1.29	0.06	0.07	0.01	0.10	0.68	3.49	4.73	0.39	0.02	0.00	0.06	15.62

Total northward component = 1.35   Total eastward component = 3.56

RDP = 3.80   DP =15.62   RDP/DP = 0.24

[all in cubic metres per metre per year]
[calculated using Bagnold's equation]

RICHARDS BAY STATION - AUTUMN 94 (03/94 04/94 05/94)

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0-1	5.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.16
-1.5	1.41	0.75	0.70	0.42	0.23	0.05	0.05	0.05	0.05	0.00	0.19	0.05	0.42	0.19	0.33	0.28	5.16
-3.3	4.13	4.22	3.98	1.55	1.45	0.23	0.56	0.47	1.17	0.75	1.31	2.06	7.03	1.45	0.61	1.41	32.40
-5.4	0.70	4.45	5.77	3.05	1.64	0.56	1.59	0.28	1.13	1.22	1.69	3.38	5.16	0.28	0.19	0.09	31.18
-7.9	0.38	3.28	3.56	1.50	2.86	0.09	0.42	0.00	0.05	0.84	3.14	3.70	1.22	0.00	0.05	0.05	21.14
-10.7	0.00	0.28	0.05	0.00	0.14	0.00	0.00	0.00	0.00	0.05	1.31	2.53	0.33	0.00	0.00	0.00	4.69
-13.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.05	0.00	0.00	0.00	0.00	0.28
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	11.7	12.9	14.0	6.52	6.33	0.94	2.63	0.80	2.39	2.86	7.88	11.7	14.1	1.92	1.17	1.83	%100

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
5.4																	
-7.9	0.02	0.14	0.15	0.07	0.12	0.00	0.02	0.00	0.00	0.04	0.14	0.16	0.05	0.00	0.00	0.00	0.92
-10.7	0.00	0.10	0.02	0.00	0.05	0.00	0.00	0.00	0.00	0.02	0.46	0.88	0.11	0.00	0.00	0.00	1.63
-13.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.06	0.00	0.00	0.00	0.00	0.34
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.02	0.24	0.17	0.07	0.17	0.00	0.02	0.00	0.00	0.05	0.88	1.10	0.17	0.00	0.00	0.00	2.89

Total northward component = 0.72 Total eastward component = 1.36

RDP = 1.54 DP = 2.89 RDP/DP = 0.53

[all in cubic metres per metre per year]
[calculated using Bagnold's equation]

RICHARDS BAY - AUTUMN 95 (03/95 04/95 05/95)

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0-1	5.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.15
-1.5	1.89	0.97	0.83	0.55	0.23	0.05	0.14	0.05	0.14	0.14	0.05	0.23	0.78	0.46	0.32	0.37	7.18
-3.3	5.98	4.00	3.54	1.70	1.38	0.46	0.41	0.60	0.87	1.29	1.43	2.12	6.03	1.70	0.92	1.61	34.04
-5.4	1.75	4.19	6.95	2.39	1.56	0.51	1.20	0.23	1.47	1.79	2.71	2.90	3.77	0.09	0.09	0.05	31.65
-7.9	0.41	1.79	2.25	1.43	1.56	0.18	0.18	0.14	1.15	1.89	2.94	3.40	0.92	0.00	0.05	0.00	18.31
-10.7	0.09	0.18	0.00	0.00	0.32	0.00	0.00	0.00	0.05	0.09	1.01	1.84	0.00	0.00	0.00	0.00	3.59
-13.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.00	0.00	0.09
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	15.2	11.1	13.5	6.07	5.06	1.20	1.93	1.01	3.68	5.20	8.19	10.5	11.5	2.25	1.38	2.02	%100

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
5.4																	
-7.9	0.02	0.08	0.10	0.06	0.07	0.01	0.01	0.01	0.05	0.08	0.13	0.15	0.04	0.00	0.00	0.00	0.81
-10.7	0.03	0.07	0.00	0.00	0.11	0.00	0.00	0.00	0.02	0.03	0.36	0.65	0.00	0.00	0.00	0.00	1.27
-13.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.06	0.00	0.00	0.00	0.00	0.11
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.05	0.14	0.10	0.06	0.18	0.01	0.01	0.01	0.07	0.12	0.55	0.86	0.04	0.00	0.00	0.00	2.20

Total northward component = 0.62 Total eastward component = 0.88

RDP = 1.08 DP = 2.20 RDP/DP = 0.49

[all in cubic metres per metre per year]
[calculated using Bagnold's equation]

RICHARDS BAY STATION - SPRING 94 (09/94 10/94 11/94)

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0-1	2.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.65
-1.5	0.88	0.47	0.19	0.28	0.05	0.00	0.05	0.05	0.09	0.05	0.05	0.33	0.19	0.23	0.28	0.14	3.31
-3.3	3.96	2.28	2.84	1.44	1.07	0.09	0.51	0.61	0.70	0.98	1.40	2.00	3.49	0.98	0.47	1.16	23.98
-5.4	0.51	3.07	5.68	2.05	1.54	0.51	1.26	0.74	1.86	1.26	1.68	3.12	2.47	0.05	0.00	0.14	25.93
-7.9	0.19	4.05	9.22	2.47	3.40	0.09	0.28	0.05	0.28	1.40	3.31	3.54	0.51	0.05	0.00	0.05	28.86
-10.7	0.05	3.21	2.56	0.14	0.84	0.00	0.00	0.00	0.00	0.42	3.12	3.40	0.05	0.00	0.00	0.00	13.78
-13.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.65	0.74	0.00	0.00	0.00	0.00	1.49
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	8.24	13.0	20.4	6.38	6.89	0.70	2.09	1.44	2.93	4.19	10.1	13.1	6.70	1.30	0.74	1.49	%100

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
5.4																	
-7.9	0.01	0.18	0.40	0.11	0.15	0.00	0.01	0.00	0.01	0.06	0.14	0.15	0.02	0.00	0.00	0.00	1.26
-10.7	0.02	1.12	0.90	0.05	0.29	0.00	0.00	0.00	0.00	0.15	1.09	1.19	0.02	0.00	0.00	0.00	4.83
-13.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.80	0.91	0.00	0.00	0.00	0.00	1.82
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.02	1.30	1.30	0.16	0.44	0.00	0.01	0.00	0.01	0.32	2.03	2.26	0.04	0.00	0.00	0.00	7.91

Total northward component = 0.41   Total eastward component = 1.67

RDP = 1.72   DP = 7.91   RDP/DP = 0.22

[all in cubic metres per metre per year]
[calculated using Bagnold's equation]□

RICHARDS BAY STATION - SPRING 95 (09/95 10/95 11/95)

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0-1	4.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.67
-1.5	0.78	0.32	0.41	0.41	0.37	0.09	0.09	0.09	0.18	0.05	0.27	0.09	0.50	0.37	0.09	0.37	4.49
-3.3	3.16	1.24	2.24	2.52	1.74	0.46	0.55	0.69	1.19	0.92	1.33	2.11	5.08	0.92	0.55	0.37	25.05
-5.4	0.96	1.97	6.23	2.34	1.60	0.55	1.47	0.46	2.20	1.79	3.02	6.59	4.21	0.05	0.00	0.09	33.52
-7.9	0.73	2.24	7.10	1.69	1.69	0.46	0.46	0.09	0.18	1.42	4.76	3.98	0.50	0.00	0.05	0.00	25.37
-10.7	0.23	1.37	0.78	0.09	0.32	0.00	0.00	0.00	0.00	0.09	1.28	1.65	0.00	0.00	0.00	0.00	5.82
-13.8	0.09	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.69	0.00	0.00	0.00	0.05	1.10
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	10.6	7.19	16.8	7.05	5.72	1.56	2.56	1.33	3.75	4.26	10.9	15.1	10.3	1.33	0.69	0.87	%100

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
5.4																	
-7.9	0.03	0.10	0.32	0.08	0.08	0.02	0.02	0.00	0.01	0.06	0.21	0.18	0.02	0.00	0.00	0.00	1.13
-10.7	0.08	0.49	0.28	0.03	0.11	0.00	0.00	0.00	0.00	0.03	0.46	0.59	0.00	0.00	0.00	0.00	2.07
-13.8	0.11	0.06	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.86	0.00	0.00	0.00	0.06	1.37
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.23	0.65	0.65	0.11	0.19	0.02	0.02	0.00	0.01	0.10	0.90	1.62	0.02	0.00	0.00	0.06	4.57

Total northward component =-0.00 Total eastward component = 1.18

RDP = 1.18 DP = 4.57 RDP/DP = 0.26

[all in cubic metres per metre per year]
[calculated using Bagnold's equation]

RICHARDS BAY STATION - SUMMER 93-94 (12/93 01/94 02/94)

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0-1	4.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.44
-1.5	0.42	0.74	0.60	0.51	0.32	0.28	0.32	0.19	0.14	0.05	0.19	0.05	0.14	0.00	0.05	0.05	4.03
-3.3	3.15	7.82	1.99	2.27	2.31	2.82	1.44	0.93	1.67	1.02	0.60	0.00	0.37	0.09	0.09	0.09	26.67
-5.4	2.36	8.70	2.87	2.18	3.33	1.71	2.22	1.06	1.57	0.65	0.05	0.00	0.00	0.00	0.00	0.00	26.71
-7.9	2.50	7.41	4.81	1.94	3.94	2.36	1.99	0.83	2.04	0.51	0.00	0.00	0.00	0.00	0.00	0.00	28.33
-10.7	0.65	2.31	1.25	0.60	1.71	1.06	0.46	0.23	0.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.26
-13.8	0.00	0.00	0.00	0.14	0.19	0.00	0.05	0.00	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	13.5	26.9	11.5	7.64	11.8	8.24	6.48	3.24	6.57	2.22	0.83	0.05	0.51	0.09	0.14	0.14	%100

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
5.4																	
-7.9	0.11	0.33	0.21	0.09	0.17	0.10	0.09	0.04	0.09	0.02	0.00	0.00	0.00	0.00	0.00	0.00	1.25
-10.7	0.23	0.82	0.44	0.21	0.60	0.37	0.16	0.08	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.26
-13.8	0.00	0.00	0.00	0.17	0.23	0.00	0.06	0.00	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.68
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.34	1.14	0.65	0.47	1.00	0.48	0.31	0.12	0.66	0.02	0.00	0.00	0.00	0.00	0.00	0.00	5.19

Total northward component =-0.84 Total eastward component =-3.03

RDP = 3.15 DP = 5.19 RDP/DP = 0.61

[all in cubic metres per metre per year]
[calculated using Bagnold's equation]

RICHARDS BAY STATION - SUMMER 94/95 (12/94 01/95 02/95)

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0-1	3.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.29
-1.5	0.65	0.42	0.23	0.28	0.42	0.00	0.09	0.09	0.05	0.00	0.42	0.09	0.00	0.09	0.19	0.09	3.10
-3.3	1.81	3.38	4.95	1.94	0.93	0.74	0.51	0.93	1.48	0.83	1.16	1.94	2.45	0.37	0.42	0.23	24.07
-5.4	0.37	1.76	6.16	2.64	1.76	1.06	1.57	0.88	2.41	1.67	1.44	3.47	1.39	0.00	0.00	0.05	26.62
-7.9	0.23	3.56	8.19	3.01	5.42	0.69	0.74	0.05	0.37	1.94	3.66	4.35	0.42	0.05	0.00	0.14	32.82
-10.7	0.14	0.97	1.06	1.06	1.81	0.00	0.00	0.00	0.00	0.28	2.50	1.76	0.05	0.05	0.00	0.00	9.68
-13.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.32	0.00	0.00	0.00	0.00	0.42
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	6.48	10.0	20.6	8.94	10.3	2.50	2.92	1.94	4.31	4.72	9.26	11.9	4.31	0.56	0.60	0.51	%100

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
5.4																	
-7.9	0.01	0.16	0.36	0.13	0.24	0.03	0.03	0.00	0.02	0.09	0.16	0.19	0.02	0.00	0.00	0.01	1.44
-10.7	0.05	0.34	0.37	0.37	0.64	0.00	0.00	0.00	0.00	0.10	0.88	0.62	0.02	0.02	0.00	0.00	3.41
-13.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.40	0.00	0.00	0.00	0.00	0.51
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.06	0.50	0.74	0.51	0.87	0.03	0.03	0.00	0.02	0.18	1.16	1.21	0.03	0.02	0.00	0.01	5.36

Total northward component = 0.26 Total eastward component =-0.05

RDP = 0.26 DP = 5.36 RDP/DP = 0.05

[all in cubic metres per metre per year]
[calculated using Bagnold's equation]

RICHARDS BAY STATION - WINTER 94 (06/94 07/94 08/94)

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0-1	3.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.67
-1.5	1.68	0.77	0.36	0.36	0.18	0.05	0.00	0.00	0.05	0.09	0.18	0.32	0.32	0.09	0.27	0.63	5.34
-3.3	8.65	4.66	1.59	0.86	1.04	0.23	1.09	0.36	1.13	1.13	0.91	2.36	5.75	2.17	1.09	1.40	34.42
-5.4	2.36	5.53	4.85	1.54	1.63	0.23	0.77	0.14	1.18	1.68	2.76	2.72	4.03	0.05	0.00	0.27	29.71
-7.9	1.40	4.08	2.31	0.41	1.00	0.05	0.00	0.00	0.14	0.95	3.31	3.44	0.91	0.05	0.00	0.09	18.12
-10.7	0.27	1.77	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.54	3.17	1.63	0.23	0.00	0.00	0.00	7.74
-13.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.32	0.00	0.00	0.00	0.00	0.77
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.09	0.00	0.00	0.00	0.00	0.14
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.09
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	18.0	16.8	9.24	3.17	3.85	0.54	1.86	0.50	2.49	4.39	10.8	10.9	11.2	2.36	1.36	2.40	%100

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
5.4																	
-7.9	0.06	0.18	0.10	0.02	0.04	0.00	0.00	0.00	0.01	0.04	0.15	0.15	0.04	0.00	0.00	0.00	0.82
-10.7	0.10	0.64	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.20	1.14	0.59	0.08	0.00	0.00	0.00	2.79
-13.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.57	0.40	0.00	0.00	0.00	0.00	0.97
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.30	0.00	0.00	0.00	0.00	0.45
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.00	0.00	0.00	0.00	0.65
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.16	0.82	0.15	0.02	0.04	0.00	0.00	0.00	0.01	0.24	2.01	2.09	0.12	0.00	0.00	0.00	5.67

Total northward component = 1.41 Total eastward component = 3.08

RDP = 3.39 DP = 5.67 RDP/DP = 0.60

[all in cubic metres per metre per year]
[calculated using Bagnold's equation]

RICHARDS BAY STATION - WINTER 95 (06/95 07/95 08/95)

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0-1	3.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.17
-1.5	1.40	0.72	0.23	0.23	0.18	0.00	0.00	0.00	0.05	0.09	0.23	0.05	0.23	0.27	0.23	0.45	4.35
-3.3	8.65	4.26	1.86	1.45	0.91	0.18	0.68	0.50	0.59	0.54	1.22	1.86	4.03	2.58	1.36	1.77	32.43
-5.4	1.81	4.85	6.39	1.86	0.18	0.05	0.09	0.09	0.91	1.59	1.54	2.72	4.80	0.23	0.09	0.27	27.45
-7.9	1.00	5.93	6.25	0.91	0.27	0.00	0.00	0.00	0.09	1.45	1.99	3.71	2.67	0.00	0.00	0.05	24.32
-10.7	0.05	1.59	0.91	0.09	0.00	0.00	0.00	0.00	0.00	0.82	1.95	1.49	0.50	0.05	0.00	0.00	7.43
-13.8	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.32	0.00	0.00	0.00	0.00	0.86
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	16.1	17.4	15.6	4.53	1.54	0.23	0.77	0.59	1.63	4.48	7.43	10.1	12.2	3.13	1.68	2.54	%100

m/s	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
5.4																	
-7.9	0.04	0.27	0.28	0.04	0.01	0.00	0.00	0.00	0.00	0.07	0.09	0.17	0.12	0.00	0.00	0.00	1.09
-10.7	0.02	0.57	0.33	0.03	0.00	0.00	0.00	0.00	0.00	0.29	0.70	0.54	0.18	0.02	0.00	0.00	2.67
-13.8	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.40	0.00	0.00	0.00	0.00	1.08
-17.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
>20.7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	0.06	0.89	0.61	0.07	0.01	0.00	0.00	0.00	0.00	0.36	1.42	1.10	0.30	0.02	0.00	0.00	4.85

Total northward component = 0.41 Total eastward component = 1.62

RDP = 1.67 DP = 4.85 RDP/DP = 0.35

[all in cubic metres per metre per year]
[calculated using Bagnold's equation]

Appendix 2

Dune crest positions (m) for the 23 foredunes measured in the study area from July 1993 to February 1996.

Cross-section No.	Dune No.	July 1993	Dec. 1993	Feb. 1994	July 1994	May 1995	Feb. 1996
1	1	70	70	-	70	65	65
2	2	41	41	41	41	41	41
4	2	112	112	119	122	126	122
4	3	49	51	51	51	51	49
5	2	118	118	-	118	118	118
5	3	88	88	89	88	88	88
6	2	89	86	88	86	85	89
8	3	43	45	44	45	45	43
7	2	101	101	-	103	102	101
7	3	72	70	72	75	74	72
8	3	72	-	62	75	74	72
9	1	139	-	139	134	130	121
9	2	27	27	23	26	26	26
10	1	140	-	144	142	140	133
11	1	107	107	122	121	121	121
12	1	124	-	123	121	119	124
13	1	110	-	110	113	111	110
13	3	41	-	39	41	41	43
14	1	80	-	73	71	70	70
14	2	21	-	24	21	12	24
15	1	33	-	33	31	31	33
16	1	40	-	42	39	-	41

Appendix 3

A: Tugela River Mouth - 1992

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	97.83	20.14	49.44	20.01	16.19	4.80	5.52	4.36	4.49	8.56	3.69	9.86
2	134.00	20.07	48.79	16.01	12.01	4.90	5.13	4.52	4.74	8.17	4.63	8.86
3	211.40	19.32	84.36	15.51	11.90	4.63	4.86	4.68	4.09	6.94	42.01	10.10
4	153.20	58.43	97.06	12.98	9.11	4.60	5.41	4.40	4.10	5.79	21.62	10.04
5	117.60	47.10	111.40	13.37	7.60	4.55	5.67	4.88	5.31	5.57	18.03	8.41
6	85.77	39.48	90.88	12.46	7.05	4.54	5.81	4.81	13.65	5.35	13.72	8.93
7	68.91	33.97	70.24	11.31	6.64	4.95	5.24		14.38	4.51	10.66	8.72
8	59.83	29.94	57.52	10.28	5.84	4.97	4.76	4.13	15.08	4.45	10.40	10.08
9	49.73	25.28	46.77	9.57	6.00	5.02	4.64	3.73	15.13	4.93	8.90	7.57
10	62.93	20.98	39.71	9.68	5.44	5.08	4.43	4.19	15.71	5.27	7.34	6.16
11	94.02	19.06	35.32	14.05	6.06	4.92	4.17	4.16	15.91	4.64	7.87	50.29
12	76.30	16.62	30.27	15.52	6.01	4.43	5.75	4.18	14.68	5.42	17.42	47.04
13	60.59	15.20	27.87	15.32	5.96	4.48	6.42	4.16	13.56	4.99	35.64	44.23
14	50.74	15.75	25.79	16.88	5.78	5.14	6.30	3.95	12.99	4.01	20.98	34.28
15	59.90	14.31	23.48	13.64	5.54	5.57	5.42	3.81	11.62	3.49	11.76	58.07
16	50.98	12.59	21.32	12.87	5.18	5.51	5.16	4.09	10.72	3.09	11.47	48.55
17	49.69	11.03	19.04	13.99	5.50	5.75	5.00	4.00	10.40	3.20	55.32	39.53
18	41.16	9.77	16.40	19.84	5.02	5.01	4.71	3.92	10.09	4.77	47.28	31.57
19	38.84	96.00	15.03	20.92	4.86	4.99	4.71	4.08	9.90	7.37	32.46	24.04
20	30.36	150.90	13.70	18.22	4.74	5.68	4.87	4.05	9.78	6.18	31.91	18.05
21	28.95	116.40	71.85	14.28	4.77	5.44	4.78	3.82	9.44	5.44	24.93	13.66
22	24.67	176.20	127.90	12.64	4.25	5.66	4.46	3.55	8.02	4.68	19.32	11.38
23	22.32	230.70	113.20	12.72	4.60	5.40	4.75	3.19	9.57	4.21	15.89	70.57
24	19.64	152.00	79.89	13.79	4.51	5.48	4.33	3.21	10.41	4.51	13.31	76.76
25	18.03	132.50	59.25	20.80	4.43	5.00	4.66	2.90	10.23	4.60	12.38	73.74
26	16.51	120.00	47.87	24.96	4.55	4.52	4.60	3.22	10.58	4.53	20.53	89.41
27	16.33	93.64	39.86	23.23	4.21	5.42	4.61	3.56	10.19	4.99	20.67	83.37
28	34.13	75.16	33.02	17.14	4.39	5.53	4.84	3.69	9.42	4.59	18.66	62.26
29	27.19	59.32	26.61	13.89	4.77	5.55	3.86	3.81	9.29	4.24	16.28	47.17
30	21.74		22.83	17.09	5.07	5.49	3.67	3.86	8.84	4.02	11.88	35.61
31	23.01		21.02		5.10		4.26	3.73		4.04		33.85

Open **Closed** **Almost Closed** No Info

B: Tugela River Mouth - 1993

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	32.78	87.57	74.63	97.18	10.09	4.53	2.39	3.30	1.22	6.17	25.34	46.58
2	42.79	105.50	64.03	83.07	10.55	4.06	2.48	2.93	1.03	5.79	21.12	43.17
3	69.50	64.82	53.40	62.33	9.51	3.92	2.51	2.31	1.00	6.16	17.38	35.96
4	66.49	38.28	45.53	49.28	9.28	3.79	2.59	1.76	0.94	10.12	16.70	31.28
5	42.72	30.55	41.06	42.60	8.89	3.81	2.63	1.29	100.00	16.71	15.90	24.42
6	35.17	23.58	95.77	70.61	7.79	3.84	2.52	1.46	1.00	35.54	15.03	21.60
7	36.35	25.48	190.10	81.35	6.60	3.51	3.02	1.78	1.93	194.10	14.56	51.50
8	26.37	37.51	197.10	86.85	7.07	3.17	3.18	1.84	4.36	457.20	13.61	54.32
9	18.81	27.52	190.90	83.21	8.14	3.15	3.26	1.96	3.75	322.50	15.06	39.15
10	44.90	39.55	176.40	79.86	7.23	3.08	3.27	1.90	2.84	192.40	15.17	44.40
11	55.37	108.70	144.10	77.36	7.00	2.80	3.18	2.19	2.11	131.10	12.72	47.48
12	108.60	135.20	85.52	60.74	6.71	2.87	3.07	3.22	1.97	128.40	12.30	33.88
13	92.73	131.10	71.86	47.69	6.09	3.09	2.77	2.86	1.65	89.94	12.36	26.20
14	64.39	147.50	134.40	39.21	5.61	3.15	2.40	2.61	1.32	82.67	14.69	21.38
15	44.61	401.50	130.10	33.67	5.56	2.88	2.43	2.58	1.22	69.83	58.90	18.43
16	38.50	344.40	224.80	30.91	23.76	2.74	2.47	2.45	1.03	49.91	65.50	17.16
17	25.35	261.40	231.80	27.44	12.55	2.54	2.35	1.85	0.80	39.38	53.85	21.21
18	19.95	206.10	155.40	24.42	10.40	2.34	2.28	2.07	0.78	39.67	42.29	20.51
19	15.17	168.80	141.40	23.52	8.21	2.19	2.35	2.44	0.79	84.51	35.20	53.46
20	38.32	133.90	106.50	23.36	9.43	2.44	2.33	2.36	0.61	73.95	37.18	63.11
21	49.23	113.50	75.78	20.83	9.82	2.54	2.35	2.16	0.46	54.19	38.70	51.14
22	35.75	106.40	86.19	20.71	9.53	2.51	2.19	2.00	0.41	50.38	47.94	37.02
23	27.74	91.61	86.03	18.36	8.99	2.46	2.44	1.95	0.59	55.18	52.93	37.11
24	19.28	98.97	68.36	16.17	8.54	2.35	2.78	1.89	2.11	89.21	43.64	31.60
25	20.54	156.10	52.90	14.75	8.12	2.59	3.01	1.68	31.00	167.90	34.57	38.73
26	41.55	129.50	43.89	12.92	7.07	2.63	2.87	1.42	45.86	70.04	27.50	49.46
27	49.73	95.54	39.89	11.41	6.32	2.52	2.58	1.26	25.96	45.63	25.83	47.93
28	46.00	92.50	33.59	10.64	5.64	2.53	2.54	1.32	13.68	34.77	28.02	126.40
29	38.19	59.32	33.01	11.70	5.23	2.35	2.64	1.71	9.98	28.80	40.77	403.50
30	35.82		86.25	11.79	5.33	2.34	3.87	1.84	7.46	36.58	34.65	244.30
31	28.12		150.00		5.09		3.67	1.47		31.61		140.90

Open Closed Almost Closed No Info

C: Tugela River Mouth - 1994

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	89.97	126.10	43.23	67.94	18.95	5.50			9.71	1.37	7.75	3.40
2	80.88	106.00	42.19	56.86	17.70	5.07			8.79	1.37	8.70	3.40
3	81.69	150.10	39.53	72.18	16.51	4.74			7.96	5.20	6.75	3.40
4	70.38	343.10	36.99	70.55	15.89	4.69			6.85	3.70	14.80	2.40
5	82.54	457.20	39.09	61.47	17.69	4.45			6.03		19.40	1.80
6	91.99	457.20	41.14	56.05	20.30	4.42			5.45	3.10	20.70	1.80
7	72.47	457.20	45.62	42.90	18.39	5.41			5.07	2.40	19.40	1.80
8	61.32	457.20	49.83	35.49	16.89	5.09			4.29	3.10	17.10	9.60
9	55.23	454.30	56.71	29.37	16.23	4.55			4.00	6.04	14.80	11.60
10	50.57	361.70	80.19	25.60	15.13	4.27			3.71	5.23	14.80	
11	383.60	386.60	85.77	24.26	13.18	4.51			3.54	4.47	10.60	
12	222.70	352.00	96.55	22.70	12.43	4.54			3.32	4.47	10.60	15.60
13	209.70	235.00	68.04	22.97	12.04	4.56			3.15	5.23	10.60	12.60
14	213.10	165.60	55.74	22.00	11.54	4.44			3.10	7.76	10.60	
15	224.60	148.50	56.23	19.90	11.04	4.15			3.05	8.66	10.60	
16	173.30	132.50	162.10	18.88	10.29	4.33			2.99	7.75	13.70	
17	129.20	121.60	268.30	17.44	9.83	4.22			2.86	6.80	14.80	
18	101.90	138.40	145.60	16.35	9.29	3.96			2.71	6.80	14.80	
19	88.17	125.60	107.1	15.13	9.11	3.89			2.57	6.80		14.20
20	144.90	96.82	94.55	14.05	9.22	3.96			2.44	6.80		
21	204.10	84.21	81.56	13.44	8.88	3.56			2.32	6.03	8.70	14.20
22	185.60	88.52	70.47	13.54	7.74	3.41			2.19		8.70	
23	166.70	76.13	61.44	14.63	7.71	3.51			1.99	9.60		14.80
24	173.00	72.91	48.44	14.86	7.55	3.29			1.78	7.75	9.60	
25	289.50	63.31	41.22	30.74	6.86	3.13			1.75	6.75	8.12	
26	214.10	63.77	43.68	37.87	6.54	3.27			1.67	6.03	8.12	
27	272.80	58.44	36.65	33.29	6.37	2.82			1.59	5.23	7.75	13.20
28	263.90	51.54	42.56	26.82	5.41	2.54			1.52	4.50	8.20	13.70
29	214.40	59.32	55.48	22.15	5.49	2.51			1.82	6.03	4.80	12.60
30	185.60		47.34	19.95	5.78	2.53			1.87	6.75	4.10	13.70
31	160.90		57.06		5.73					7.75		

Open Closed Almost Closed No Info

D: Tugela River Mouth - 1995

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1			12.60	21.90		6.03		3.70	1.32	2.43	7.75	23.20
2			14.80	21.90	13.70	6.03		3.60		1.85	6.03	
3	14.80		13.70	21.90	12.60		5.20	3.60		1.85	5.20	
4	12.60			23.20	13.70		5.20	3.10	1.08	1.32		23.20
5	14.80			23.20	18.20	5.20	5.20		1.32	1.32		21.90
6	14.80	38.70				5.20	6.00		1.32	7.75	4.47	21.90
7	9.60		21.90			4.85	4.84	3.10	1.58		3.70	23.20
8	9.60	20.70			17.10	6.03		3.10	2.43		3.70	
9	9.60	19.40	20.70		17.10	6.03			2.13	1.85	3.40	
10	7.70	19.40	23.20				5.23	3.10	1.85	3.70	3.70	
11	6.90						6.03	3.10	1.58	3.10		
12	5.20	17.10			15.90	5.20	5.23		1.58	2.30		
13	5.20	15.90	23.20		14.80	5.20	4.84		1.58	1.85	3.10	
14	5.10	19.40	19.40		13.70	5.20	4.46	4.46	1.58		21.90	
15	11.60	19.40	21.90		13.70	4.85		4.50	1.58		21.90	
16		17.10	23.20		12.60			4.50	2.43	3.60	18.20	
17		14.80	19.40		12.60		4.10	3.46	7.75	3.10	17.10	
18				19.40	11.60		4.10	2.93	3.70	4.92		
19				18.20	11.60	19.40	3.60		5.20	4.47		
20		11.60	18.20	17.10		14.80	3.06		5.20	4.92	13.70	
21		9.60		15.90		10.60	3.06	2.31	4.47		14.80	
22		14.80	24.50		8.70	10.60		2.31	6.03		18.20	
23			24.50		8.70			2.31	9.60	4.47		
24		18.20		14.80	7.70		2.93	2.13	8.66	6.03		
25				14.80	7.70		3.60	1.85	6.03			
26					6.90	7.70	3.06	1.85	6.03			
27		19.40	18.20			7.70	3.06	1.86	4.47	19.40		
28		14.80	17.10	14.80		7.70	3.06	1.63	4.47			
29			15.90		6.90	6.90		1.58	3.10		24.50	
30	18.25		21.90		6.90	6.90		1.47	2.43	10.60	24.50	
31	17.10		21.90		6.90		3.70	1.58		8.66		

Open **Closed** **Almost Closed** **No Info**