Rapid geomorphological change in an urban estuary: a case study of the Eerste River, Cape Town, South Africa.

Chantel Reneé Petersen

A mini-thesis submitted in partial fulfilment of the requirements for the degree of
Magister Scientiae in the Department of Earth Sciences, University of the
Western Cape

Supervisor: Dr Stephen Holness (University of the Western Cape)
Second Internal Supervisor: Dr Vincent Taylor (University of the Western Cape)

June 2002

Rapid geomorphological change in an urban estuary: a case study of the Eerste River, Cape Town, South Africa.

Chantel Reneé Petersen

Keywords

Eerste River estuary

Geomorphology

Temporal changes

Mouth migration

Flood effects

Hydrological effects of urbanisation

Estuarine bathymetry

Sediment analysis

Abstract

Rapid geomorphological change in an urban estuary: a case study of the Eerste River, Cape Town, South Africa.

Chantel Reneé Petersen

M.Sc. mini-thesis in the Department of Earth Sciences, Faculty of Natural Sciences, University of the Western Cape.

The Eerste River estuary is one of eleven estuaries draining into False Bay. It is an urban river system and has therefore been subjected to human interference, which has resulted in degradation. This study focuses on geomorphological change in the Eerste River estuary induced by urbanisation.

Long-term spatial variability of the estuary and river environments was mapped using aerial photographs covering a period of 62 years (1938-2000). The earlier maps (1938-1977) showed the estuary to be seasonally closed to the sea by a wind and wave-built sandbar during summer. Both the Kuils and the Eerste Rivers were highly seasonal during this time and the estuary was only open to the sea during winter months. During the period 1988-2000 the estuary no longer closed but remained open throughout the year. This was due to the change in the hydrological characteristics of the rivers with increased river flows due to stormwater runoff and treated sewage outflow from several wastewater treatment plants. The increased flows also resulted in rapid westerly mouth migration, which caused extensive dune destruction. The morphology of the estuary changed from being a closed bar-built estuary to a permanently open bar-built estuary with no tidal influence.

Short-term spatial variability in the geomorphology of the estuary was examined over a 12-month period. Nine cross-sections were used to determine the estuarine bathymetry and the sediment characteristics were determined along three. Significant floods occurred during the middle of the study period resulting in rapid geomorphological and spatial change. During the short-term study the estuary migrated back to an easterly position and due to a lower bed elevation pronounced tidal penetration occurred during spring high tides.

The pre-flood survey showed little or no tidal fluctuation whereas the post-flood survey showed variations in water levels between low and high tides. Deposition occurred in all the cross-sections, which resulted in shallowing and narrowing of the main channel. A large amount of bed scour occurred, resulting in a lowering of the estuary bed, although it was not seen in all the cross-sections due to the continuing supply of sediment from upstream. Bank erosion was minimal where the vegetation aided in stabilisation, while significant undercutting occurred where no or sparse vegetation was found.

Deposition was shown by the extensive sandbanks deposited after the flood and by a thin layer of fine sand which covered the vegetation on the right bank due to overbank flow. Sediment characteristics displayed by the estuary was of typical fluvial origin and marine sediment was found closer to the mouth.

Declaration

I declare that *Rapid geomorphological change in an urban estuary: a case study of the Eerste River, Cape Town, South Africa* is my own work, that it has not been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicted and acknowledged as complete references.

Chantel Reneé Petersen June 2002

Signed:.......................................

Acknowledgements

I would like to thank Dr S. Holness for his expert knowledge and encouragement throughout this thesis. I also wish to thank Dr V. Taylor for his comments, support and encouragement. Also to Mr A.C.T. Scheepers for his opinions and his willingness to assist.

Furthermore I wish to thank the students and staff of the Earth Science Department who assisted with the fieldwork.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

Estuaries are known to be productive systems that support plant and animal communities and serve as breeding grounds and nurseries for fish, birds and invertebrates. They are diverse systems and play a significant environmental role. However, due to increased population and therefore urbanisation these systems are increasingly being degraded, as they are particularly sensitive to man-induced disturbances (Ramm, 1990). The coastal zone is subjected to industrialisation, recreation and disposal of storm and wastewater where urban rivers offer a convenient and cost effective transport route for these outputs (Ramm, 1990; Luger, 1994). All these impacts result in deterioration of river environments and this is eventually reflected in their estuaries (O'Callaghan, 1990).

Most of the estuaries in False Bay, including the Eerste River estuary, are fed by urban river systems and have been subjected to the effects of urbanisation. Historically, the Eerste River was highly seasonal with low flows during summer and increased flows during winter months. The result of this was an estuary closed by a wind and wave-built sandbar during summer, which would be breached with the first winter rains (Morant, 1991, Harrison, 1998).

However, urbanisation in the catchment increased which led to an increase in river flows from stormwater runoff and treated sewage effluent. The Kuils River underwent similar changes and formed a confluence with the Eerste River to form its major tributary. A deterioration in water quality resulted due to urban encroachment on the Khayelitsha wetlands in the Kuils River catchment, which caused ecological degradation to the rivers and estuary (Luger, 1994). Due to the hydrological changes in both rivers a change occurred in the estuary morphology. Initial studies suggest that it was transformed from an estuary that was periodically open to the sea to one that remained permanently open (Harrison, 1998). Observations suggest that the increased base flows have caused rapid westward inlet migration together with extensive dune destruction.

Limited estuarine features were displayed. These changes were the main motivation for the present study.

The Eerste River estuary is considered as one of the most important estuaries in False Bay (Harrison, 1998) and yet very few studies have focussed on the physical aspects of the estuary, which would provide information on its dynamics. The study will therefore focus on the geomorphology of the estuary. Information will be provided on the sediment distribution by physical sediment analysis, estuary bathymetry, which will be determined by cross-sectional profiles and the long-term changes in morphology will be illustrated by mapping aerial photographs. The maps will be used to illustrate changes in the river environment and the mouth morphology.

1.1. AIMS AND OBJECTIVES

This study aims to identify and document long and short-term geomorphological changes in the estuary of the Eerste River.

The objectives of the study are:

- to identify long-term spatial changes from aerial photographs
- to document the short-term effects of flooding on an open bar-built estuary
- to document short-term changes to the bathymetry
- to document short-term changes in sediment patterns

The initial chapters to follow include a literature review and summarises the site-specific context of the Eerste River estuary, as well as the methodologies used to obtain both the long-and short-term results. Thereafter the results will be shown, followed by the interpretation thereof. The concluding chapter will summarise the main findings of the research and provide recommendations for possible further studies on the estuary.

CHAPTER 2. STUDY AREA

2.1. ESTUARIES OF FALSE BAY

False Bay is the largest bay in South Africa and has an area of approximately 900km^2. It is square-shaped and semi-enclosed between Cape Point and Cape Hangklip and is situated on the southwest coast of South Africa. The Peninsula Mountains occurs on the west side, the Hottentots Holland Mountains on the eastern side and the north shore area constitutes the Cape Flats. Eleven estuaries, including the Eerste River estuary, drain into False Bay (Grundlingh and Largier, 1991; Harrison, 1998). (Table 1)

2.2. LOCATION

The Eerste River estuary is situated approximately 36km southeast of Cape Town (Wiseman and Sowman, 1992; Harrison, 1998) (Figure 1). Figure 2 illustrates the local area surrounding the estuary. The Eerste River has its headwaters in the Jonkershoek Mountains where it flows in a westerly direction to Stellenbosch and then southerly to Macassar to discharge into False Bay (Ninham Shand, 1993). The Kuils River is a major tributary and the confluence with the Eerste River is approximately 4km from the mouth. The Eerste River has a length of 40km (Heydorn and Grindley, 1982). The total catchment of the two rivers, which is 710km^2, is the largest in the False Bay area and the Kuils River comprises approximately 45% of the catchment (Morant, 1991; Harrison, 1998). The Macassar Waste Water Treatment Works (WWTW) is located on the western side of the estuary and the eastern side is a security area associated with the Somchem factory. As a result the estuary is only accessible from the west bank (Wiseman and Sowman, 1992).

Table 1. Comparison of estuaries in False Bay based on their physical attributes (after Morant, 1991; Harrison, 1998)

Estuary	**Catchment area**	**River length**	**Estuarine status**	**Major impacts**
Buffels (Wes)	3km^2	2.3km	No estuarine characteristics	Alien vegetation encroachment
Elsies	17km^2	7.5km	No estuarine characteristics	Road and rail bridges, embankments, alien vegetation, damming
Silvermine	26km^2	12.2km	Limited estuarine characteristics	Pollution, residential development
Zand (Zandvlei)	83km^2	2.5 km	Viable nursery function	Dredging, recreational use, marine and residential developments
Zeekoe	93km^2		No estuarine characteristics	Sewage effluent, stormwater runoff, light industry, general pollution
Eerste	710km^2	40km	Viable nursery function	Sewage effluent, stormwater runoff, general pollution, alien vegetation
Lourens	140km^2	19.4km	Minor nursery role	Sewage outflow pollution, stormwater runoff, residential development, general pollution
Sir Lowry's Pass	49km^2	13.7km	No estuarine characteristics	Stormwater runoff, organic pollution, rural development
Steenbras	74km^2	18.7km	Limited estuarine characteristics	Two dams
Rooiels	21km^2	10.4km	Viable nursery function	Bridge and road embankments
Buffels (Oos)	24km^2	7.5km	Possible nursery function	Dam, Pringle Bay township encroachment

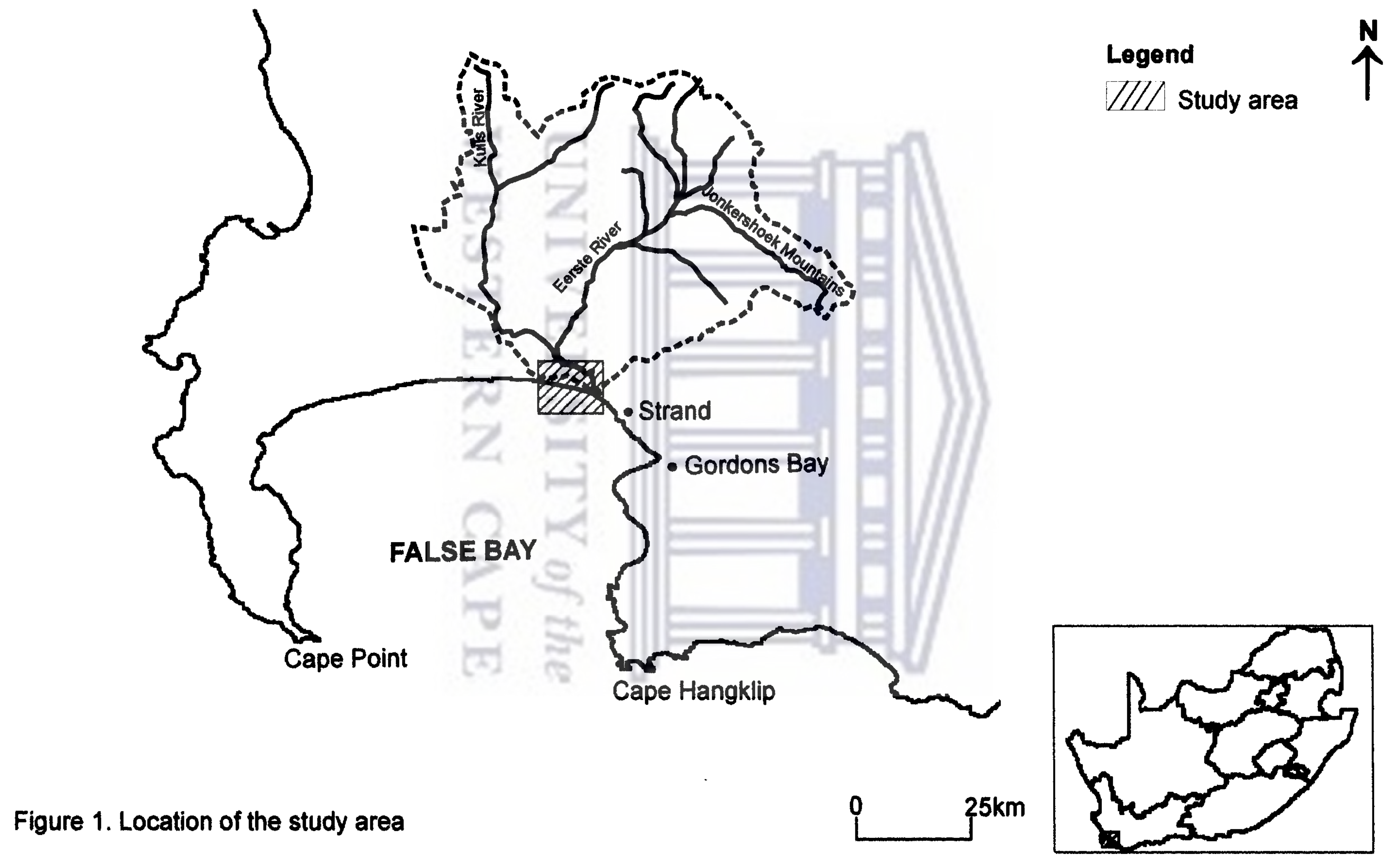

Figure 1. Location of the study area

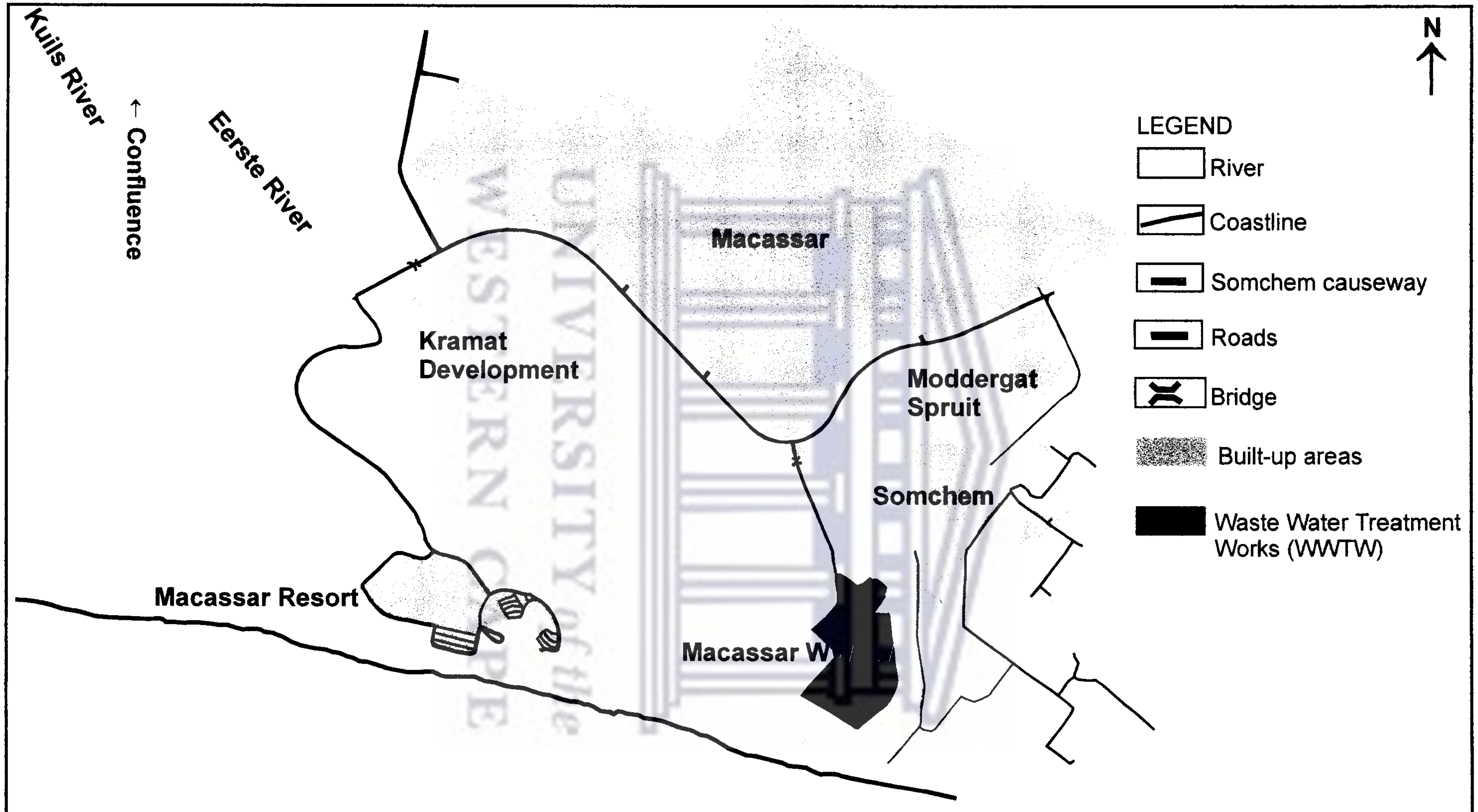

Figure 2. Map showing the local area surrounding the estuary

2.3. CATCHMENT CHARACTERISTICS

Figure 3 shows the catchment boundary of the Eerste/Kuils River basin and the locations of the major wastewater treatment works, dams, tributaries and abstraction points. Landuse in the Eerste/Kuils River catchment consists of residential, industrial and agricultural areas. The Eerste River originates in the Jonkershoek Forest Reserve with the middle reaches flowing through mainly agricultural land and the town of Stellenbosch (Wiseman and Simpson, 1989). The upper reaches of the Kuils River consist largely of residential areas and the lower reaches are occupied by high-density low cost residential developments like the Khayelitsha Township. Also close to the confluence with the Kuils River in the Zandvliet area, the river flows through mostly agricultural land and open space, which was formerly the playing fields of the Macassar sports complex. The lower reaches after the confluence are mostly undeveloped and unmanaged open land where the Moddergat Spruit enters the river. In the estuary section the Somchem factory is located on the eastern bank and the Macassar Waste Water Treatment Works (WWTW) on the western bank (Wiseman and Sowman, 1992; Ninham Shand, 1999).

The Kuils and Eerste Rivers have changed from being highly seasonal to perennial (Harrison, 1998). Winter spates are not affected by catchment activities in the Eerste River but the flood characteristics of the Kuils River have changed due to extensive urbanisation in the catchment (Morant, 1991). This has led to an increase in surface runoff, which enters the river via overland flow from urban areas and via the stormwater system in informal urban areas. The lower reaches of the river experience regular flooding because of the low-lying nature of the settlements on both banks. Flooding of the Eerste River rarely occurs (Ninham Shand, 1999).

Beside surface runoff these rivers also receive treated sewage effluent from a number of WWTW located in their catchments. Scottsdene, Bellville, Kuils River and Zandvliet WWTW discharges effluent into the Kuils River. The Stellenbosch

WWTW discharges effluent via the Veldwagters River, into the Eerste River, together with the Macassar WWTW. The average flow rates are: Scottsdene-1.5Mℓ per day, Bellville-36Mℓ, Kuils River-1Mℓ, Zandvliet-18Mℓ, Stellenbosch-13.5Mℓ and Macassar-14Mℓ per day. The Elsenberg WWTW, which is a smaller plant, discharges 0.1Mℓ per day into the Eerste River (Ninham Shand, 1993).

The Kleinplaas balancing and diversion dam in the upper reaches of the Eerste River diverts approximately 80% of the natural river inflow (Huizinga *et al.*, 2001). The Kleinplaas Dam has regulated the upper section of the Eerste River since 1981 and is part of the Riviersonderend-Berg River Water Transfer Project (Heydorn and Grindley, 1982; Wiseman and Simpson, 1989). Riparian farmers and property owners abstract water from the Eerste River along most of its length. The Lower Eerste River Irrigation Board (LERIB) has two abstraction points along the river, one below the confluence with the Plankenbrug River and a lower one located just above the confluence with the Blouklip River (Wiseman and Simpson, 1989).

When the demand for water exceeds the available run-off in the lower river reaches, water is released from the Theewaterskloof Dam via the Kleinplaas Dam, mostly during the summer months from November to March. Most of the water released is again abstracted by the riparian owners and very little, if any, reaches the lower river reaches. The total amount of water abstracted by the LERIB and other riparian owners is not known, as no records exist. The Stellenbosch Municipality also abstracts water from the river and the Stellenbosch dams in Idas Valley further reduce the winter flows (Wiseman and Simpson, 1989; Huizinga *et al.*, 2001).

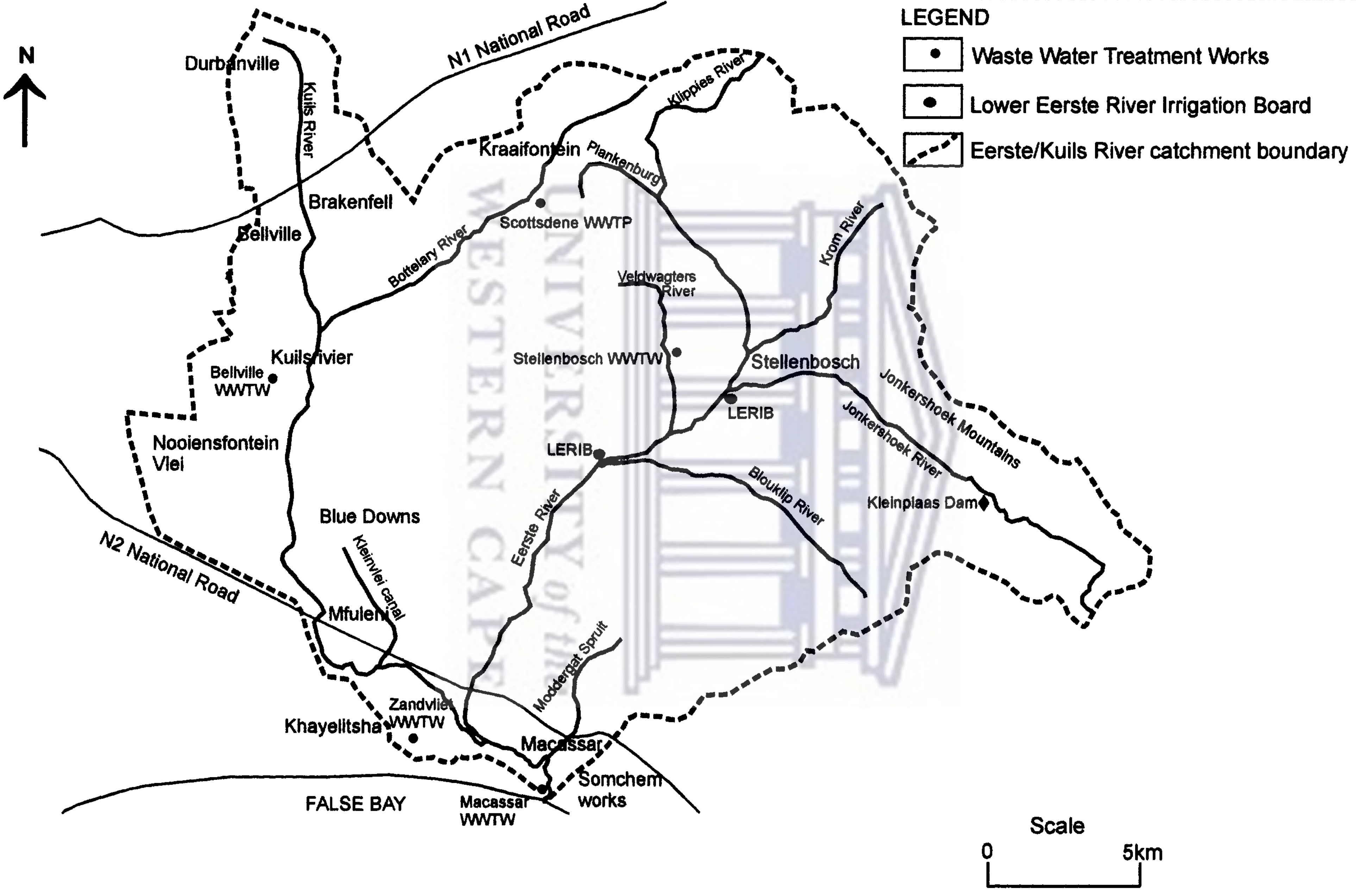

Figure 3. Map showing locations of WWTW and extraction points along the Eerste/Kuils River (Ninham Shand, 1999)

2.4. GEOLOGY

The lower mountain slopes of the catchment have mainly slate and quartzite of the Malmesbury Group, intruded by Cape Granite (Heydorn and Grindley, 1982). Sedimentary rocks along the contact have been metamorphosed into resistant hornfels. Table Mountain Sandstone overlay these formations and results in the steep fronts of the Jonkershoekberg, Simonberg and Stellenboschberg (Söhnge, 1991). The lower reaches of the catchment occur in the coastal plain on aeolian sand (Heydorn and Grindley, 1982).

The Pre-cambrian Malmesbury Group rocks include shale, greywacke and siltstone and are approximately 800 million years old. Due to tectonic activity Cape Granite batholiths and plutons also occur. The Malmesbury rocks and the Cape Granite are found beneath the Klipheuwel formation, which includes conglomerates and sandstone in the Klapmuts area and are of late Pre-cambrian age. Dolerite intrusions also occur but their ages are not known. Only the Graafwater and the Peninsula formations, which are the lower units of the Table Mountain Group, are found in the catchment area of the Eerste River system. The mesozoic deposits of the Karoo supergroup are no longer present in the area (Heydorn and Grindley, 1982).

Sediments in the area were formed during the Tertiary period and include well-rounded stones and marine shells. Quaternary sediments, which include sand, silt, clay and mud that accumulated in the drowned coastal area, cover tertiary sediments. Peat layers also occur between sand layers due to the presence of plant material in marsh areas. The shell fragments resulted in excess calcium carbonate and formed calcrete layers, which developed into cliffs along parts of the coastline. The sands found in the interior are reddish-brown or dark grey and sections of ferricrete and silicrete layers also occur (Heydorn and Grindley, 1982; Wright and Conrad, 1995).

Malmesbury Group rocks underlie the northern and western areas of the catchment. The sediments are Pre-cambrian and include quartzites, phyllite, greywacke and shales, which are covered by recent deposits of loam. Tertiary and recent deposits of loose sand and dune formations, which overlie extensive clay lenses, are found below the confluence of the Kuils and Bottelary Rivers. Gravel, sandstones and conglomerates as well as silicrete and calcrete also occur (Heydorn and Grindley, 1982).

Due to the geology, the surface runoff in the upper catchment contributes an important percentage of the total runoff, whereas sub-surface runoff does not play an important role. However, the rainfall infiltration that occurs in the lower reaches is such that sub-surface runoff becomes very significant (Ninham Shand, 1993).

2.5. CLIMATE

The catchments fall within the winter rainfall region and have a Mediterranean type climate (Ninham Shand, 1993). Monthly rainfall (mm) averages for 1961-1990 are shown in Figure 4 for the Cape Town International Airport, which is located in the catchment.

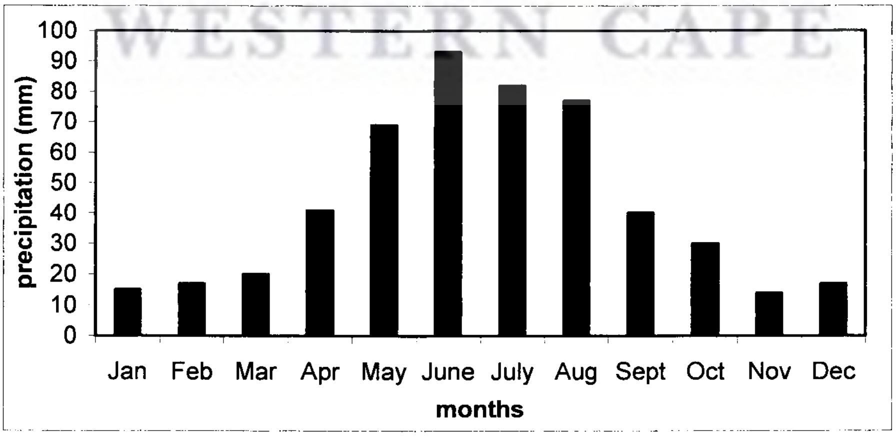

Figure 4. Average annual rainfall data for Cape Town International Airport

Cape Town is influenced by the South Atlantic anticyclone and is therefore located in the south-easterly wind regime. Westerly winds occur mainly during winter and passes south of the southern African subcontinent during summer. The highest wind velocities are recorded at Cape Point, with the fringing mountains on the eastern side of False Bay creating a wind shadow in the Eerste river area (Grundlingh and Largier, 1991).

Lighthouses at Cape Point and Danger Point have provided records of wind velocity as well as sites at Strand, Gordons Bay and Cape Town International Airport. The wind direction occurrences are shown in Table 2 for Cape Point, Strand and Gordons Bay and the wind diagrams are shown in Figure 5. The results of these records show that south-easterly winds predominate throughout the year except during June, July and August. South-easterly winds still occur during winter together with north and north-easterlies. The patterns shown are that the south-east winds dominate in the south-west arm of the bay; at the north coast southerly winds dominate and at the north-east corner south-westerly or south-easterly winds occur with easterlies dominating in the vicinity of Gordons Bay where the intensity increases, especially in spring, towards Cape Hangklip (Atkins, 1970; Wainman *et al.*, 1987).

Table 2. Wind directions occurring at sites around False Bay (after Jury, 1991)

Location	**Wind direction (% of time)**							
	NE	**S**	**SE**	**S**	**SW**	**W**	**NW**	**N**
Cape Point	5	3	35	10	12	10	12	7
Strand	0	0	14	17	10	7	17	8
Gordons Bay	9	17	8	13	15	9	7	9

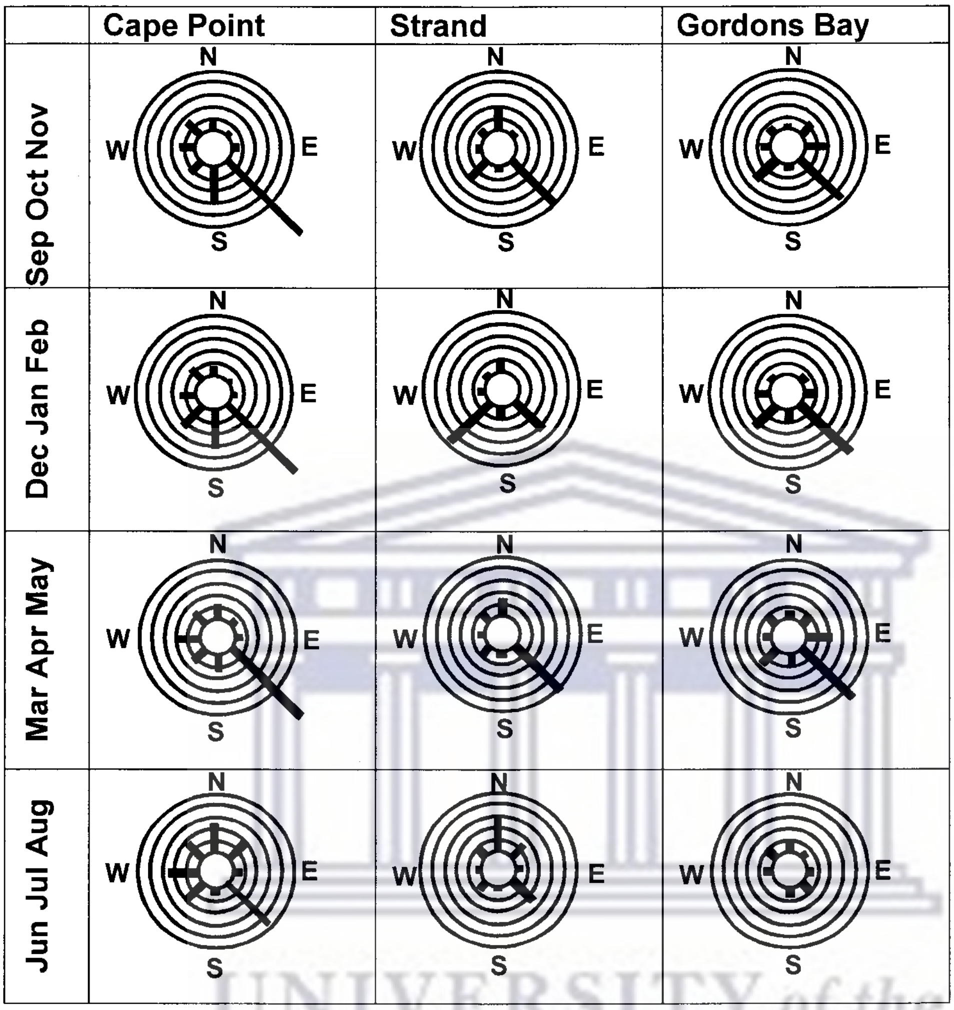

Figure 5. Wind roses for Cape Point, Strand and Gordons Bay (after Atkins, 1970)

2.6. CURRENT PATTERNS IN FALSE BAY

Slower current velocities usually occur within bays and waves are milder and generated locally (Grunlingh and Largier, 1991). Winds are the main driving force for currents within False Bay (Jury, 1991). Currents have been categorised into 4 types. Type I is characterised by a clockwise rotation, which results from south-easterly or easterly winds and occurs approximately 50% of the time. Type II is characterised by anticlockwise currents and develops under north-westerly winds, occurring less than 10% of the time. Types III and IV occurs during calm periods and coincides with tidal conditions due to their slow-moving currents. The currents move mainly towards the north during the flood and south during the ebb. False Bay experiences a semi-diurnal tide with a tidal range of approximately 0.3m during neaps and 1.9m during spring tides (Atkins, 1970; Grundlingh and Largier, 1991).

2.7. VEGETATION

The dominant vegetation types were sampled from both riverbanks during May 2001 and were identified together with the aquatic vegetation. The vegetation samples were identified by Dr L. Raitt from the Botany Department at the University of the Western Cape. The distributions of different vegetation types are shown in Figure 6. Present vegetation (2001) was found to be similar to the study undertaken by Heydorn and Grindley (1982). However, the vegetation density has increased over past years resulting in greater area cover. This increase occurred in the riparian and dune vegetation zones.

Aquatic vegetation

There were only two abundant aquatic vegetation types present. These were *Myriophyllum aquaticum* (parrots feather) and *Eichhornia crassipes* (water hyacinth) and it occurred in patches along the entire river length. In the vicinity of Somchem the aquatic vegetation increased in density. Downstream from the confluence with the Kuils River *Lemna Gibba* (duckweed) also occurred.

Semi-aquatic vegetation

The intertidal fringe vegetation consisted of *Cotula coronopifolia* (gansgras) and *Scirpus maritimus* also occurred. *Phragmites australis* reeds line both the left and right banks of the estuary. These reeds have formed dense monospecific stands and they generally grow where no or very little salt water penetrates and in areas where silt deposition occurs (O'Callaghan, 1990). A large section on the left bank, in the vicinity of transect 9, are also lined with *Typha capensis* (bulrush).

Terrestrial vegetation

The sections of the foredunes on left and right banks have large areas covered by various shrubs such as *Heteroptilus suffruticosa* (mostly found on the right bank) and *Chrysanthemoides monilifera* (both banks). *Stenotaphrum secundatum* covered an extensive area on the right bank and *Zantedeschia aethiopica* was occasionally found. On the left bank the dominant dune plants were *Arctotheca populifolia* (sea pumpkin), *Agropyron distichum* (sea wheat) and *Senecio elegans*. Alien Australian acacias are increasingly encroaching the dunes surrounding the estuary and the riparian zone. In the moist shrubland area mostly *Acacia cyclops* (Rooikrans), *Acacia saligna* (Port Jackson), *Metalasia muricata* (blombos) and *Nidorella foetida* are found.

Other dune vegetation includes *Myrica cordifolia, Trachyandra divaricata* (left bank) and *Senecio halimifolius* (right bank). *Carpobrotus acinaciformis* with *Tetragonia fructicosa* also covered large areas. The dune shrubland merged with the fore dunes on the right bank and *Pelargonium capitatum*, *Rhus laevigata* (duine taaibos) and *Sideroxylon inerme* (milkwoods) are found (Heydorn and Grindley, 1982). *Sideroxylon inerme* have legislative protection because they are part of the few remaining indigenous specimens on the Cape Flats (Ninham Shand, 1999).

In terms of vegetation both the Eerste and Kuils Rivers have a low conservation value. However, the Macassar dunes do support some natural vegetation species. Among these are *Senecio halimifolius*, *Metalasia muricata* and *Agrpyron distichum. Kiggelaria* (wildpeach) are also found along these banks (O'Callaghan, 1990; Ninham Shand, 1999). The natural vegetation on the banks of the Eerste River and estuary has mostly been destroyed by the encroachment of alien plants, which results in a loss of species. Trampling, grazing by animals, off-road vehicles and wood collection have also played a significant role (O'Callaghan, 1990; Wiseman and Sowman, 1992).

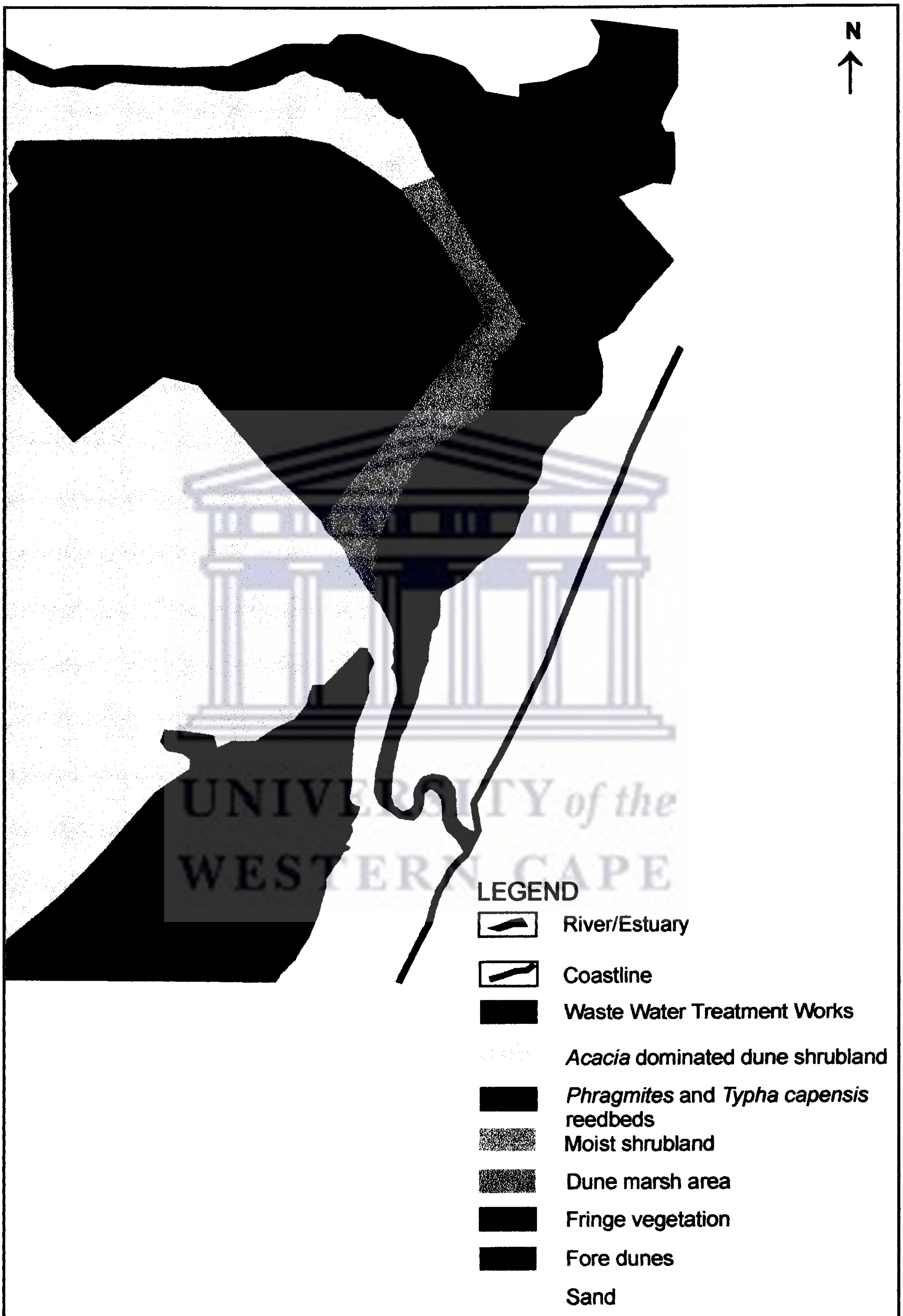

Figure 6. Vegetation map of the Eerste River estuary

Scale: 1:5000

CHAPTER 3. LITERATURE REVIEW

Estuaries can generally be defined as a partially enclosed coastal body of water that is either periodically or permanently open to the sea and within which there is a measurable variation of salinity due to the mixture of sea-water and fresh-water derived from land drainage (Whitfield, 1994). Many authors alter this definition to suite the morphology that the estuary exhibits at the time of study. Climate, river regime, sediment supply, oceanographic regime and biological processes all control estuarine morphology (Kench, 1999). Hence, estuary morphology varies depending on location. Although classifications of estuaries vary, in general estuaries can be divided into four main types. These are drowned river valleys, fjords, bar-built and estuaries produced by tectonics (Richard and Davies, 1992). A further distinction can be made between open and closed estuaries (Cooper, 2001a).

3.1. ESTUARINE MORPHOLOGY

Drowned river valleys

These are the most widespread estuary type (Ingmanson and Wallace, 1989). They are irregular shaped, found along coastal plains and formed by drowning river valleys due to a rise in sea level. The topography of these estuaries is similar to that of the drowned river valley because of low sedimentation rates. As a result depths of as much as 30m can be maintained. Wide channels often occur although this depends on the rock type. The estuary bed consists of recently accumulated sediments where mud dominates in the upper reaches and sand dominates in the mouth area. Very often wave and tidal influences occur great distances up these estuaries (Kench, 1999).

Fjords

Fjords are steep-sided and deep (300-400m) estuaries that are formed by glaciers (Ingmanson and Wallace, 1989; Richard and Davies, 1992). They develop in areas that are covered by ice sheets (Dyer, 2000). These ice sheets exerts pressure on already existing river valleys, which results in overdeepening and widening. This process tends to leave sills and rock bars at the mouths of fjords. Rocky floors are found and often only a thin layer of sediment will occur. Most of the deposition occurs at the mouth. The tidal prism (volume of water moving into and out of the estuary with tides) is small compared to the volume of river flow due to the obstructions at the mouth, which results in a smaller tidal range and poor circulation (Richard and Davies, 1992; Dyer, 2000).

Tectonically produced estuaries

These estuaries are coastal indentations formed by subsidence and faulting to create embayments (Richard and Davies, 1992). They occur in coastal areas, which undergo active mountain building such as those found on the western coast of North and South America, e.g. San Francisco Bay (Gross and Gross, 1996).

Open bar-built estuaries

Estuaries of this type normally maintain an inlet that is permanently open to the sea. These inlets can display a great variety in their morphology and a distinction can be made between open non-barred estuaries and open bar-built estuaries. Barred estuaries are classified as those, which have a supratidal barrier with a surface channel (Cooper, 2001a) and where a linear barrier beach also exists (Reinson, 1992). A non-barred estuary can develop within a drowned river valley and may have sand accumulation at the outlet. These estuaries also lack a supratidal barrier that can result in closure. Barrier estuaries can be subdivided into river-dominated, wave-dominated and tide-dominated (Reinson, 1992; Cooper, 2001a).

A river-dominated estuary is completely dependent on fluvial discharge to maintain its inlet (Cooper, 2001a). These estuaries develop in areas, which have high rainfall and surface runoff to rivers. In South Africa these estuaries mostly occur along the KwaZulu-Natal coast. Floods are also common in these areas, with the most significant morphological changes occurring during times of flood.

This was shown by studies conducted by Cooper (1993), Cooper (1994), Cooper *et al.* (1990) and Lindsay *et al.* (1996).

In wave-dominated estuaries wave action plays a significant role at the mouth. The sediment transported alongshore forms a spit that constricts the mouth and builds outwards. This process will continue until the tidal currents, which increase with the decreasing mouth area, reach equilibrium by eroding sediment from the tip of the spit as quickly as it is transported by littoral drift. Upstream of the estuary the river processes will dominate resulting in a low energy zone in the middle reaches. These estuaries are found to occur along microtidal or mesotidal coasts (Dyer, 2000).

Tide-dominated estuaries have a large enough tidal prism to maintain open inlets by extreme tidal currents (Reinson, 1992). The tidal influence decreases upstream of the estuary and the river flows will dominate resulting in sandbank formation at the mouth, which are aligned with the current flow (Dyer, 2000). However, in South Africa these estuaries exist even with a relatively low tidal prism. It has been found that tidal estuaries can even maintain their inlets with little or no fluvial discharge (Cooper, 2001a).

Closed bar-built estuaries

This estuary type also commonly occurs. It forms when a spit or barrier bar develops across the estuary mouth (Richard and Davies, 1992). These estuaries form in regions dominated by a seasonal rainfall regime and as a result the estuary also experiences seasonal discharge with mouth closure during the dry seasons (Schumann and Pearce, 1997). The closure of a tidal inlet is to a great extent controlled by wave action (Reddering, 1988; Whitfield, 1992), with longshore currents transporting sand to the tidal inlet to form a bar across the estuary mouth and thereby preventing intrusion of sea-water. Mouth closure is related to the back-barrier water levels depending on whether the levels are higher than or within range of the sea tide levels. This is again related to the height of the sand bars, which results in mouth closure. When these systems are perched a high berm forms and impounds water at higher levels than most high tides (Cooper, 2001a).

A balance will exist between inputs from fresh-water inflow, barrier overwash and rainfall, and outputs by evaporation, seepage and evapotranspiration by fringing vegetation in closed perched systems (Cooper, 2001a). Usually tidal currents will erode the bar but if erosion is inefficient it will move shoreward and increase in height. The bar could also be breached during floods (Reddering, 1988; Lindsay *et al.*, 1996) and/or due to barrier overwash related to storm surges (Reinson, 1992).

Due to the higher bed levels these lagoons undergo a draining effect when open, which means that previously submerged bed areas are exposed subaerially. These estuaries will only remain open while the river flow is strong enough to maintain the inlet after which it will again be closed by the sand bar. Despite their high bed elevations some estuaries retain their inlets below sea level and this allows intrusion by sea-water (Cooper, 2001a). The tidal prism will also determine whether the tidal inlet remains open, closed or constricted (Reddering, 1988).

In South Africa this type of estuary often occurs on the southwestern and eastern Cape coast. Studies conducted by Largier and Slinger (1991) and Largier and Taljaard (1991) showed the seasonal regime of the Palmiet estuary in the southwestern Cape. Schumann and Pearce (1997) demonstrated that closure of an estuary could also result from a reduction in river flows due to anthropogenic effects such as dams.

It is important to note that estuaries can change type depending on their hydrological characters. For example an estuary, which was once periodically closed, could become permanently open. It could also become a river mouth during times of flooding when the mixing zone (fresh and saline water) is forced seawards (Whitfield, 1992). Changes in the wave energy and tidal prism can also cause a change in morphology. This is especially true when a tidal prism increases and a microtidal coast exhibits tide-dominated features (Reinson, 1992).

3.2. TIDAL RANGE

Estuaries have different tidal ranges and three can be distinguished. These are microtidal, mesotidal and macrotidal estuaries (Richard and Davies, 1992; Kench, 1999).

Microtidal estuaries

These estuaries have a tidal range of less than 2m. Upstream of the estuary fresh-water flows dominate the estuarine processes, while outside the mouth wind-driven waves dominate. South African estuaries have a maximum tidal range of approximately 2m and are therefore microtidal (Whitfield, 1992; Allanson and Read, 1995). In estuaries of this type ebb-and flood tide currents are weak with wave energy having a greater control on inlet morphology (Kench, 1999).

Mesotidal estuaries

The tidal range for mesotidal estuaries ranges between 2-4m (Richard and Davies, 1992). Stratification becomes less significant and tidal currents play a greater role in circulation (Pethick, 1984). These estuaries are associated with two features by which they can be distinguished, namely: flood and ebb tide deltas as well as tidal meanders in the landward channel (Reddering and Rust, 1990).

Macrotidal estuaries

Tidal range greater than 4m occurs in macrotidal estuaries (Richard and Davies, 1992). The tidal and residual currents' (currents resulting from the mixing of fresh and saline water) influence will extend several kilometres upstream due to the tidal dominance. A characteristic of macrotidal estuaries is the presence of elongated sand bars (Pethick, 1984; Cooper, 1994). These estuaries also have a very distinct funnel shape, as the channel decreases in width in an upstream direction and flares at the estuary mouth (Kench, 1999).

3.3. ESTUARINE CIRCULATION

Circulation within an estuary is caused by the wind, tidal flow and river flow (Ingmanson and Wallace, 1989). Certain estuaries display different types of circulation patterns with changes in river flow or sea-water intrusion (Largier and Taljaard, 1991).

3.3.1. Salt-wedge or highly stratified estuary

If the tidal range is small and the estuary experiences a large inflow of river water, very little mixing of fresh and saline water will occur, the fresh-water will overlay the more saline water. The saltier body of water will be thick at the estuary mouth but thins as the channel bed rises upstream, so forming the salt-wedge (Pethick, 1984). Such a layered structure in an estuary can also be referred to as being highly stratified. These conditions result due to the inflow of large amounts of low salinity or warm water relative to stirring as a result of tides and winds. Fjords found along the Norway coast, Canada and Western New Zealand belong to this class. Various bar-built coastal plain estuaries on the South African coast are also highly stratified e.g. the Palmiet estuary on the southwestern coast of South Africa (Largier and Slinger, 1991).

The study on the Palmiet estuary by Largier and Slinger (1991) was conducted during winter and the circulation pattern that occurs is considered typical for all bar-built estuaries on South Africa's coast. River flows are much higher during winter than summer along the southwestern coast and due to the increase no stratification occurs during neap tide. During spring tide stratification reaches a maximum as the tidal inflow is increased (Largier and Taljaard, 1991). Studies by Schroeder *et al*. (1990) have also shown stratification-destratification patterns in

Mobile Bay in Alabama, where destratification occurs with strong discharges and returning to stratified conditions when discharge decreases. These conditions also occurred in the bar-built Eerste River estuary (Harrison, 1998). When spring tide is reached the tidal prism is increased and the river flow is decreased, which results in a damming effect because the inflow of sea-water is strong enough to prevent the simultaneous outflow of fresh-water (Largier and Taljaard, 1991; Largier and Slinger, 1991).

The inflow of sea-water results in a tidal intrusion front (plunge line) where mixing will occur. Stratified conditions will exist landward of the front, but not on the seaward side. The plunge line can clearly be seen by a change in surface watercolour as it moves upstream with increasing tidal intrusion (Largier and Slinger, 1991).

During spring high tides the salt-wedge will be moved further upstream and when persistent winds blow the salt transport is further aided (Slinger and Taljaard, 1994; Schumann and Pearce, 1997). On the ebb tide the saline water is usually removed from the estuary. This happens when friction acts on both the salt-water and fresh-water layers resulting in the removal of the top layer of sea-water with the outflowing fresh-water. The bottom layer will gradually become less saline. For the salt-wedge to be maintained more salt-water intrusion must occur.

This process adds to the water volume and thereby increases the flow towards the mouth (Dyer, 2000). In a similar way winds can also cause destratification within an estuary. Studies have shown that during low and moderate flows strong winds can result in more homogenous river water (Schroeder *et al.*, 1990).

Sometimes obstructions such as sills trap saline water in the upper reaches and the salt-water can remain resident in the estuary over a number of tidal cycles before being removed (Slinger and Taljaard, 1994). Studies conducted by Schumann and Pearce (1997) showed that the salt-wedge can also penetrate further upstream during low flows with an increased tidal range when no obstructions occur at the mouth e.g. when flood tidal deltas are scoured away during a flood.

3.3.2. Partially mixed estuaries

In these estuaries the vertical salinity gradient exhibits varying degrees of mixing or stratification between the out flowing layer of fresh-water and the inflowing layer of bottom sea-water (Seaman and van As, 1998). Due to a larger tidal range and less river inflow more mixing occurs in partially mixed estuaries, although not complete (Ingmanson and Wallace, 1989). Strong tidal currents together with residual currents move a large amount of suspended load and bedload material into the estuary from the sea. Marine rather than fluvial processes dominate these estuaries (Pethick, 1984). As a result these estuaries are also known as wave-dominated estuaries (Cooper, 1994).

3.3.3. Fully mixed estuaries

An estuary that widens towards the sea but maintains a constant depth will experience vigorous tidal flow so that the halocline (interface between lighter fresh-water and dense salt-water) is almost vertical. The salinity remains constant from the bottom to the top and due to the Coriolis effect the fresh and salt-water will flow on opposite sides of the channel and mixing will occur across the estuary (Ingmanson *et al.*, 1989; Seaman and van As, 1998). When lateral mixing occurs the tidal current is strengthened so that the marine sediment is deposited on one bank and river sediment on the other (Pethick, 1984). Estuaries can also be dominated by tidal currents and during such conditions no variation in salinity occurs vertically or horizontally, but it does decrease gradually upstream (Ingmanson and Wallace, 1989).

Permanently open South African estuaries are also classified according to the above-mentioned types. Even though tides and tidal currents are mainly responsible for the mixing processes in permanently open estuaries, floods also play a significant role. This is due to the fact that energy derived from floodwater could change the mixing process from tide-dominated to river-dominated. In temporarily open estuaries both tide and river influence become significant during the open phase of the mouth and during the closed phase mixing occurs by wind (Whitfield, 1992).

3.4. SEDIMENT CHARACTERISTICS

Estuaries mature by the infilling of sediment as estuarine environments generally act as sediment traps (Richard and Davies, 1992). However, this process depends on whether enough sediment is available, the efficiency of sediment delivery processes and the ability of estuaries to trap sediment. The dominant forces, which are wave, river and tidal processes, will determine how fluvial and marine sediments are distributed in an estuary (Kench, 1999).

3.4.1. Wave-dominated estuaries

Kench (1999) found that wave-dominated estuaries in Australia had a tripartite zonation of facies. The upper reaches consist of fluvially derived sediment and this section of the estuary is considered to be the most complex. The reason being that this sediment is very diverse because it could be supplied from a variety of sources example from riverbanks, channels, floodplains, etc. As a result the sediments are poorly sorted and contain sands, gravels and mud. The centre of the estuary consists of a mud basin with relatively deep-water depths. As this is a low energy zone, deposition usually occurs and the sediment is dark grey to black containing a considerable amount of organic matter and shell foraminifera. The high-energy marine environment dominates the third zone. The sediment consists of coarse, shelly quartzitic sands, which are deposited by the waves and tidal currents.

3.4.2. River-dominated estuaries

In these estuaries sediments consists of mostly fine material (Kench, 1999). In South Africa estuaries of this type have shallow or intertidally exposed back barrier areas where the fluvial sediment extends until or close to the landward margin of the estuary barrier. Large volumes of sediments supplied from the catchments and hinterlands make this possible. Due to the filled nature of these estuaries, further sediment supplied, passes through and is deposited in the sea (Richard and Davies, 1992; Kench, 1999). A river-dominated estuary therefore displays a bipartite facies division, where marine influences are minimized or limited due to steep gradients and high fluvial discharge (Cooper, 1993).

A study conducted on the river-dominated Mvoti (Cooper, 1994) and the Mgeni (Cooper, 1993) estuary on the Natal coast of South Africa showed a similar result. He found that the estuary maintained a more or less constant sediment volume over a long time period. Although sediment volumes were temporarily reduced by scouring during river floods it was quickly replaced and the estuary again maintained equilibrium. Additional sediment was deposited in the sea.

3.4.3. Tide-dominated estuaries

Tide-dominated estuaries are usually associated with well-developed flood tidal deltas as was found in studies conducted in estuaries such as St Lucia and Sundays, which was documented by Cooper (2001a). Similar studies conducted on estuaries on the United States East coast also showed progressive bedload sediment movement into estuaries. The landward movement of sediment was associated with flood-tidal dominance and from studies such as these it was concluded that these estuaries served as storage for marine sediment (Cooper, 2001a).

Tidal estuaries do not usually exhibit a tripartite facies zonation, but change in a landward direction from coarse-grained tidal bars to high-energy sand flats to extensive intertidal fluvial mudflats. However, when an estuary has a low macrotidal range or is microtidal, it is not uncommon to find a tripartite zonation because the wave processes and fluvial discharge are similar to those, which cause such a zonation (Reinson, 1992). An example of this was documented by

Cooper (2001a), which coincided with the findings of Kench (1999) for sediment distribution in wave-dominated estuaries. Lindsay *et al*. (1996) showed the same results in their study on the Mfolozi estuary.

Thus estuaries vary greatly in their morphological characteristics and the estuary type depends largely on its location. Morphology can determine the circulation pattern within an estuary as well as whether or not tidal intrusion will occur (Reinson, 1992; Kench, 1999). Circulation patterns are dependent on wind, discharge and tidal inflow. The amount of tidal inflow depends on the volume of discharge and the actual geomorphology of the estuary (Ingmanson and Wallace, 1989; Schumann and Pearce, 1997). Sediment characteristics within estuaries are controlled by their different environmental settings where the distribution and transport of sediment will depend on whether the estuary is dominated by tides, waves or river flow. Changes in the hydrology of an estuary will result in changes in morphology, tidal regime, circulation patterns and sediment distribution.

CHAPTER 4. RESULTS AND DISCUSSIONS

4.1. LONG-TERM CHANGES IN MORPHOLOGY

4.1.1. METHODOLOGY

Mapping based on aerial photographs from 1938 (Job no: 126), 1953 (Job no: 335), 1966 (Job no: 534), 1977 (Job no: 786), 1988 (Job no: 919), 1996 (Job no: 994) and 2000 (Job no: 1033) was used to show long-term changes in the Eerste River estuary. Most of the photographs were at different scales and had to be changed to a common approximate scale of 1:12000 for comparison. The study aims to compare the changes that occurred within the river and estuarine environments. These include the estuary morphology, the catchment and the riparian and dune vegetation. The aerial photographs were scanned and on screen digitizing was used to map each photograph.

4.1.2. RESULTS

1938

The 1938 (Figure 7) photograph was taken during the summer months and show that the estuary was closed from the sea by a sandbar. This reflects the high seasonality of the Eerste River. The Kuils River flowed into a system of marshlands and was not a tributary at this time. The narrow river channels also illustrate the low flow of the Eerste River. A westerly lagoon (A) is weakly developed from channels in the area where the Macassar Waste Water Treatment Works (WWTW) is presently located. A backshore lagoon (B) opened to the sea on the eastern side. It was extensively developed being more than 2500m in length and approximately 250m wide. Due to the low flow the lagoon is disconnected from the river but when flows increase the lagoon can extend to both the western and eastern sides (Heydorn and Grindley, 1982). A permanent wetland/marsh (C) also occurs in the area.

At this time the estuary was perched above sea level for much of the year and as a result was probably only slightly tidal. Sea-water also entered the lagoon by barrier overwash during spring high tides (Heydorn and Grindley, 1982).

Sparse vegetation occurs on the fore dunes and was increasingly being encroached on by denser vegetation. Very little indigenous vegetation occurred on the dunes surrounding the river due to invasion by alien Australian acacias especially *Acacia saligna* and *Acacia cyclops*. The acacias had been planted around the Eerste River mouth by official bodies, local government and central government organisations as early as 1885 (O'Callaghan, 1990). No roads, very few sand paths and open sand areas existed. A small percentage of land was cultivated during this time.

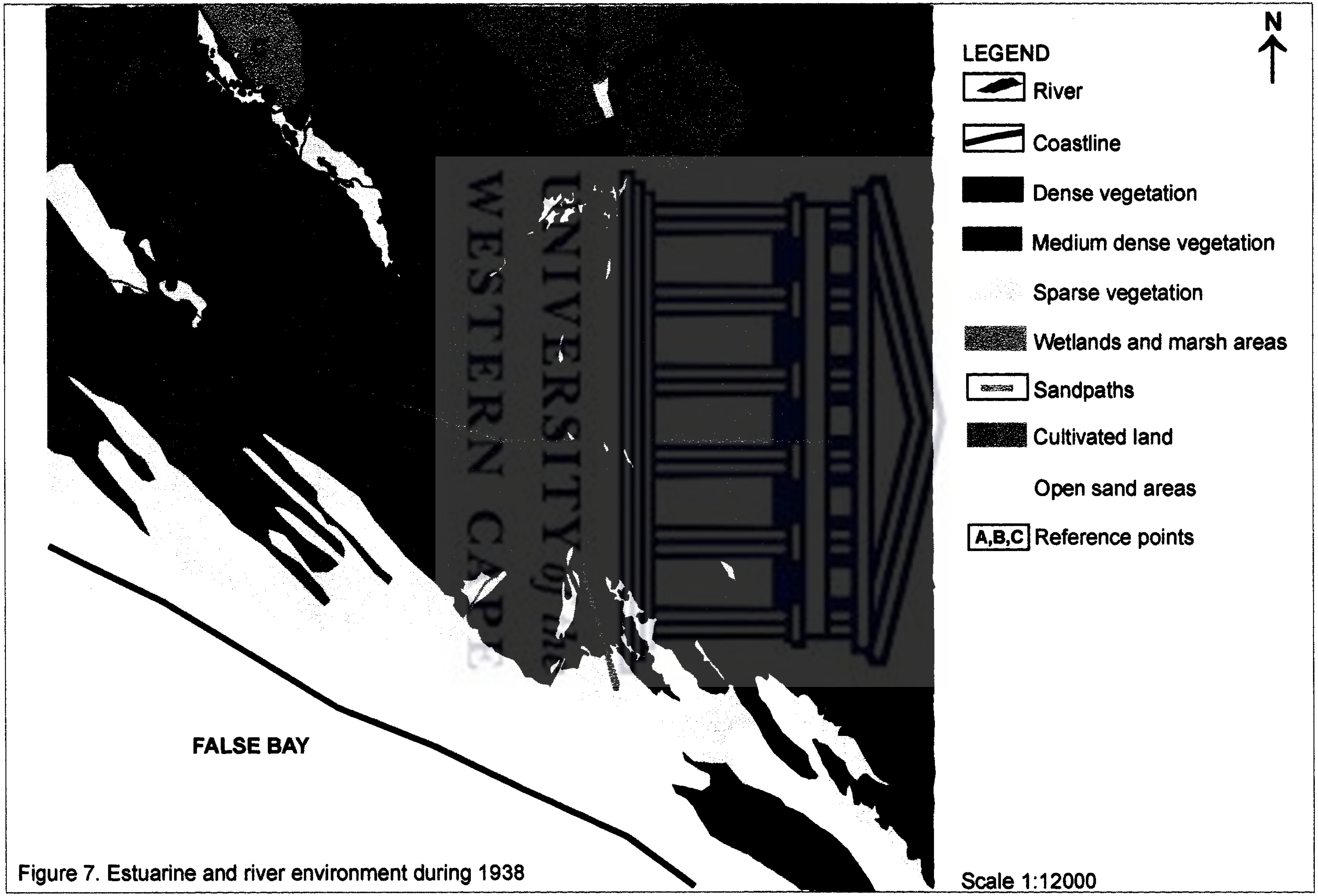

Figure 7. Estuarine and river environment during 1938

1953

In 1953 (Figure 8) the estuary is still shown as closed to the sea as the photograph was taken during summer. The permanent wetland occupied a larger area, which could possibly be related to the increase in surface water area due to an increase in runoff associated with developments in the catchment (O'Callaghan, 1990). It was also separated into two sections by sparse vegetation. No lagoon existed on the eastern side and a western lagoon of approximately 400m in length had developed (Heydorn and Grindley, 1982). The estuary mouth had migrated 360m over 15 years in a westerly direction. The beach area (D) showed an increase in width from the east to west side.

Sections of dense riparian vegetation are mostly seen on the right bank (west side) of the river while vegetation with a medium density occurs on the left bank. The vegetation along the lagoon section are also medium dense. The patches of dense vegetation had increased and also the amount of sand paths and open sand areas. However, certain areas on the western dunes of the estuary also showed a decrease in the dense vegetation to medium dense and sparsely vegetated fore dunes. Dune vegetation on the eastern side was decreased due to the construction of the Somchem factory (E). The percentage of cultivated areas also showed an increase.

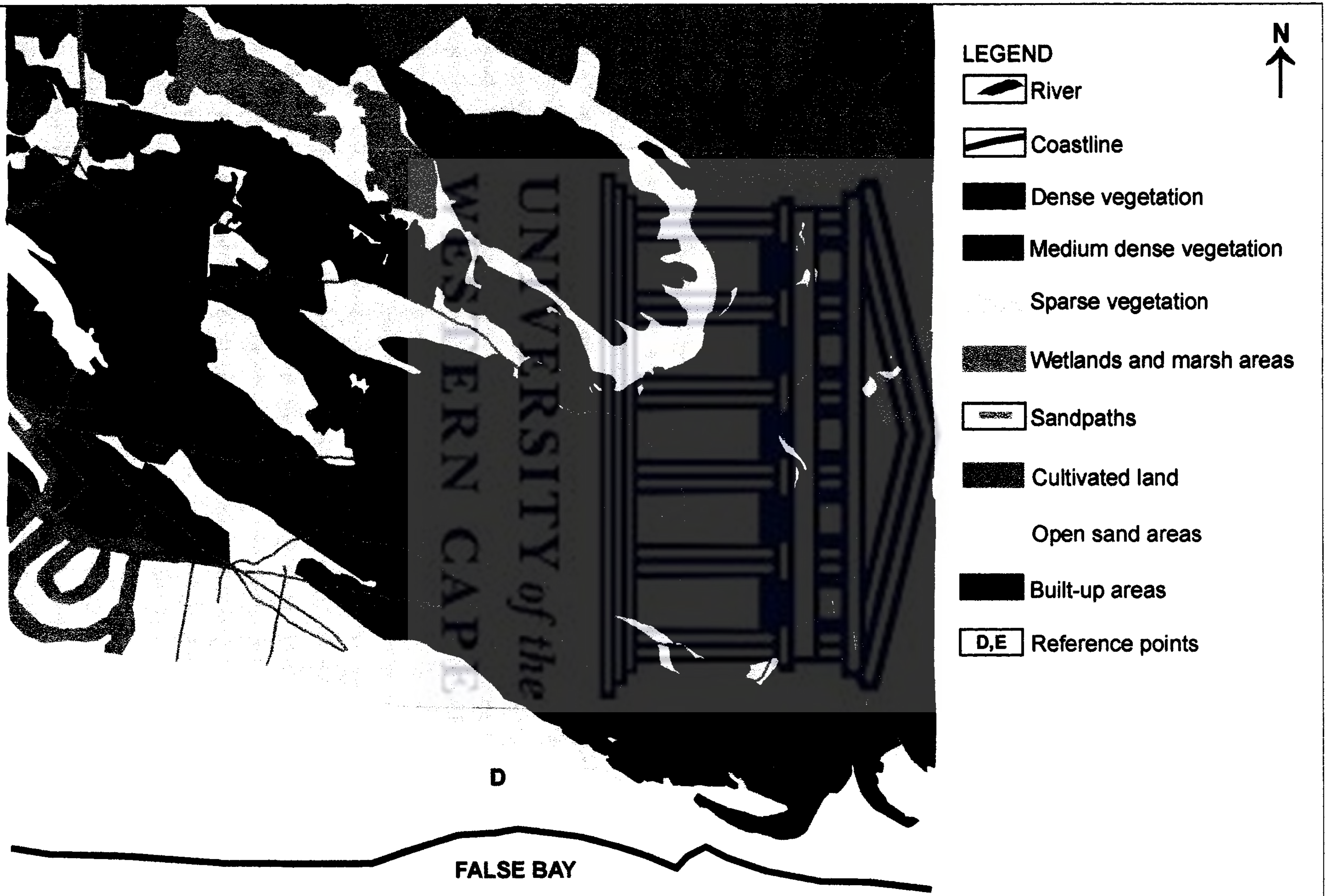

Figure 8. Estuarine and river environment during 1953

1966

During this year a sandbar also blocked the estuary as the photograph was taken during summer (Figure 9). The wetland shown on the 1953 photograph was still present and maintained a similar form while the wetlands had increased along the river course. O'Callaghan (1990) documented the same occurrence in his study on the Eerste River estuary. The eastern lagoon was weakly developed while the western lagoon was extensively developed with a small meander. From 1953 to 1966 the estuary migrated 174m to the west.

The vegetation in the estuarine section increased in density on both the western and eastern sides. Riparian vegetation along the river course depicted a similar picture to that which occurred in 1953 with medium density occurring in the upper reaches and very dense in the lower reaches. Although the surface water had increased the vegetation resulted in narrowing of the river channel. Cooper (1994) documented a similar change in the historical mapping of the Mvoti estuary along the KwaZulu Natal coast. The dune vegetation showed dense stands with more growth encroaching on the sparsely vegetated areas and thereby reducing the amount of open sand areas. The width of the beach area was also reduced.

Sand paths on the dune areas also showed an increase as a result of further developments. The completion of the Somchem factory resulted in further destruction of dune vegetation. The Moddergat Spruit (F) came into existence at this time for additional drainage and dense vegetation also occurred in this riparian zone.

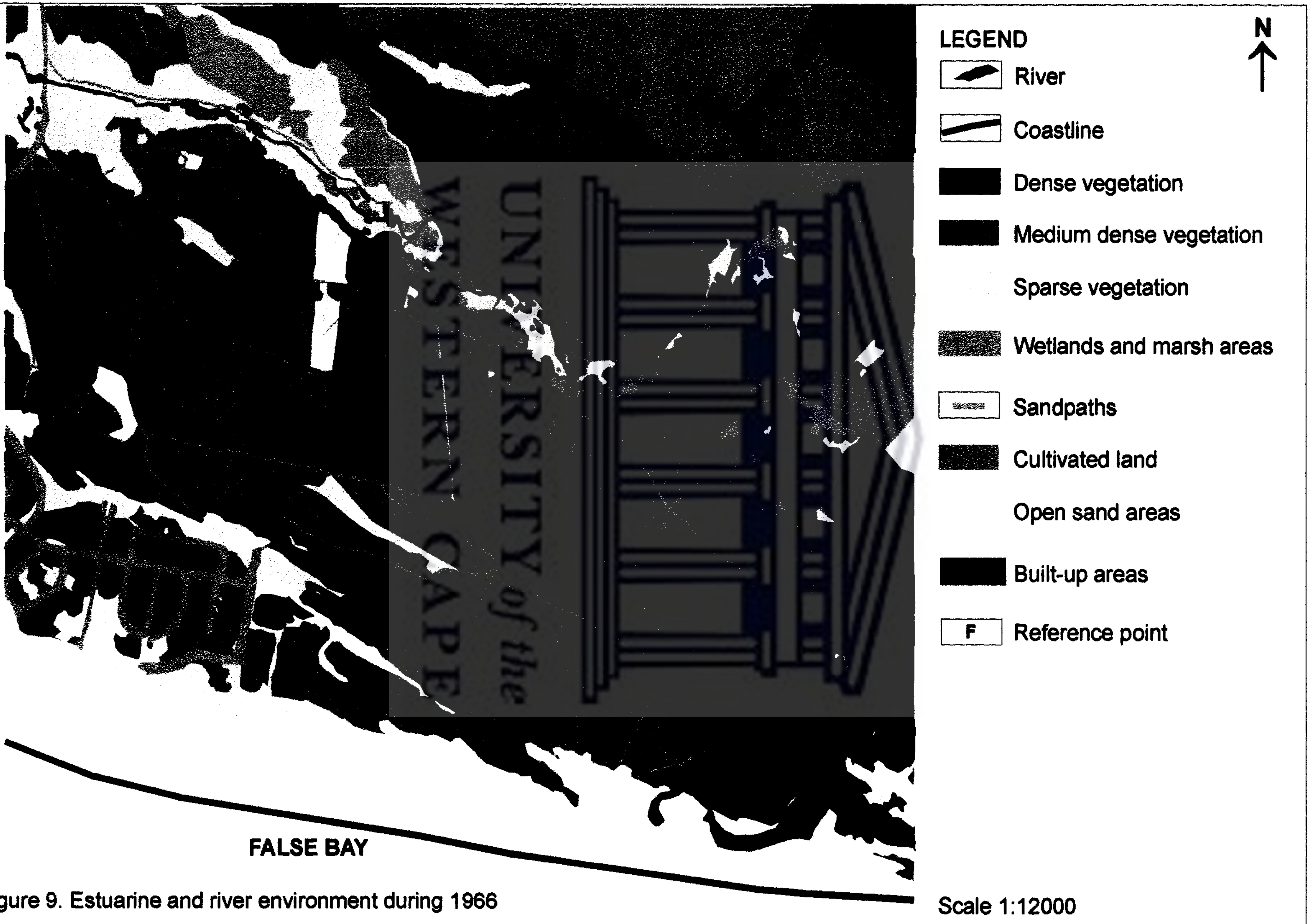

Figure 9. Estuarine and river environment during 1966

1977

A similar picture is depicted in this photograph as with the previous years as the estuary is again blocked from the sea (Figure 10). The eastern lagoon increased in area since 1966 but it became a stagnant body of water because it was cut-off by a causeway (G) constructed by Somchem during 1977. The western lagoon became a deep-water lagoon, which was 650m long and 100m wide (Heydorn and Grindley, 1982). The estuary migrated a further 56m since 1966.

The density of the dune vegetation was decreased and most of the dense vegetation was only found in the riparian zone of the river and along the Moddergat Spruit, which showed an increase in surface water area. The wetland areas had dried up since 1966 and were replaced by sparse and medium dense vegetation for most of the river length. The permanent wetland still remained and the vegetation separating it was now medium dense. The riparian vegetation in the lagoon section was also reduced to a medium density. Vegetation on the eastern side of the estuary was destroyed due to the construction of the causeway and on the western side by the construction of the Macassar WWTW (H). The beach area increased again because of the destruction of the fore dunes on the western side.

Certain sand paths became more defined and roads came into existence. This was due to the development of the Macassar residential area (I) and also the Macassar WWTW and the old water tank (J). All the developments in the area resulted in large areas of open sand and a decrease in previously cultivated areas.

Figure 10. Estuarine and river environment during 1977

1988

The river reaches the sea in this photograph (taken during winter), forms a slight meander and shows westerly migration of 136m since 1977 along the beach (Figure 11). Seasonality was reduced due to changes in the hydrological characteristics of the river. Although the western lagoon parallel to the coast increased in area the outlet to the sea showed only a narrow channel. The eastern lagoon still exists and now forms part of a wetland with dense vegetation occurring on either side. More wetland development occurred on the dunes (K) in the vicinity of the now fully operational Macassar WWTW. Increases in hard surfaces and the discharge of treated sewage effluent into the river caused increases in river flows (O'Callaghan, 1990). This increased flow resulted in a connection forming between the Kuils and Eerste Rivers (Wiseman and Simpson, 1989). The Kuils River added stormwater, surface runoff and treated sewage effluent from the Kuils River catchment, which had increased to a great extent. A new housing development (L) also occurred.

Although a large percentage of alien vegetation was destroyed with the construction of the Macassar WWTW it had re-established on the dunes reducing the open sand areas by replacing it with medium dense and dense vegetation. As a result the beach area had also decreased in width. The riparian zone along the entire river consisted of dense vegetation on both the right and left banks. Dense vegetation occurred along the right bank of the lagoon and medium dense vegetation occurred on the left bank. Riparian vegetation along the Moddergat Spruit was reduced to a medium density and the Macassar residential area replaced all the cultivated land in the vicinity. Sand paths on the dunes decreased and permanent roads and bridges came into existence leading to the developed areas.

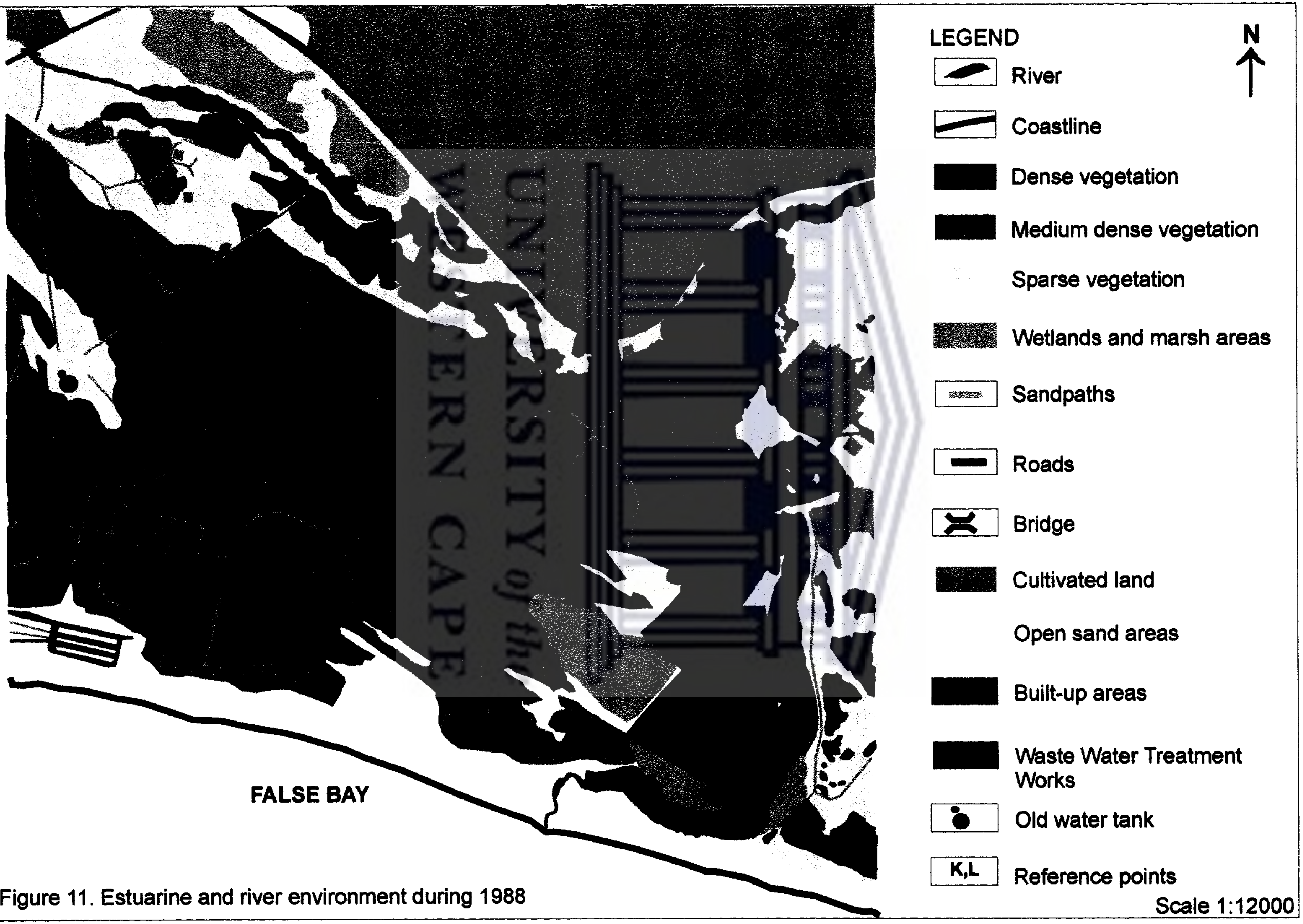

Figure 11. Estuarine and river environment during 1988

1996

This summer photograph shows that the estuary is open throughout the year (Figure 12). The lagoon shows further westward migration of 60m and definite meandering at the entrance to the sea. The eastern wetland (old eastern lagoon) had completely dried up and was replaced by a medium dense *Phragmites* reed bank. The presence of these reeds could be an indication that very little or no salt-water penetrated the estuary at this time (O' Callaghan, 1990). This suggests that the estuary has become river-dominated due to increased flows from urban areas and wastewater treatment works. The wetland in the vicinity of the Macassar WWTW had decreased in area while the permanent wetland showed an increase with no vegetation separation.

The dense vegetation in the riparian zone on both the left and right banks had increased resulting in a narrow river channel and a large percentage of the western and eastern dune was invaded by more dense alien vegetation. As a result the open sand areas are almost completely covered and the beach area has decreased in width. The riparian vegetation of the Moddergat Spruit was also replaced with more dense vegetation.

During this time the Macassar Resort (M) was completed and the Kramat area (L) was fully developed.

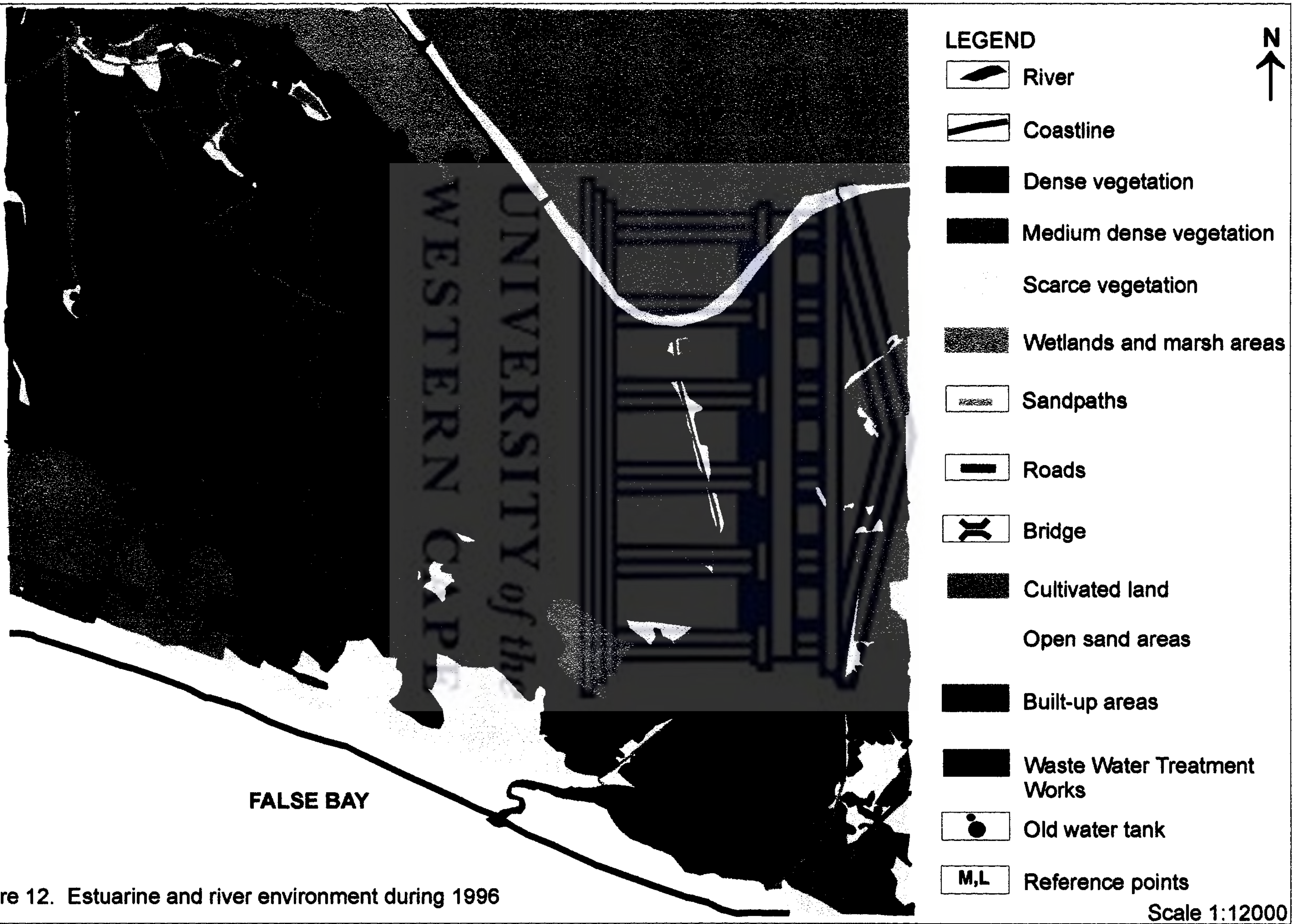

Figure 12. Estuarine and river environment during 1996

2000

The estuary continued to migrate in a westerly direction with the entrance to the sea now much closer to the Macassar Resort (Figure 13). Since 1996 the estuary migrated 304m. The lagoon showed an increase in water area and length. The increase in the water surface area could explain the development of a new wetland (N) in the dune area and also the decrease in the dense vegetation along both riverbanks. Dense riparian vegetation existed along the banks of the lagoon while the permanent wetland showed an increase but was separated by vegetated areas.

Although a large percentage of the dune area still consisted of dense vegetation, a section of the area was cleared resulting in open sand. The fore dunes consisted of dense vegetation and a small area was still sparsely vegetated. This could be related to the extensive dune destruction, which occurred with the westward mouth migration. As a result the previously sparsely vegetated dunes were destroyed causing the densely vegetated dunes to become new fore dunes. The vegetation on the eastern estuary side increased in density together with the section of reed bank. The beach area maintained a similar width to that of 1996 although the barrier beach section was the narrowest it had been throughout all the years.

New sand paths developed around the dune wetland in the vicinity of the Macassar WWTW and the same roads are in place as in 1996. Similar conditions exist as in 1988 and 1996 except that urbanisation has increased.

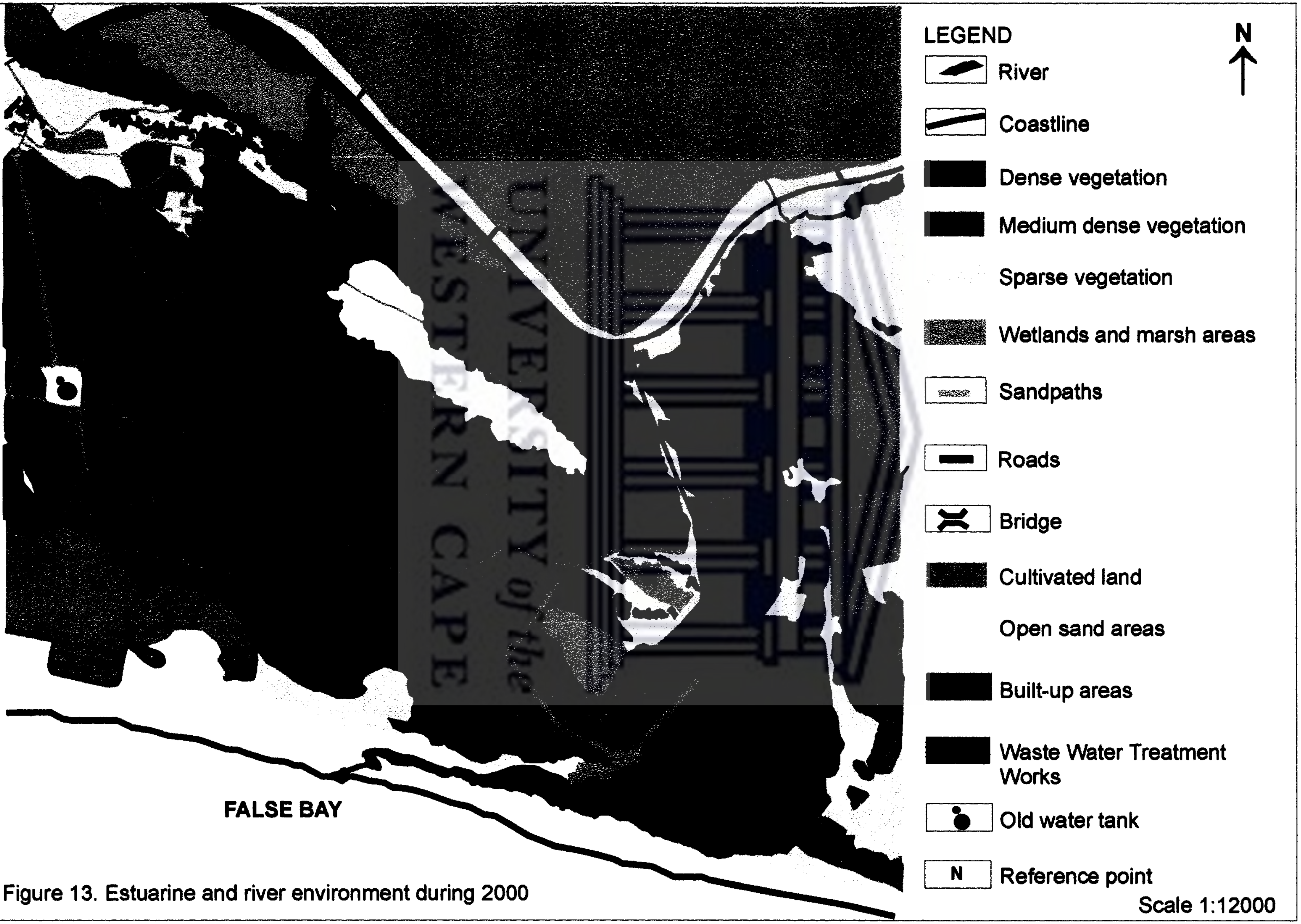

Figure 13. Estuarine and river environment during 2000

4.1.3. DISCUSSION

Estuary characteristics

Morphological changes

The Eerste River estuary is classified as microtidal. The inshore wave energy of the Eerste River mouth was calculated as 10% above the mean for the other river mouths around False Bay (Heydorn and Grindley, 1982). It is therefore located on a medium energy beach and is wave-dominated. Upstream the estuary is dominated by fresh-water while outside the mouth, wind-driven waves dominate (Pethick, 1984). Historically the Eerste River was classified as a closed bar-built estuary due to its high seasonality because it would be closed by a wind and wave-built sandbar during summer. Table 3 summarises the main morphological changes in the estuary.

As a result of being wave-dominated a relatively high berm would develop due to the coarse-grained barrier sediment (Cooper, 2001a). The sandbar would be breached with the first winter rains usually during May (Morant, 1991; Harrison, 1998). This morphology type is clearly seen during the years 1938 until 1977. During this time the estuary was perched above sea level and the tidal intrusion was minimal during the open mouth phases due to barrier overwash of sea-water into the lagoon on spring high tides with the total salinity depending on the amount of overwash that occurred (Cooper, 2001a). As a result the estuary often became hypersaline during summer due to low river flows and continuing evaporation (Heydorn and Grindley, 1982; Harrison, 1998).

Table 3. Summary of the main results found from the maps of 1938-2000

Period	**Years**	**Direction and distance migrated (m)**	**Rate migrated over period (myr^{-1})**	**Mouth morphology**	**Major developments (Human impact)**
1938				Closed, with extensive eastern lagoon	No developments, only cultivated areas and alien vegetation encroachment
1938-1953	15	West 359	23.93	Closed, with no eastern lagoon, extensive western lagoon	Somchem development, alien vegetation
1953-1966	13	West 174	13.38	Closed, with extensive western lagoon and weakly developed east lagoon	Further Somchem development, Moddergat Spruit, alien vegetation
1966-1977	11	West 56	5.09	Closed, with extensive western lagoon and stagnant eastern lagoon	Somchem, Macassar residential area, Macassar WWTW, causeway and road development, alien vegetation
1977-1988	11	West 136	12.36	Open, with reduced seasonal influence, extensive western lagoon and stagnant eastern lagoon becoming a marsh/wetland area	Somchem, Macassar residential area, Macassar WWTW completed. More road development. New Kramat area housing development. Influence from Kuils River catchment, alien vegetation
1988-1996	8	West 60	7.5	Open, with reduced seasonal influence, extensive western lagoon and no eastern lagoon	Same as during 1988 with a new Macassar Resort development
1996-2000	4	West 304	76	Open, with reduced seasonal influence, extensive western lagoon almost reaching the Resort and no eastern lagoon	Same as during 1996

From 1988 until 2000 a change in the morphology of the estuary is seen, which was a direct result of changes in the river catchment. The estuary changed from being seasonally closed, to one that remained permanently open. The volume of fluvial discharge determines the estuary type and due to the large volumes of fresh-water input by stormwater runoff and treated sewage effluent the system became a river-dominated bar-built estuary (Cooper, 2001a); Huizinga *et al.*, 2001). The reason for this was that the sandbar could no longer form because the river flow was sufficient to remove the sediment from the mouth faster than it was transported by littoral drift (Dyer, 2000).

Westerly inlet migration was shown throughout all the years. The rate and direction of channel migration is controlled by the magnitude of net longshore sediment supply, the volume of river discharge and the tidal range (Reinson, 1992; Dyer, 1994). Migration of inlets commonly occurs on wave-dominated coasts due to the important role wave action has in transporting and depositing sediment. In a similar way tides can also become important in that they too deposit sediment necessary for migration (Reddering, 1983).

Inlets can only migrate if the accreting barrier increases in size above and below the high tide level. Sand would have to be transported from below the water level to be deposited above it. This can only be accomplished by wave action. Barrier growth by wind is limited because wind can only transport dry sand and intertidal sand does not often dry before the following high tide. Wave action is therefore necessary for barrier accretion, which essentially controls inlet migration. (Reddering, 1983). An inlet usually migrates in the direction of longshore drift and in the Eerste River estuary the current is predominantly westward (Heydorn and Grindley, 1982; Reddering, 1983).

Westward migration occurred due to the deposition of sediment on the eastern end of the barrier by waves and tides and by erosion on the western end. This process is further aided when floods occur (Reddering, 1983). Migration could occur very easily as there is no natural barrier and the right bank consisted of uncohesive sediment. The vegetation present on the bank does not assist in stabilization and as a result undercutting occurred and eventual collapse (Reddering and Esterhuysen, 1987; Cooper, *et al*., 1990; Cooper, 1994). Under these increased fresh-water flow conditions the estuary could be classified as a river mouth with no mixing of sea-water and fresh-water to create an estuarine environment (Whitfield, 1994).

SHORT-TERM CHANGES

4.2. CROSS-SECTIONAL PROFILES

4.2.1. METHODOLOGY

The initial fieldwork was completed during the months of April and May 2001 and the re-survey was completed during November 2001. Cross-section locations within the estuary are shown in Figure 14. A total of nine cross-sections were completed and located at 50m intervals. Metal rods were placed on both the left and right grass banks to serve as reference points. Nylon cord was strung between the rods to serve as a vertical reference. To obtain the channel form the depth of the channel was measured at 1m intervals across the profile from the left to the right bank. GPS surveys of the estuary were undertaken during May and November 2001 to produce up to date maps, which are shown in Figure 17. The cross-sections also served as sites for the examination of sediment accumulation or removal. A photographic record was also kept.

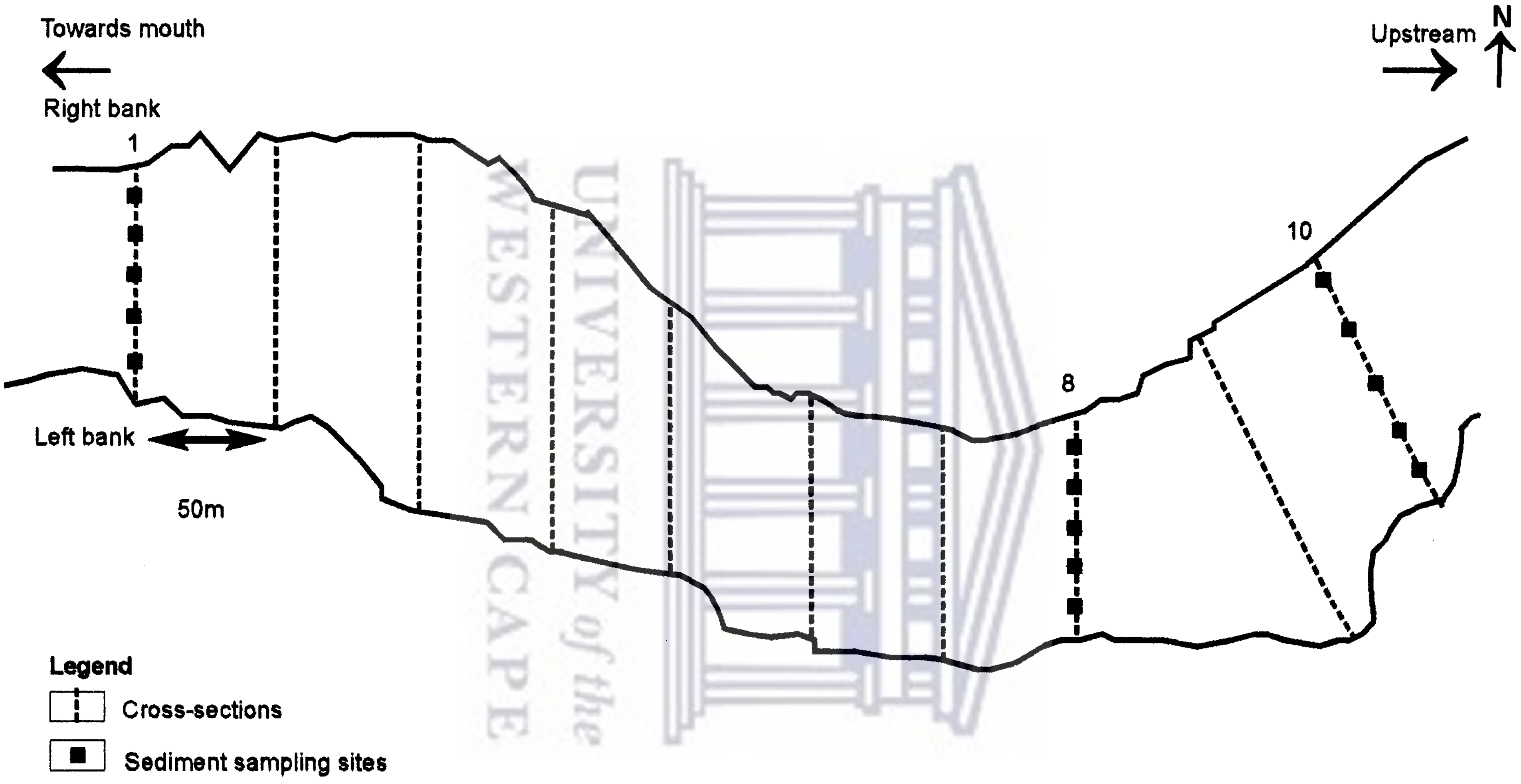

Figure 14. Map showing the locations of the cross-sections and sediment samples

Approximate scale: 1:3000

4.2.2. PRE-FLOOD OBSERVATIONS

During this time (May 2001) the river mouth showed rapid westward migration. As a result extensive dune destruction occurred on the right bank (Figures 15 and 16). The highest dunes were approximately 10m high. High flows of water eroded the base of the dunes, which resulted in slumping where the vegetation also formed part of the slumped material. The most dune erosion occurred during August and September 2001. The mouth locations during the pre-and post-flood surveys are shown in Figure 17.

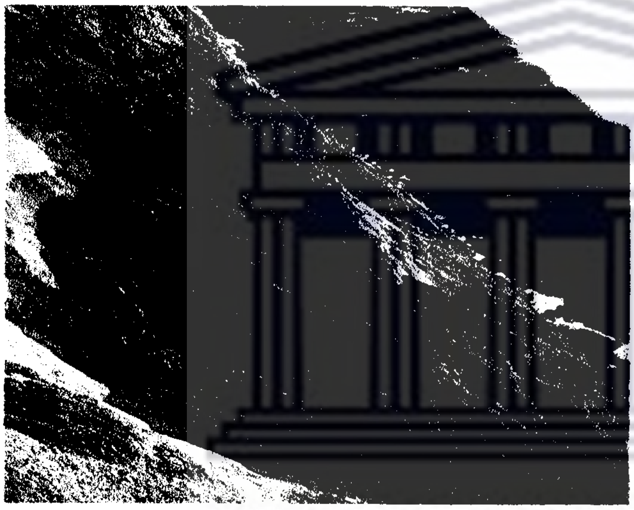

Figure 15. Vegetation forming part of the slumped material

Figure 16. Photograph showing the extent of dune destruction

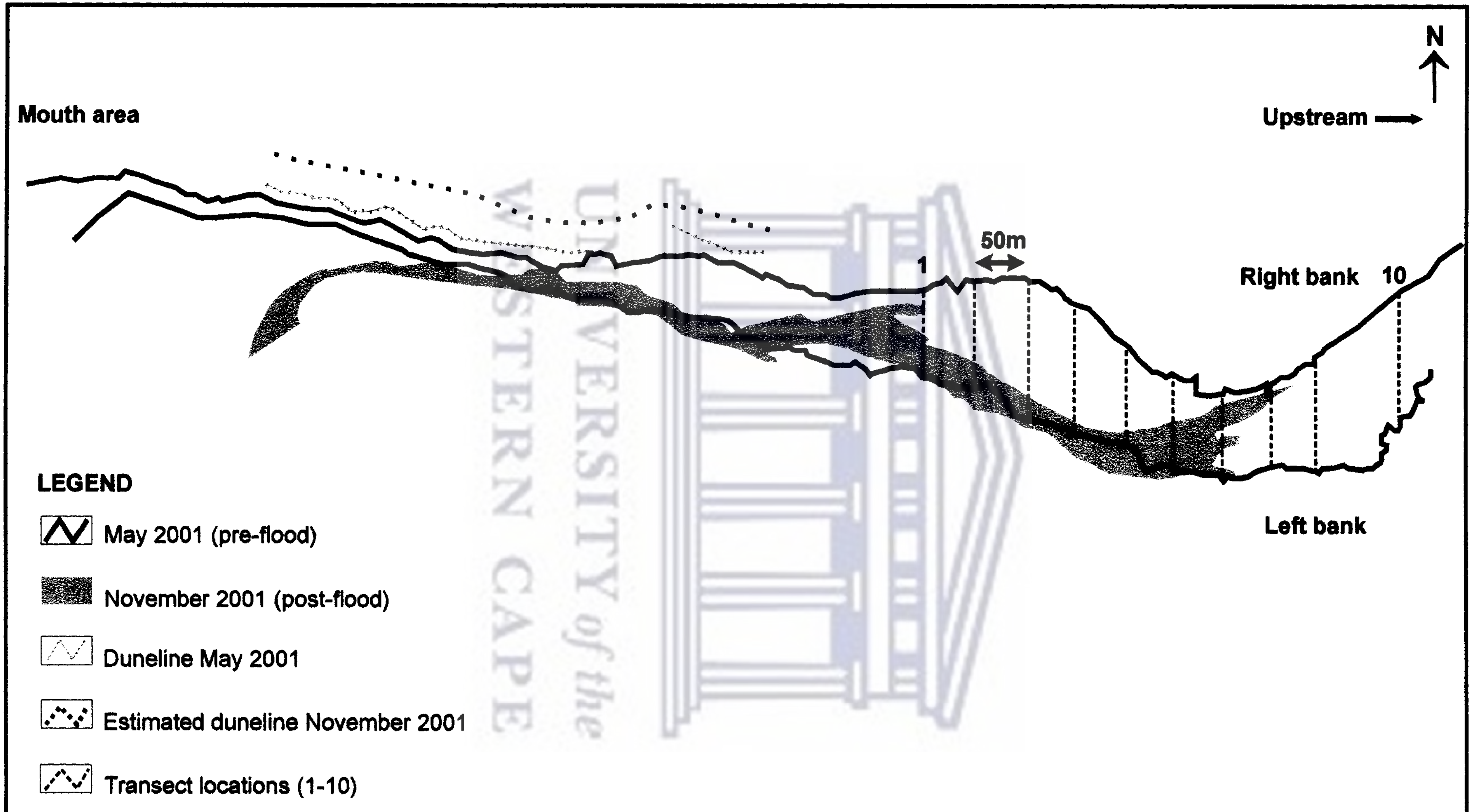

Figure 17 . GPS survey maps during May and November 2001

Scale: 1:6917

Although some overwash of sea-water on the sandspit occurred during rough seas and high tides (Figures 18 and 19) tidal influence on the estuary was minimal. No sandbanks were exposed at any time and the water level showed minimal daily fluctuation.

Figure 18. Channel formed as a result of barrier overwash

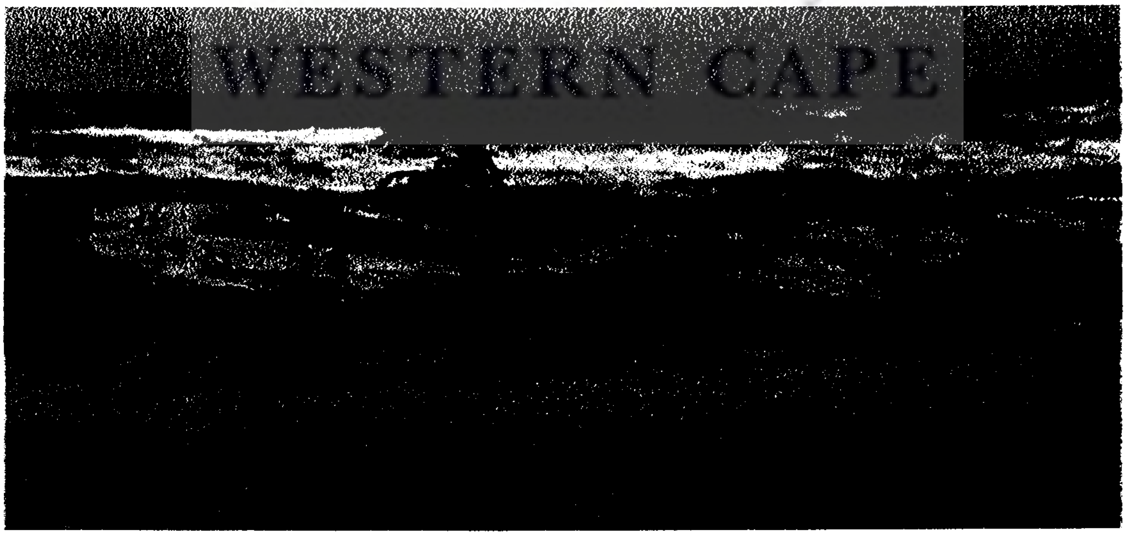

Figure 19. Overwash occurring during high tide

The right bank was densely vegetated at all the transects and the left bank was sparsely vegetated at cross-sections along transects 4, 5, 6 and 7. No vegetation was found on the left bank at transect 8 and at transect 9 floating aquatic vegetation occurred. An extensive reed bank on the left bank side occurred together with "parrots feather" just after transect 9. A thick layer of unconsolidated mud and organic debris covered the riverbed at transects 7, 8 and 9.

The first heavy rainfall occurred during July and the flood peak occurred on the 5th July 2001. The river mouth had increased its width by several meters due to the increased water flow and strong seas. As a result the barrier separating the river from the sea also decreased in width and length (Figures 20 and 21). The right bank located upstream of the estuary had been completely flooded where only the vegetation tops could be seen (Figures 22 and 23).

Figure 20. Mouth area and extensive barrier (arrowed) before the flood

Figure 21. Mouth area and decreased barrier (arrowed) after the flood peak

Figure 22. Right bank upstream of the estuary before the flood

Figure 23. Right bank upstream of the estuary during the flood but after the flood peak (same area)

4.2.3. POST-FLOOD OBSERVATIONS

November 2001

Extensive sandbanks exist at both the left and right bank sides at all the transects and are exposed during low tide (Figure 24). The post-flood GPS survey also showed this (Figure 17). Figure 25 shows the sandbanks completely covered during high tide. Small amounts of mud are found in areas near the banks with thick deposits occurring in the centre of the channel. Mud depths ranged from 1.15m at the cross-section along transect 1 to over 2.3m along transect 8. The depths were measured using a metal rod of a known length. The vegetation density increased on the left bank especially in the vicinity of transects 7 and 8 and the aquatic vegetation was removed.

January 2002

Water level measurements were recorded on a spring high and low tide and on a neap high and low tide using a measuring staff. The water level readings at transect 1 during the spring tide showed a tidal range of 0.95m. The water level measurements at neap tide showed a 0.50m range. Barrier overwash also occurred. No salinity measurements were recorded to determine how far upstream the tidal influence penetrated but a clear difference in watercolour was observed between the downstream and upstream sections of the estuary. At low tide the river water had a predominantly brown colour (Figure 26) but with tidal influence the watercolour was blue (Figure 27).

The estuary had migrated back to a more or less stable easterly position after the winter floods. A reason for this could possibly be related to the influence of the sea by strong wave action. Previously the river was relatively narrow and was separated by a relatively wide sandspit/barrier. This barrier had now decreased in width, which means that a narrow barrier now separates a much broader river, due to floods, from the sea (Figure 21). The strong sea influence together with a broad river caused a narrow and lower area of the barrier to be breached resulting in the present easterly outlet. An abandoned westerly arm is still present along the beach.

Figure 24. Sandbanks exposed subaerially during low tide (30 January 2002)

Figure 25. Photograph showing the same area with sandbanks completely covered during high tide (30 January 2002)

Figure 26. Watercolour during low tide

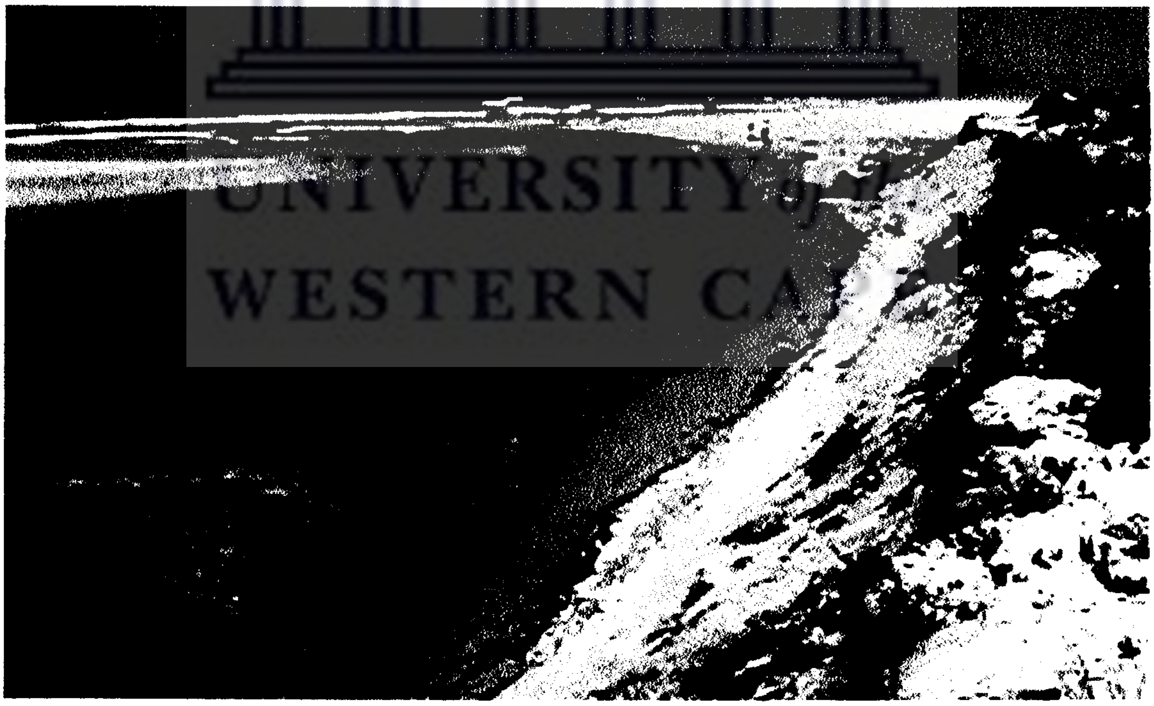

Figure 27. Watercolour with tidal influence

The present channel outlet or mouth area also has a much lower bed elevation than previously. The outlet section consists mainly of loose sand, which means that this section could easily be scoured due to the difference in water elevation level between the estuary and the sea. Floods can also temporarily increase the tidal prism due to erosion of these intertidal sediments (Cooper, 2001a); Cooper, in press b). The increase in the mouth area with a change in tide from low to high is shown in Figures 28 and 29.

It was found that certain estuaries change their morphology from tide-domination to wave-domination. This occurs due to progressive infilling of sediments in the estuary, which eventually decreases the tidal prism (Pendòn *et al.*, 1998). This could explain the increase in the tidal influence in the Eerste River estuary as large amounts of sediment was scoured from the estuary allowing an increase in the tidal prism. As a result sea-water can now penetrate the estuary and cause sufficient mixing to classify it as a true estuarine environment (Whitfield, 1992) with a typical circulation pattern of an open bar-built estuary (Largier and Taljaard, 1991).

Figure 28. Mouth area during low tide

Figure 29. Mouth area during high tide

Observations on a spring tidal cycle showed that possible stratification occurred within the estuary. Clear mixing of fresh and saline water could be seen by the presence of the tidal intrusion front or plunge line shown in Figure 30.

Figure 30. Plunge line (arrowed) present in the vicinity of transect 1

The plunge line was moved upstream as full spring tide was reached and it dissipated downstream as the tide dropped. The tidal influence was sufficient to prevent the outflow of the river water, which caused a damming effect. This resulted in stratified conditions on the landward side and unstratified conditions on the seaward side of the estuary (Largier and Taljaard, 1991; Schumann and Pearce, 1997). Persistent winds occur at the estuary and this also assists in the movement of salt upstream. Wind has very little effect when channels are narrow but in the Eerste estuary the channel in the lagoonal section is wide enough for the wind to have an effect on the mixing process (Slinger and Taljaard, 1994; Schumann and Pearce, 1997). Marked temperature differences also occurred with the surface water having a higher temperature than the bottom water.

Historically, stratification also occurred in the estuary. At measuring stations in the lower and middle reaches salinity layering occurred with fresh-water overlaying cooler marine water. During the winter months the salinity measurements were zero throughout with the river flowing strongly to sea (Harrison, 1998). A similar observation was made on the neap tide during January 2002 where the tidal influence was restricted to the lower mouth area of the estuary.

Although tides have a significant effect on the estuary it would have to be the main factor maintaining the inlet to classify it as being tide-dominated (Cooper, 2001a). This study suggests that an estuary located on a microtidal coast can exhibit a tide-dominated morphology if the tidal prism is increased. This occurrence is possible because the size of the tidal prism is related to the volume of discharge i.e. when low flows prevail the tidal prism is increased (Reinson; 1992). The outflowing river, despite the tidal influence, presently still maintains the inlet of the Eerste River estuary. It will only be possible to conclude whether the estuary is dominated by tides when normal summer flow conditions return.

4.2.4. CROSS-SECTION RESULTS

The water levels had dropped considerably during the post-flood survey when compared to levels during the pre-flood survey. Cross-sections that were located in the straight channel, closest to the mouth, retained their channel shape after the flood. The main changes that occurred were smoothing of the channels, mostly due to deposition although erosion also occurred.

Pre-flood results

The channel profiles at transect 1 showed a sandbank on the left bank side at 5-36m and the deepest section occurred at 38-71m. No sandbank was found on the right bank side.

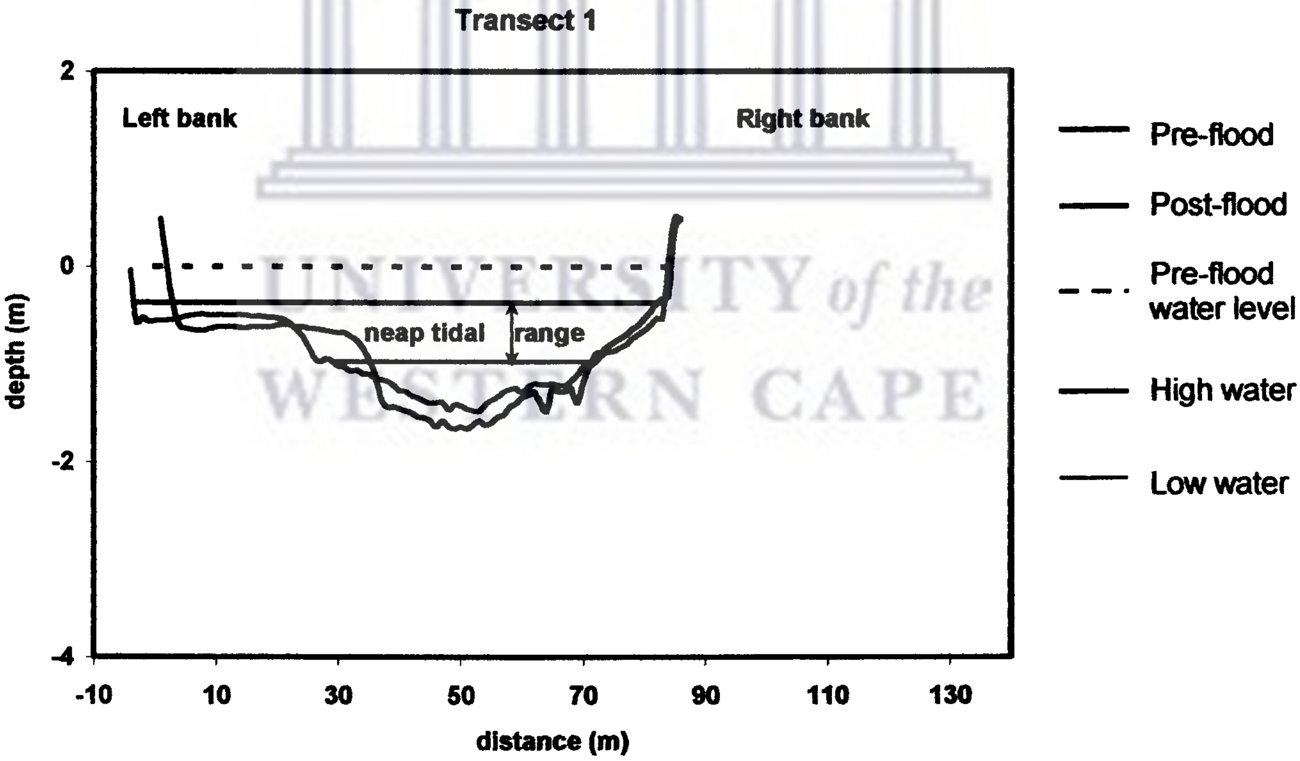

Figure 31. Pre-and post-flood cross profiles for transect 1

In transect 2 the sandbank occurred at 1-31m on the left side. A steep decent occurred to form the deep section at 36-52m. The sandbank on the right bank side occurred between 79m and 102m with a step to a smaller sandbank between 105m and 111m. A smaller sandbank was found at 6-20m in transect 3. The deepest section occurred between 20m and 49m on the left side of the channel. An extensive sandbank developed on the right side at 57-120m.

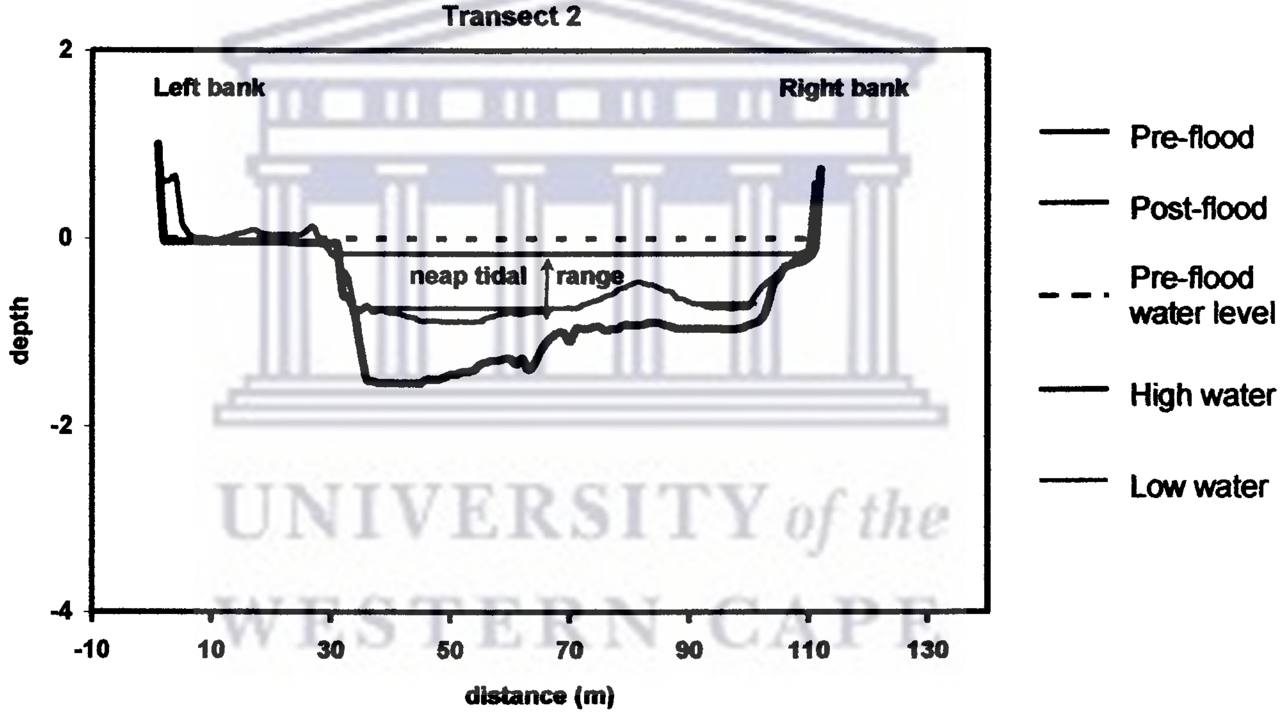

Figure 32. Pre-and post-flood cross profiles for transect 2

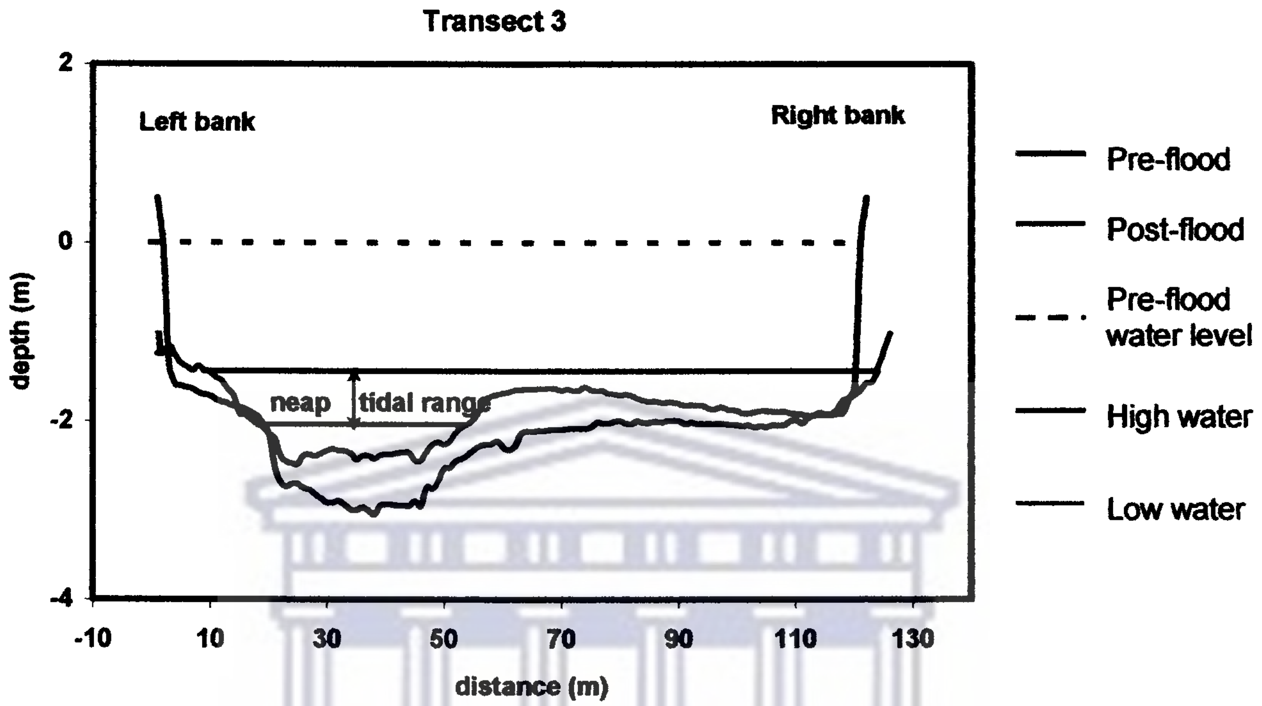

Figure 33. Pre-and post-flood cross profiles for transect 3

In transect 4 a similar sandbank on the left side as in transect 3 was found between 5m and 19m. An extensive right bank sandbank occurred at 52-104m with the deep section at 20m-34m. Transect 5 showed a sandbank at 6-15m and the deep channel section occurred at 20-36m on the left bank side. A right sandbank was found between 45m and 84m.

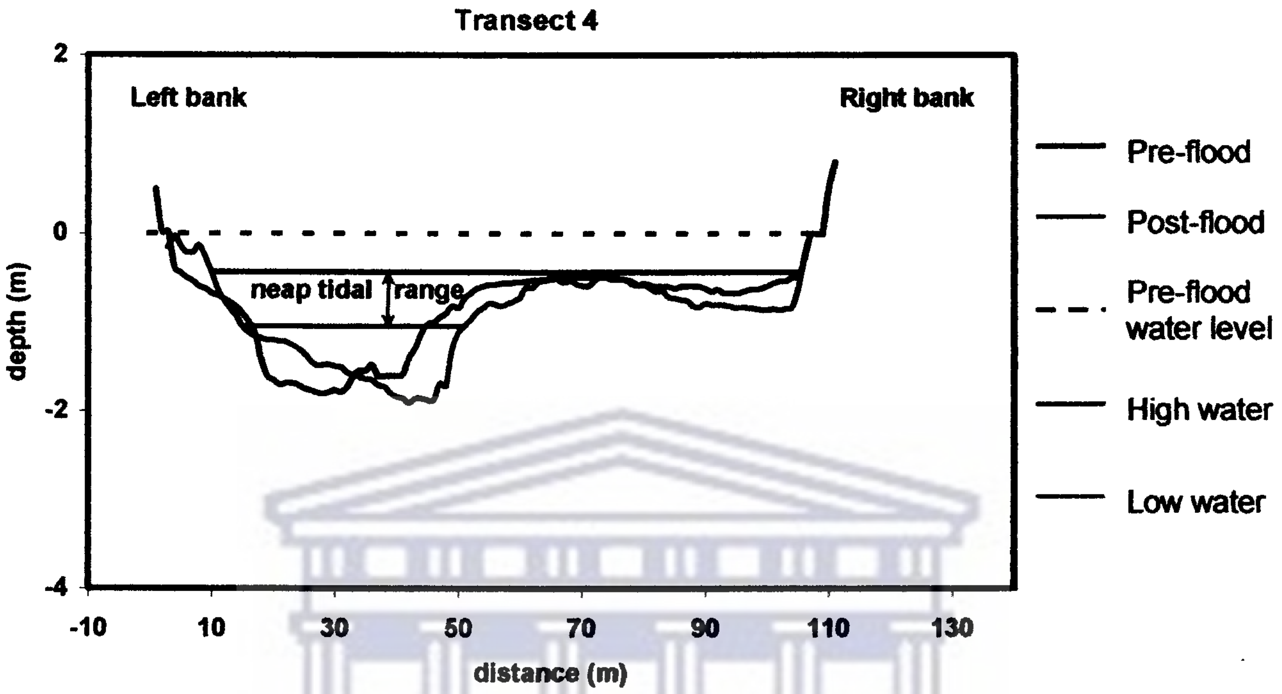

Figure 34. Pre-and post-flood cross profiles for transect 4

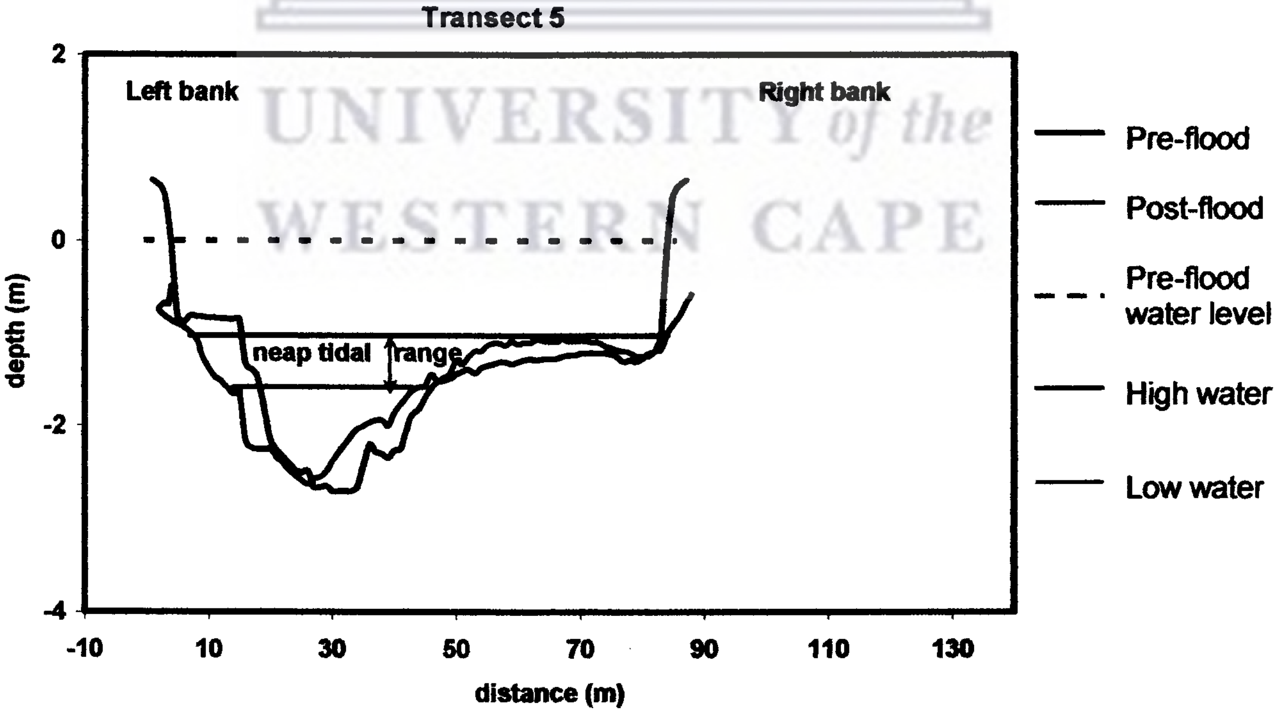

Figure 35. Pre-and post-flood cross profiles for transect 5

A more or less even channel depth occurred throughout the channel profile at transect 6 and no sandbanks were found. Transect 7 showed a steep channel decent from the bank on the left side of the profile with a sandbank occurring at 2-32m. The deep section was found on the right bank side at 84-91m resulting in no sandbank formation. In transect 8 a small sandbank was found at 6-9m with the deepest section occurring on the left side at 19-33m. A sandbank also occurred on the right side at 50-80m.

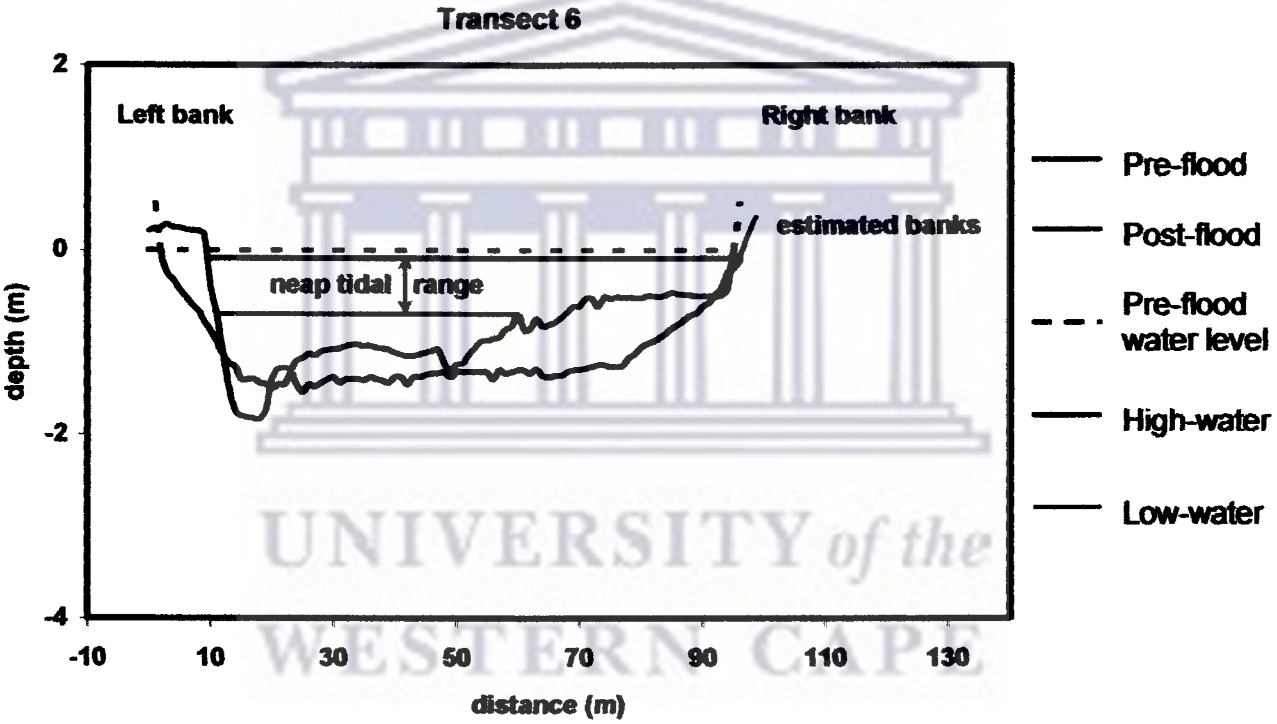

Figure 36. Pre-and post-flood cross profiles for transect 6

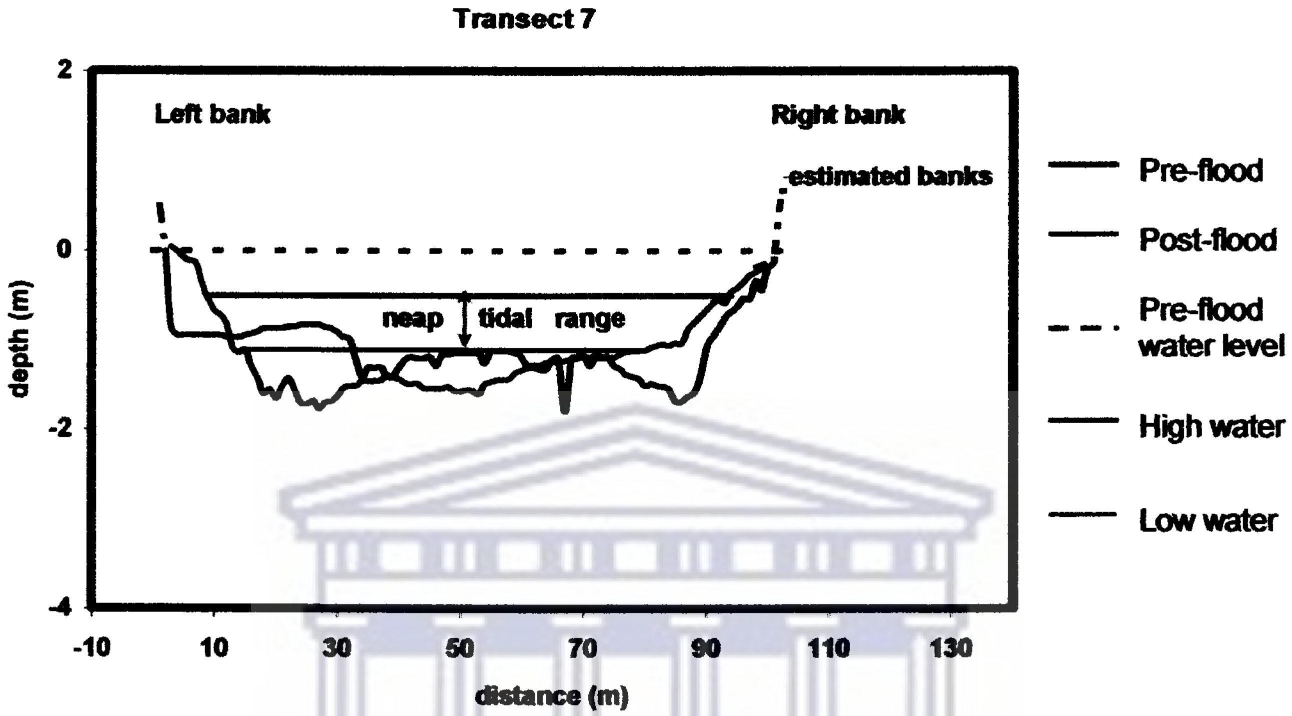

Figure 37. Pre-and post-flood cross profiles for transect 7

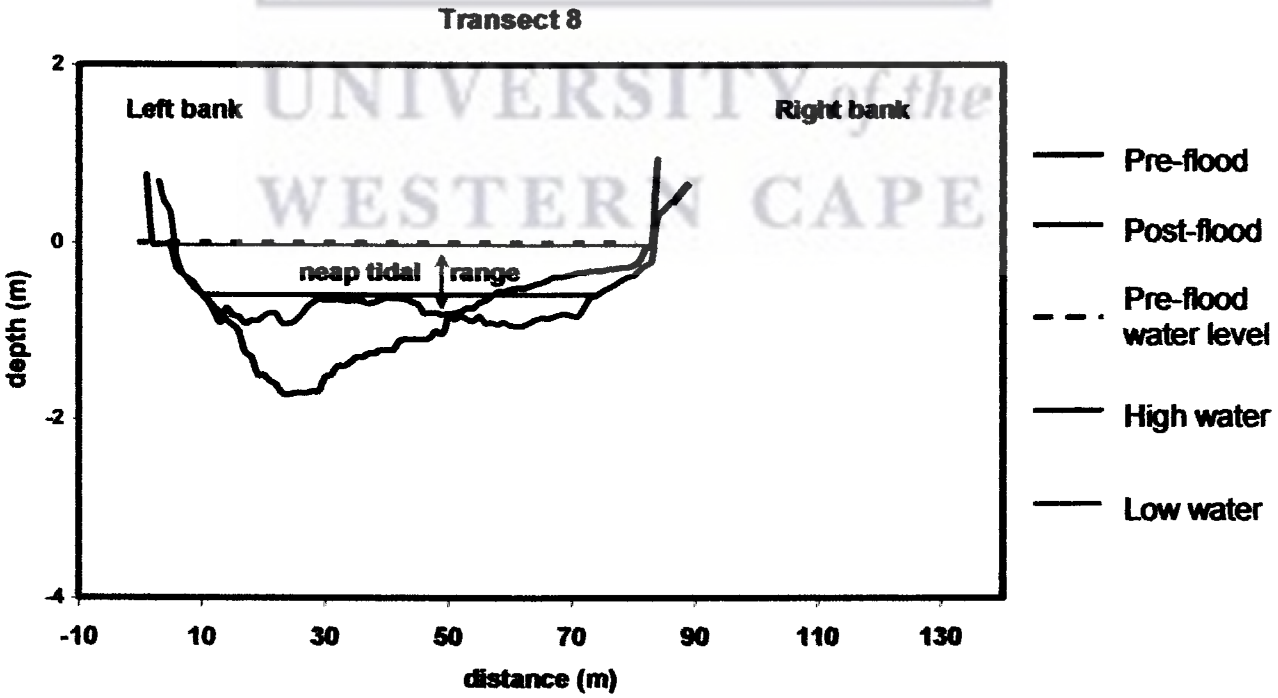

Figure 38. Pre-and post-flood cross profiles for transect 8

Transect 9 showed an extensive sandbank on the left side between 0-48m. The deep channel section occurred between 75m and 88m on the right side with a smaller sandbank found at 94-100m.

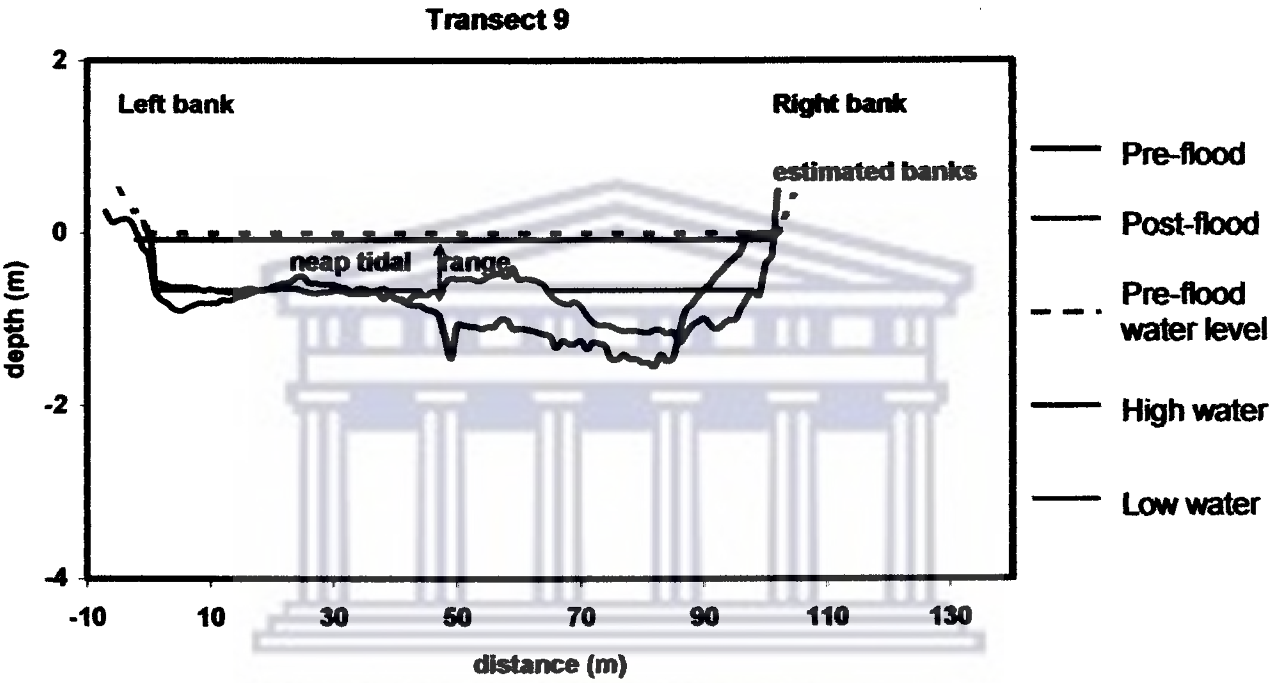

Figure 39. Pre-and post-flood cross profiles for transect 9

Post-flood results

Changes in cross-sections are summarised in Table 4. In transect 1 the first 5m of the left bank were eroded. A sandbank was found at 0-21m. The next 5-21m showed that deposition occurred on the existing sandbank, which was now exposed. The last 15m (21-36m) of the sandbank were eroded and deposition occurred throughout the centre channel at 36-71m, which also formed the main flow channel. Minimal erosion occurred on the right bank side between 74m and 85m.

Transect 2 showed deposition for the first 3m occurring at the left bank. The first sandbank (5-30m) remained stable with minimal deposition and erosion is shown at 30-32m. A second sandbank occurs at 79-87m and a third at 100-110m. The drop-off from the left sandbank showed a smoother decent and a large amount of deposition occurred from 35-104m throughout the channel with no change at the right bank. Transect 3 showed very little change to the channel shape. Minimal erosion occurred at the left (15-20m) and right bank (114-120m) and the profile showed deposition throughout the entire channel from 20-112m with most occurring between 20m-80m. The sandbank was found at 53-112m after which the grass bank occurred.

In transect 4 some deposition is shown on the left bank side at 5-12m and in the low tide channel at 20-34m. Deposition has now occurred, shifting the deepest channel section to between 42m and 50m with erosion occurring between 34m and 65m. The sandbank was found at 53-104m while the last 25m found at 81-104m were eroded with the right bank still intact.

In transect 5 erosion occurred between 8-20m on the left bank side of the channel and therefore removed the small sandbank that was found between 6m-15m of the profile. A more extensive sandbank occurred at 43-83m. Deposition occurred between 25m and 79m. This included a section of the low tide channel, which resulted in further shallowing and also on the right side of the estuary.

Erosion occurred at 83-93m eroding part of the right bank. The deepest channel section occurred between 20-32m. Transect 6 showed a steep drop-off from the left bank with deposition at 2-11m. Erosion only occurred between 12m and 18m and this section also presently forms the deepest part of the channel. Deposition was again found between 22m and 90m with most occurring at 50-90m of the profile. The sandbank was formed at 60-90m.

Deposition occurred on both the left (2-11m) and right (73-100m) bank sides in transect 7. The profile showed that erosion had occurred between 12m and 62m. This included the last 20m of the previous sandbank on the left bank side found between 12m and 32m, which also formed the deep section of the channel. A smaller sandbank occurred at 73-92m. Transect 8 shows deposition in the first section of the profile, from 6-9m and 12-50m. From 50-80m some deepening occurred due to erosion and a smaller sandbank was exposed between 75-85m.

In transect 9 three channels occurred which was separated by two sandbanks occurring between 17-38m and 48-65m. The first channel occurred between 1m and 12m, also where erosion occurred, the second between 38m and 40m and the third between approximately 62m and 98m of the profile. The right bank side showed erosion occurring between 88 and 98m and deposition occurred in the centre of the profile at 41-87m with most occurring between 50m and 70m.

Table 4. Summary table comparing the pre-and post-flood situations showing the sandbanks, erosion, deposition and deep channel sections from the left to right bank

Transect	**Pre-flood description**		**Post-flood description**			
	Sandbanks (m)	**Deep section (m)**	**Sandbanks (m)**	**Erosion (m)**	**Deposition (m)**	**Deep section (m)**
1	5-36	38-71	0-21	0-5 21-36 74-85	5-21 36-71	Shallow channel
2	1-31 79-102 105-111	36-52	5-30 79-87 100-110	30-32	0-3 35-104	Shallow channel
3	6-20 57-120	50-49	53-112	15-20 114-120	20-112	Shallow channel
4	5-19 52-104	20-34	53-104	34-65 81-104	5-12 20-34	42-50
5	6-15 45-84	20-36	43-83	8-20 83-93	25-45	20-32
6	No sandbanks	Even channel depth	60-90	12-18	2-11 22-90	12-18
7	2-32	84-91	73-92	12-62	2-11 73-100	12-32
8	6-9 50-80	19-33	75-85	50-80	6-9 12-50	50-80
9	0-48	75-88	17-38 48-65	1-12 88-98	41-87	62-98

4.2.5. CROSS-SECTIONS DISCUSSION

The morphology and sediment characteristics of a river will play a significant role in determining the amount of erosion or deposition that occurs during high or low river flows (Lane *et al.*, 1996). The tidal influence had increased to a great extent and instead of the entire lagoon area being covered by water with a minimal depth variation, shallow sections developed into intertidal areas, which became dry during low tide and showed a great variation in water depth between tides. The survey conducted during May 2001 showed a more or less constant water level because the estuary had a higher bed elevation and a balance existed between the fresh-water inflow and losses via seepage, outflow and evaporation. During the November 2001 survey the bed levels were lowered, which resulted in a draining effect where formerly submerged areas were exposed subaerially between tides (Figures 24 and 25). Cooper (2001a) documented the same occurrences in perched closed estuaries in South Africa, such as the Mhlanga, Mdloti and uMgababa estuaries located in KwaZulu Natal.

A channel change in transects 6, 7, 8 and 9 could be associated with the bend in the channel where the left side was the outer bend and the right side the inner bend. A study conducted by Cooper (1994) on the Mvoti estuary showed similar enlargement of channels occurred after a flood event caused by erosion of an outside bank. As transect 8 and 9 are located on the bend the most erosion was also expected to occur on the left bank side. Although some erosion is seen at transect 9, most occurred on the right bank side in transect 8 and 9 where undercutting of the grass banks resulted. Increased deposition in the centre channels are shown in both transects 8 and 9.

In transect 7 most of the erosion occurred on the left bank side with deposition occurring on the right bank side. This was expected, as the cross-section was located on the bend where the outer bend occurred on the left side of the channel. The same trend is displayed in the November survey for transect 6 and transect 5, where sediment is deposited on the right side (inner bend). This trend is also evidenced by overbank flow where sediment was deposited on the right bank at transects 5, 6 and 7. A thin veneer of fine sediment covered the vegetation on the right bank, which showed that the erosivity of the overbank flow was low away from the main channel flow (Cooper, 1994). The erosion that occurred at the left bank, in the form of undercutting, at transects 5 and 6 resulted in a steeper decent from the banks into the channels, especially at transect 6. In transect 4 most of the erosion occurred on the right side of the low tide channel and deposition on the left side.

Transect 1, 2 and 3 were located on the straight section of the lagoon. In transect 3 the channel shape underwent very little change and deposition occurred throughout the profile. This trend is also displayed in transects 1 and 2. However, transect 2 also show two distinct channels separated by a sandbank. In transect 1 the low tide channel occurs within the same deep channel section, which occurred during the May survey and some bank erosion occurred on the left bank. Overall, transects 1, 2 and 3 show the least changes to their channels due to more even energy flows associated with straight channels.

Although erosion was a result of the winter flooding more deposition occurred. The sediment present within the estuary contained very low percentages of silt and clay and the muddy sediments consisted mostly of very fine sand. The type of sediment which occurred were therefore easily transported and their distributions indicated both the stages of scour and low velocity settling associated with a flood (Cooper, 1993). Floodwaters also have a greater discharge and sediment transport is therefore easily accomplished. Figures 40, 41, 42 and 43 show part of the effects of the flood in the lagoon section.

Figure 40. Photograph showing a gravel road area before the flood

Figure 41. Photograph showing the same area after the flood (6 July 2001)

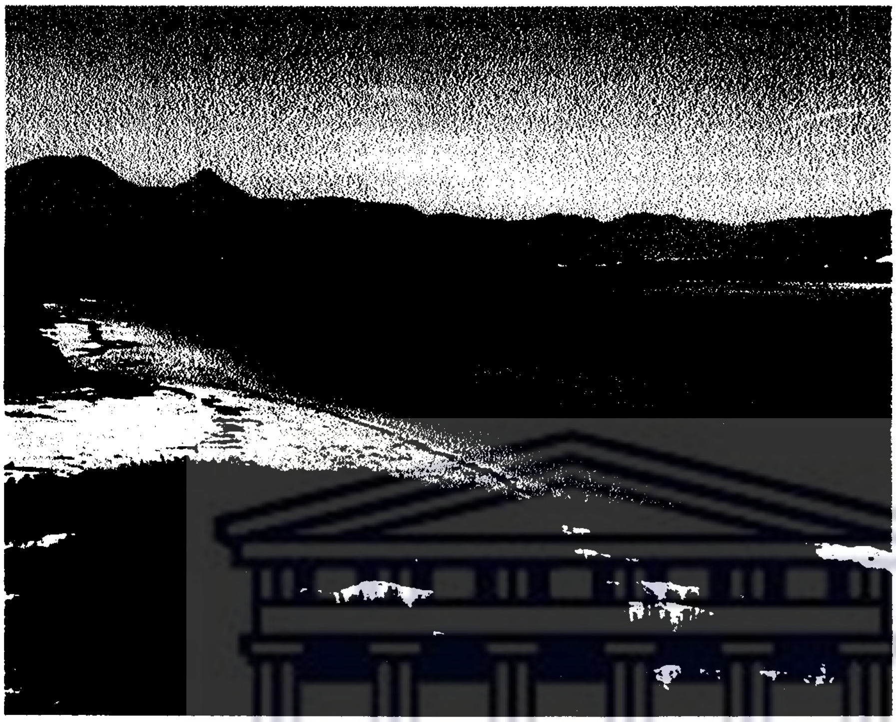

Figure 42. Photograph showing the area upstream from transect 1 before the flood

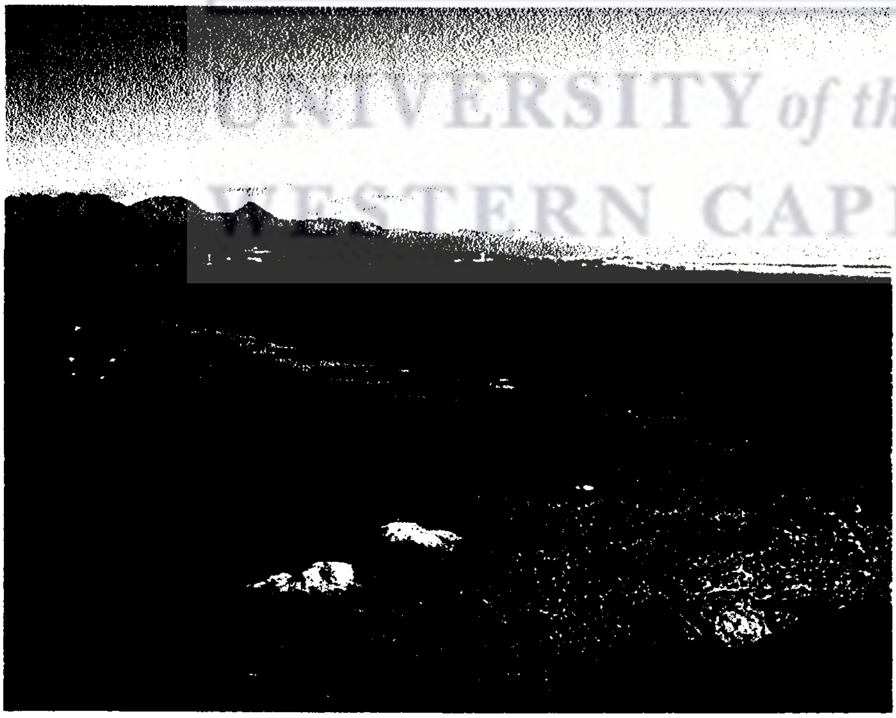

Figure 43. Photograph showing the same area after the flood (6 July 2001)

Due to these reasons there is no doubt that a large amount of sediment was scoured from the channel during the flood, which resulted in lowering of the estuary bed. This was evidenced by the large amount of tidal penetration that occurred at high tides after the flood. The bank erosion, which occurred at transects 1, 5, and 6 on the left bank and at transects 8 and 9 on the right bank, was possible due to the floodplain characteristics (Cooper, 1994). The left banks at transects 5 and 6 consisted of uncohesive marine sand, which was sparsely vegetated and therefore erosion could easily occur (Reddering and Esterhuysen, 1987).

However, the transects do show that deposition occurred even though the floodwaters had an increased discharge. This meant that fluvial sediment supplied from upstream had been deposited after the flood (Cooper *et al*., 1990). Flood events will only show significant scouring when no sediment is supplied from upstream. This does not often occur because the increase discharge will have an increased flow competence and erosivity. Flows can also result in changes to upstream channels such as re-alignment or expansion and in this way make more sediment available for downstream transport, which will eventually be deposited (Lane *et al*., 1996).

4.3. SEDIMENT CHARACTERISTICS

4.3.1. METHODOLOGY

Surface sediment samples were collected from transects 1 and 8 and from an additional transect (transect 10) further upstream where the lagoon section of the estuary began during May and November 2001. Five samples were taken at approximately 20m intervals across each profile from the left to right banks. The sediment was analysed for organic matter content and grain size. Figure 14 shows the locations where the samples were collected.

Grain sizes were determined by sieving analysis where the samples were sieved for 15 minutes and then weighed to obtain the different sand fraction measurements. Clay and silt percentages were determined by settling tube analysis where a pipette was used to obtain a 25ml sample at 10 seconds, 4 min, 16 min, 30 min and 16 hours at specified depths of 2.5, 22.1, 22.1, 10.3 and 8.1cm respectively. The beakers containing the samples were placed in an oven at 105°C for 2 hours to evaporate the excess water. Thereafter the samples were weighted and the difference was calculated to determine the sample amounts.

Only samples 8.4, 8.3, 8.5, 10.2, 10.3 and 10.4 were analysed for silt and clay because the remaining samples did not contain sufficient fine sediment. Most of the samples had a small amount of sediment less than 53μm and a standard weight was set at 5g of soil. Anything below this amount was not used for the settling tube analysis because the low amounts made no significant change to the samples. The organic matter content was determined using the loss on ignition method where the weight loss was measured, which occurs when organic matter oxidises at high temperatures (550°C) (Rowell, 1994). Both the organic matter content and sieving analysis were determined following the methods of Rowell (1994).

4.3.2. SEDIMENT RESULTS

A layer of fine unconsolidated sediment occurred in the centre channel during both the pre-and post-flood surveys. The results of the soil survey show clear spatial variations in sediment deposition within the estuary.

Pre-flood results

In transect 1 fine sand dominates in all the samples except at sample 1.2. Fine sand comprised 45% of sample 1.1, 32% of sample 1.2, 63% of 1.3, 69% of 1.4 and 70% of sample 1.5, which showed an increase from the left to right bank. The medium sand fraction remained more or less constant throughout transect 1 and ranged between 20-24%. The coarse sand comprised 11% and 13% in 1.1 and 1.2 respectively but showed a decrease toward the right bank. The same trend was shown for the very coarse sand with 29% occurring in 1.1 and 23%

occurring in 1.2. Approximately 11% occurred in 1.3 where 1.4 and 1.5 contained 2% and 6% respectively. Low organic matter percentages occurred throughout except at 1.2, which contained 9%. Sample 1.1, 1.3, 1.4 and 1.5 contained 1.4%, 2.2%, 2% and 2.2% respectively. Less than 3% of clay and approximately 22% of silt occurred only in 1.2.

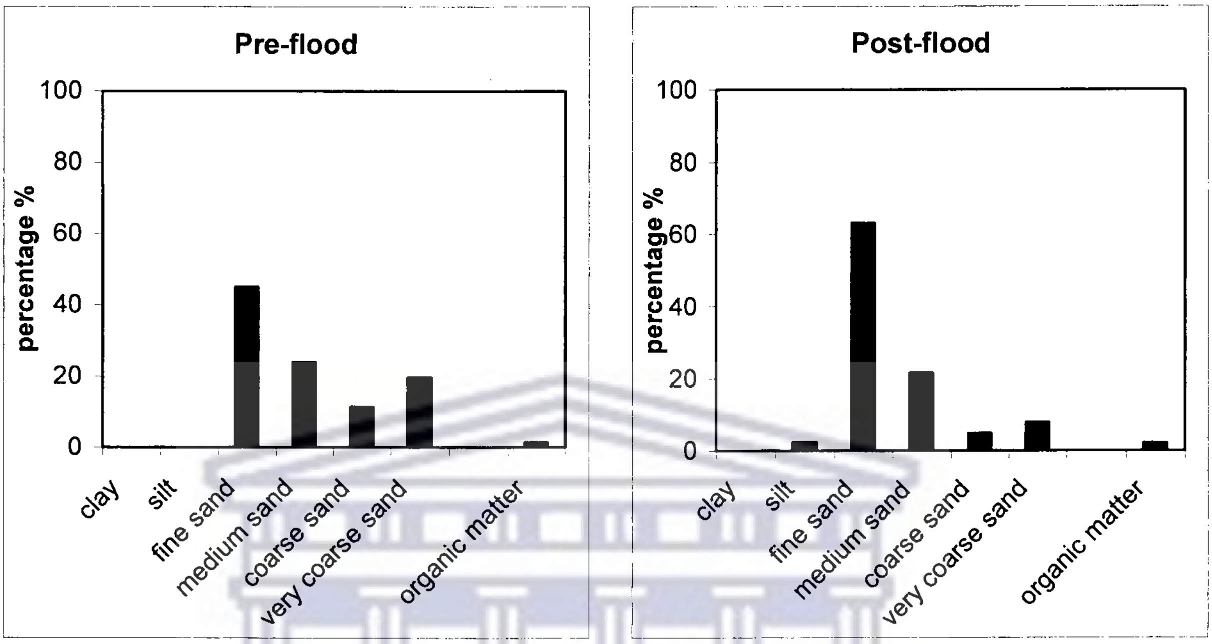

Figure 44. Pre-and post-flood sediment and organic matter results for sample 1.1

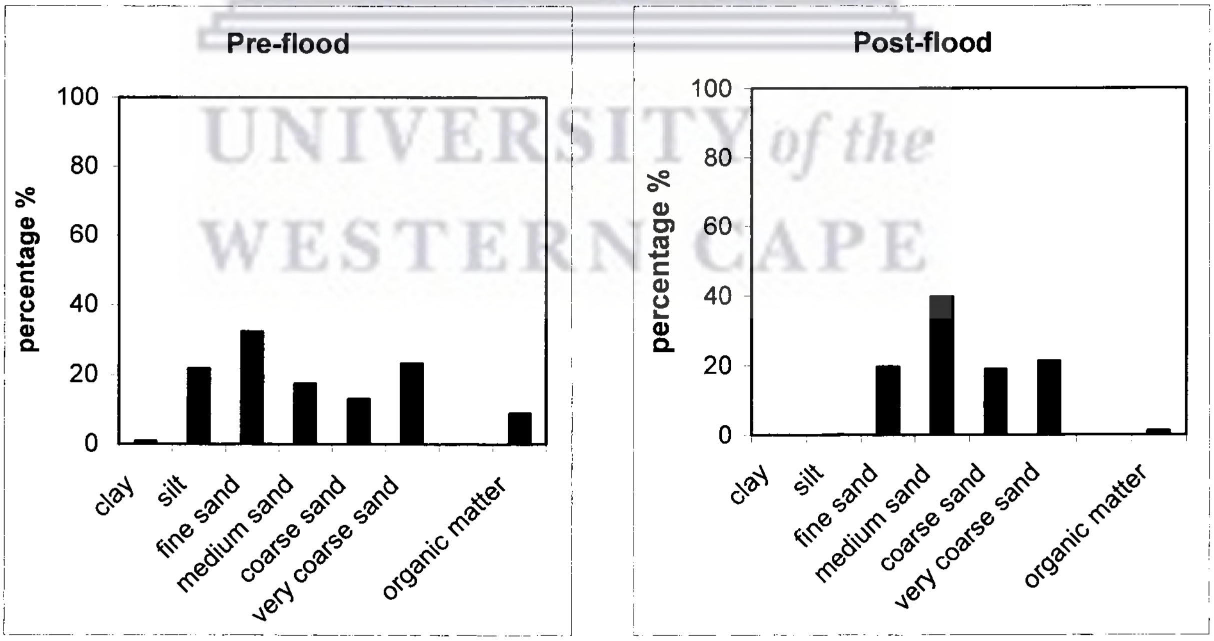

Figure 45. Pre-and post-flood sediment and organic matter results for sample 1.2

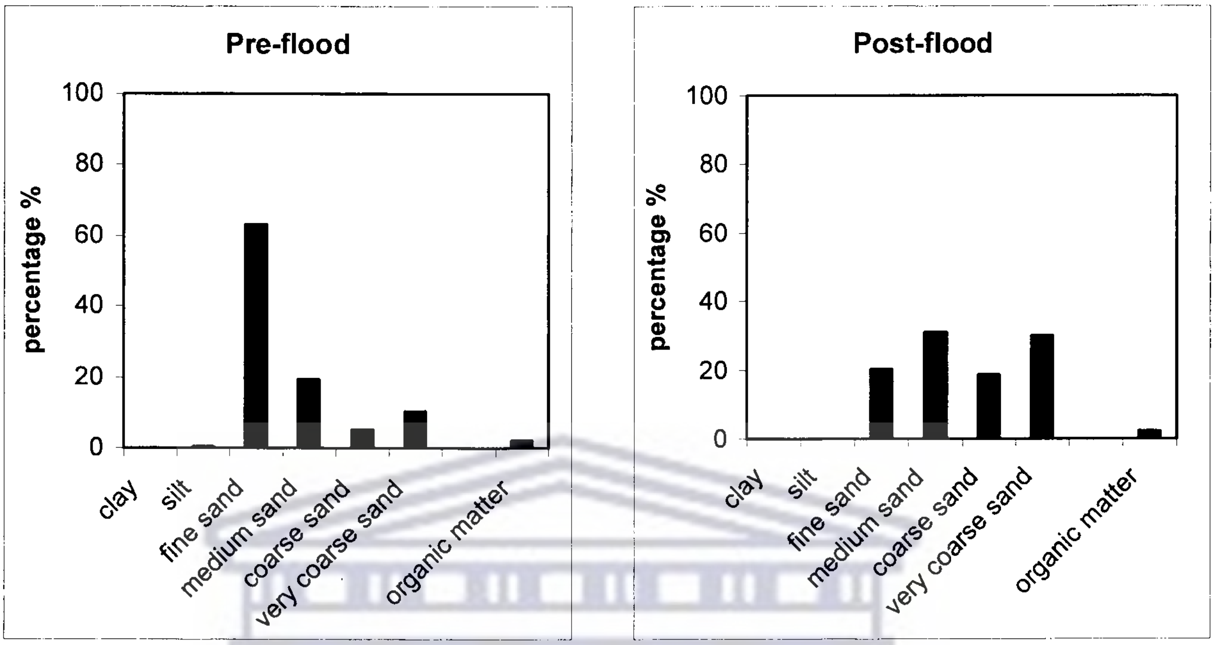

Figure 46. Pre-and post-flood sediment and organic matter results for sample 1.3

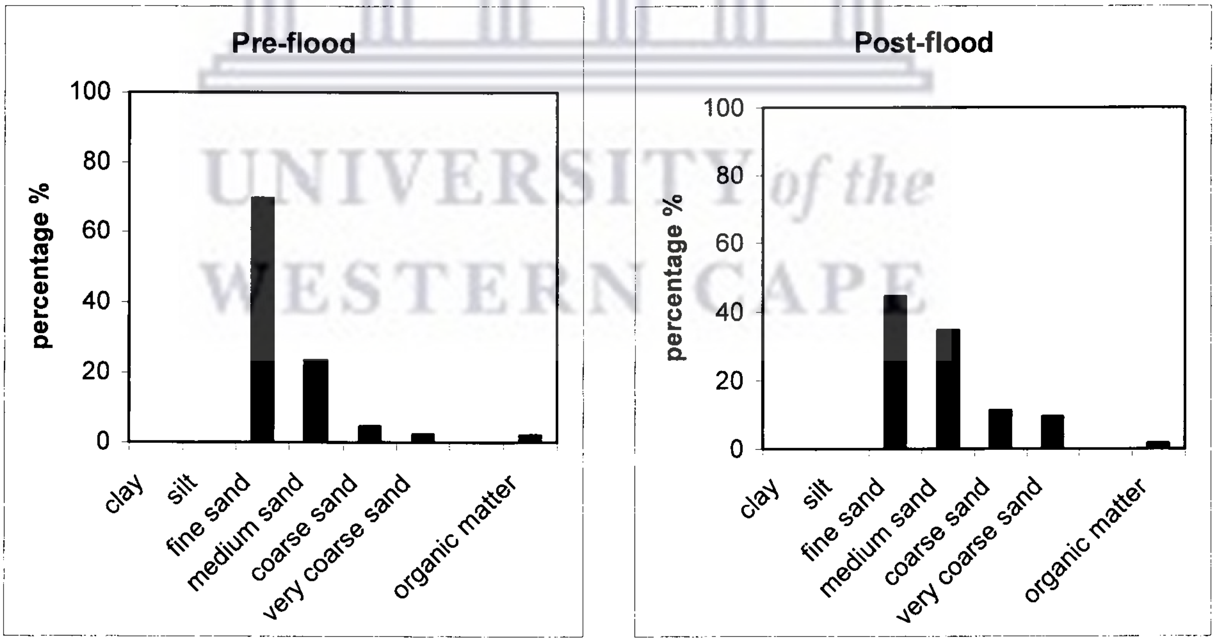

Figure 47. Pre-and post-flood sediment and organic matter results for sample 1.4

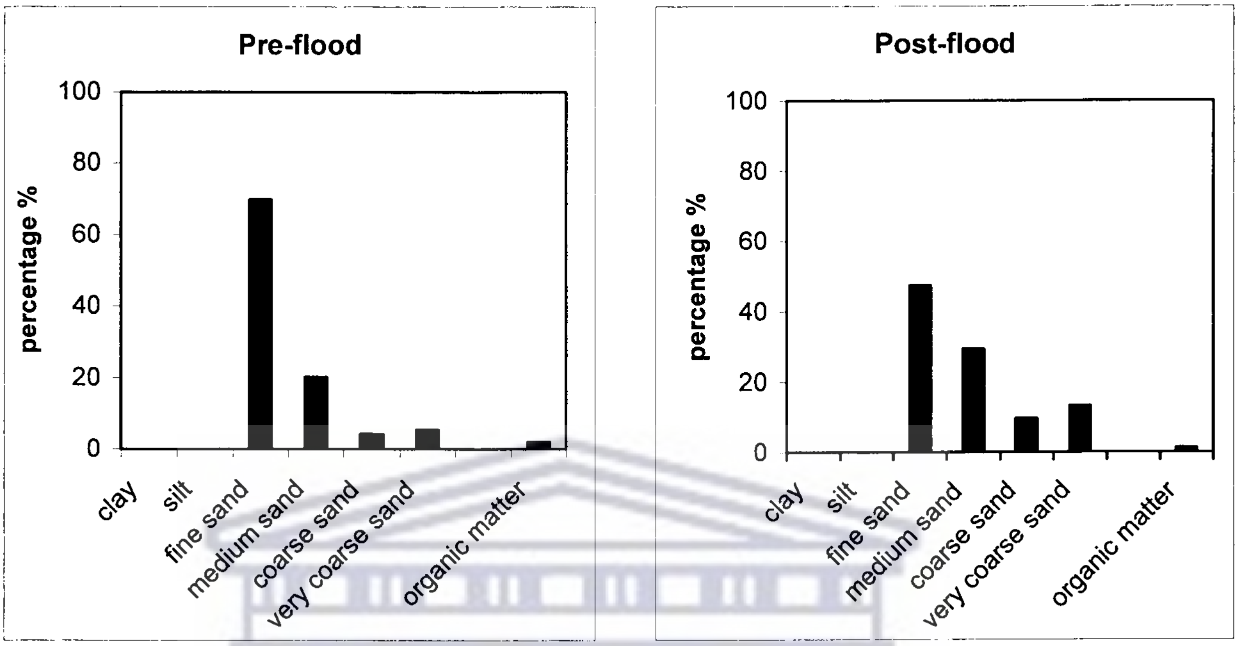

Figure 48. Pre-and post-flood sediment and organic matter results for sample 1.5

Fine sand dominated throughout the samples of transect 8. In sample 8.1, 53% occurred, 8.2 and 8.3 contained 60%, 8.4 contained 43% and 8.5 contained 63%. The highest percentage of medium sand at 32% occurred in sample 8.1 with 12% in 8.2, 8.3 and 8.5 and 10% in 8.4. Coarse sand followed a similar pattern throughout with values ranging from 6-12%. Very coarse sand comprised 8% in sample 8.1 and 8.2 and 9% in sample 8.3. Slight increases occurred in 8.4 to 18% and 8.5 to 15%. Sample 8.2 showed the highest percentage of organic matter at 15% and 8.4 at 11% with 8.1, 8.3 and 8.5 having percentages lower than 6%. Silt was present in the centre samples, 8.2 (5%), 8.3 (7%) and 8.4 (14%). No clay occurred in transect 8.

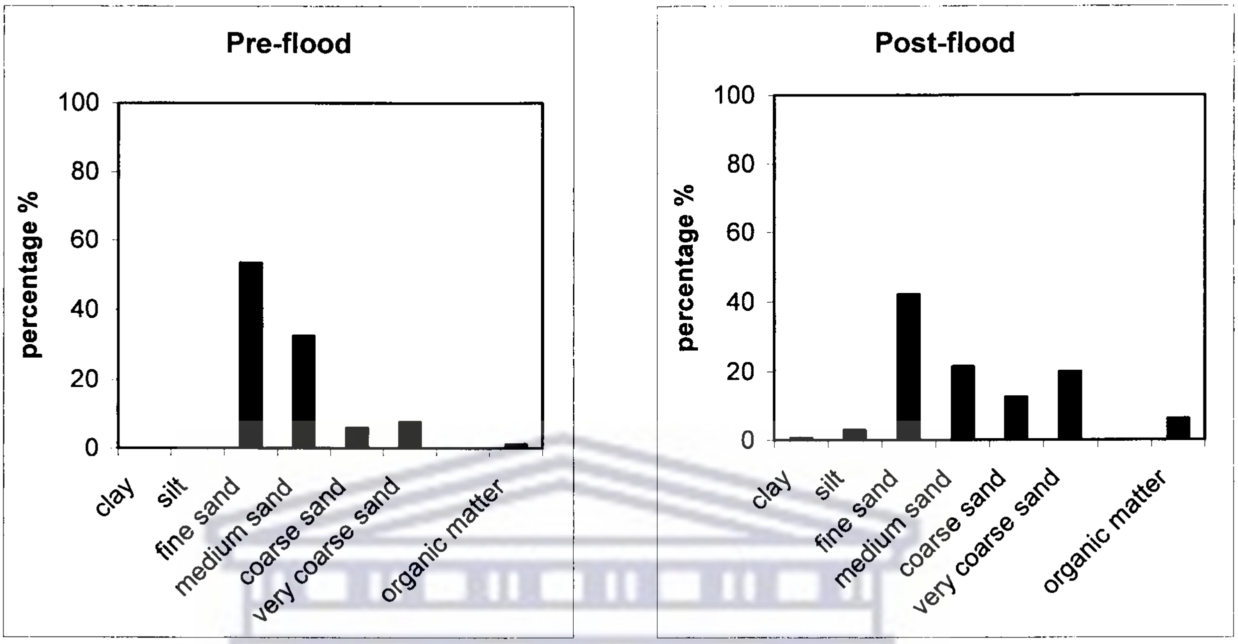

Figure 49. Pre-and post-flood sediment and organic matter results for sample 8.1

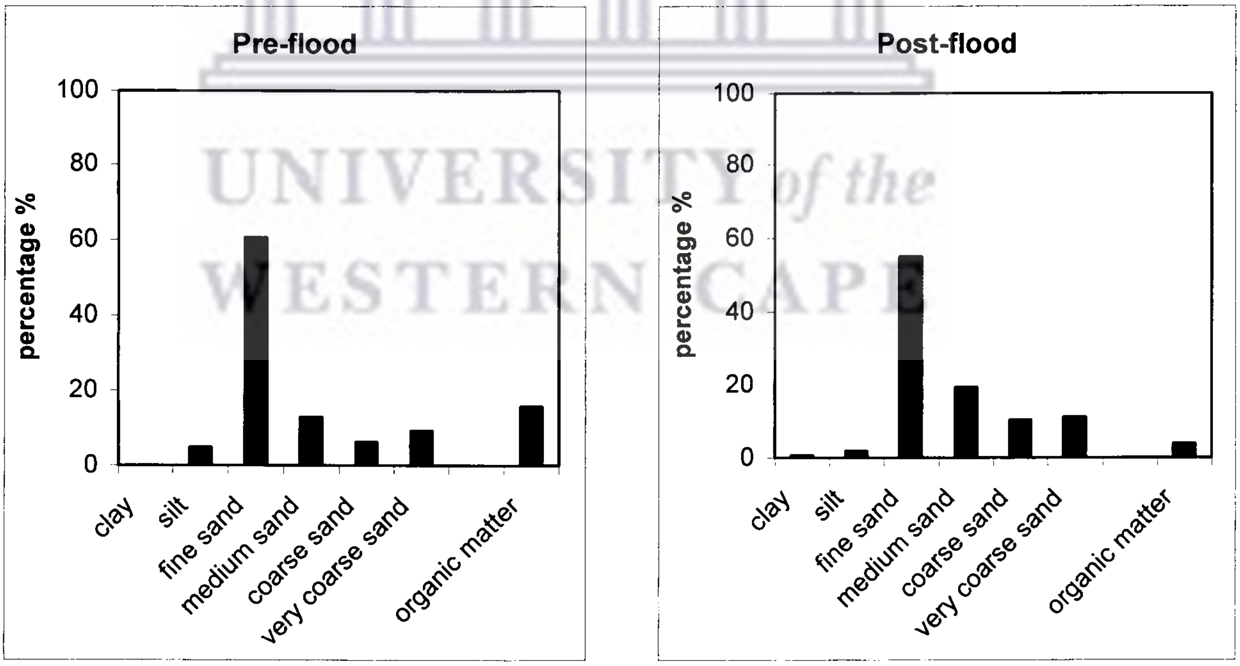

Figure 50. Pre-and post-flood sediment and organic matter results for sample 8.2

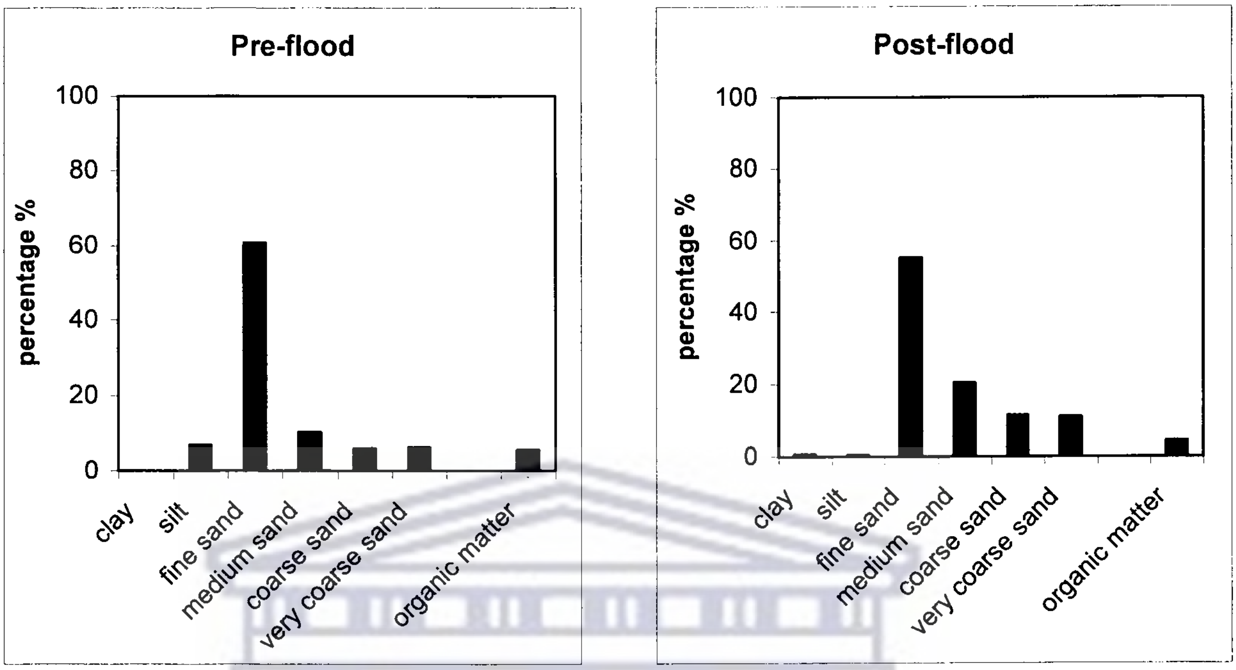

Figure 51. Pre-and post-flood sediment and organic matter results for sample 8.3

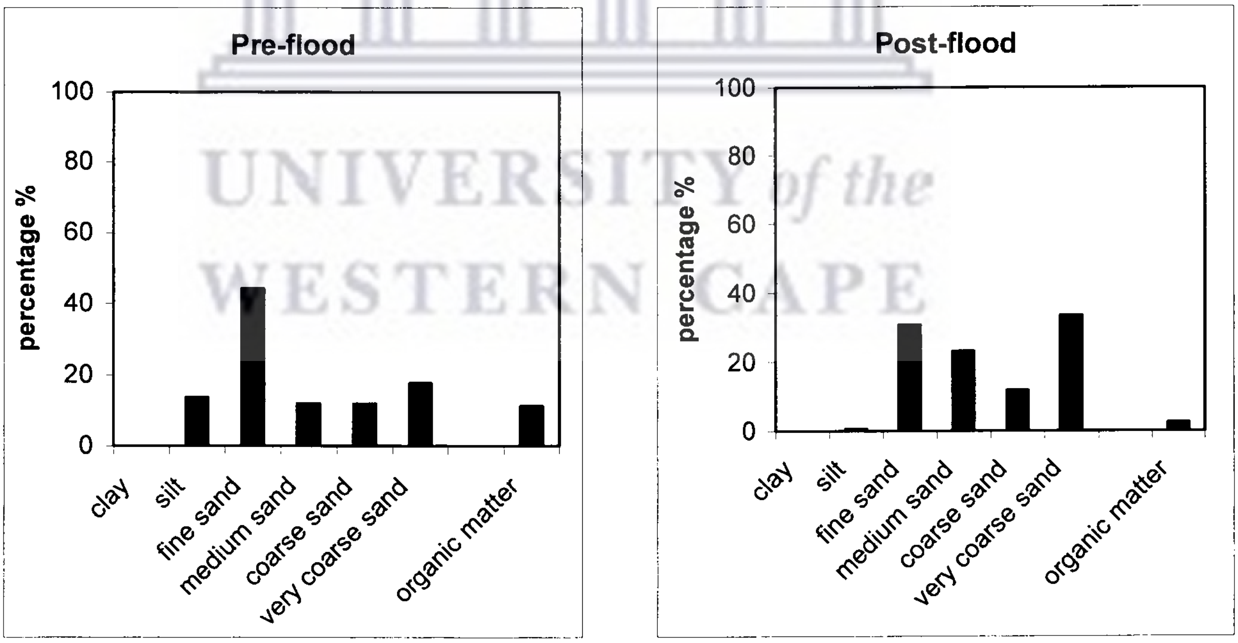

Figure 52. Pre-and post-flood sediment and organic matter results for sample 8.4

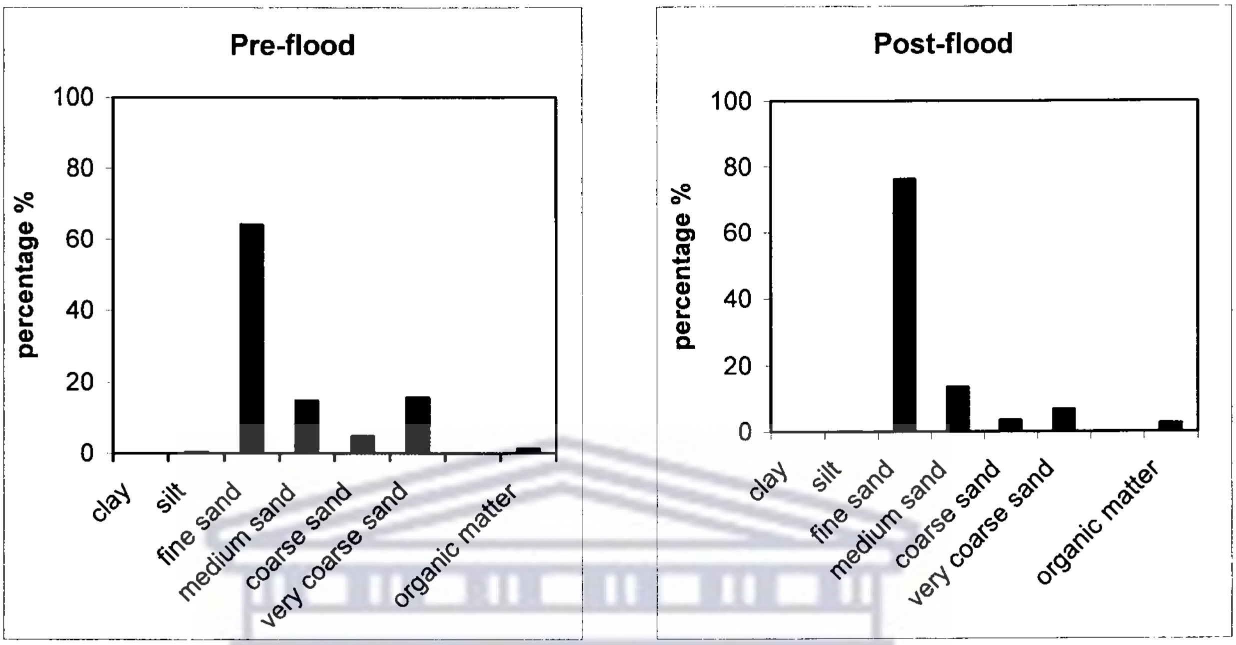

Figure 53. Pre-and post-flood sediment and organic matter results for sample 8.5

In transect 10 fine sand was present in high percentages in all the samples except 10.5 where 31% occurred. In 10.1 and 10.2, 72% occurred, in 10.3, 78% occurred and in 10.4, 83% occurred. The two end samples showed a higher percentage of medium sand with 10.1 having 16% and 10.5 having 30%. The centre samples (10.2, 10.3, 10.4) contained low values of less than 7%. The coarse and very coarse sand showed the same distribution throughout where 10.5 showed the highest percentages with 18% coarse sand and 22% very coarse sand. Low percentages of organic matter occurred at 10.1 (1.3%), 10.2 (6%), 10.3 (5%), 10.4 (6%) and 10.5 (0.8%). No clay or silt was found in 10.1 and 10.5. In 10.2 only 5% of clay and 11% of silt occurred and in 10.4 approximately 8% of silt was found with no clay. Sample 10.3 contained 4% clay and 9% silt.

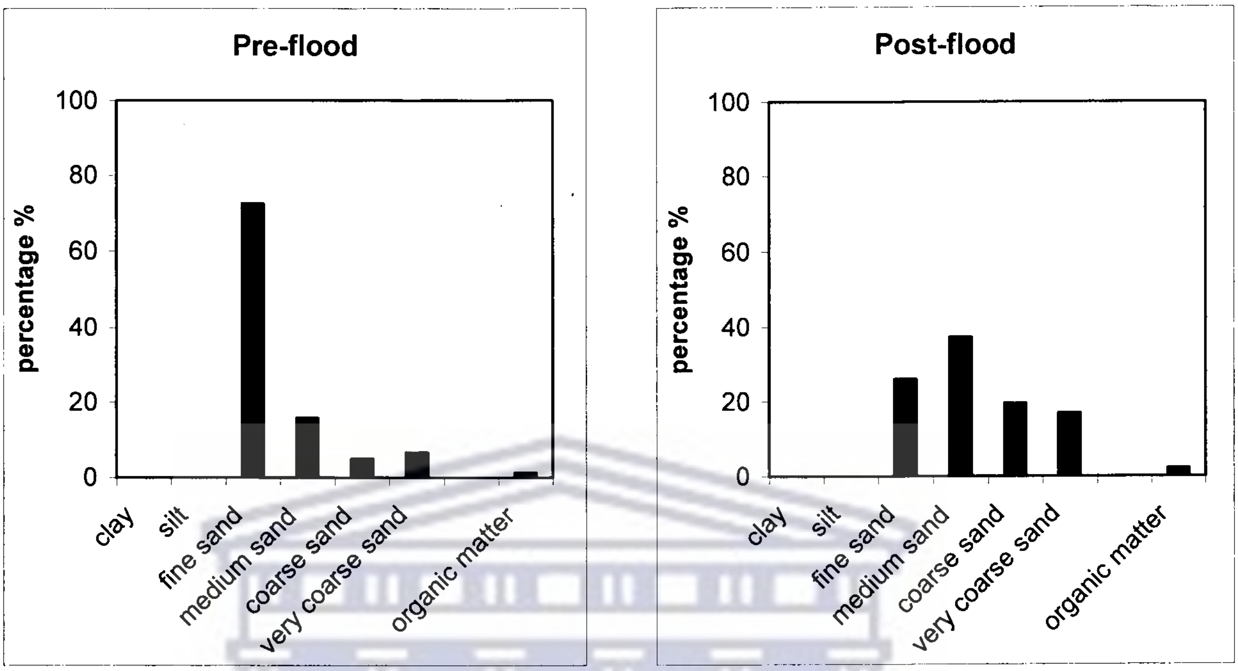

Figure 54. Pre-and post-flood sediment and organic matter results for sample 10.1

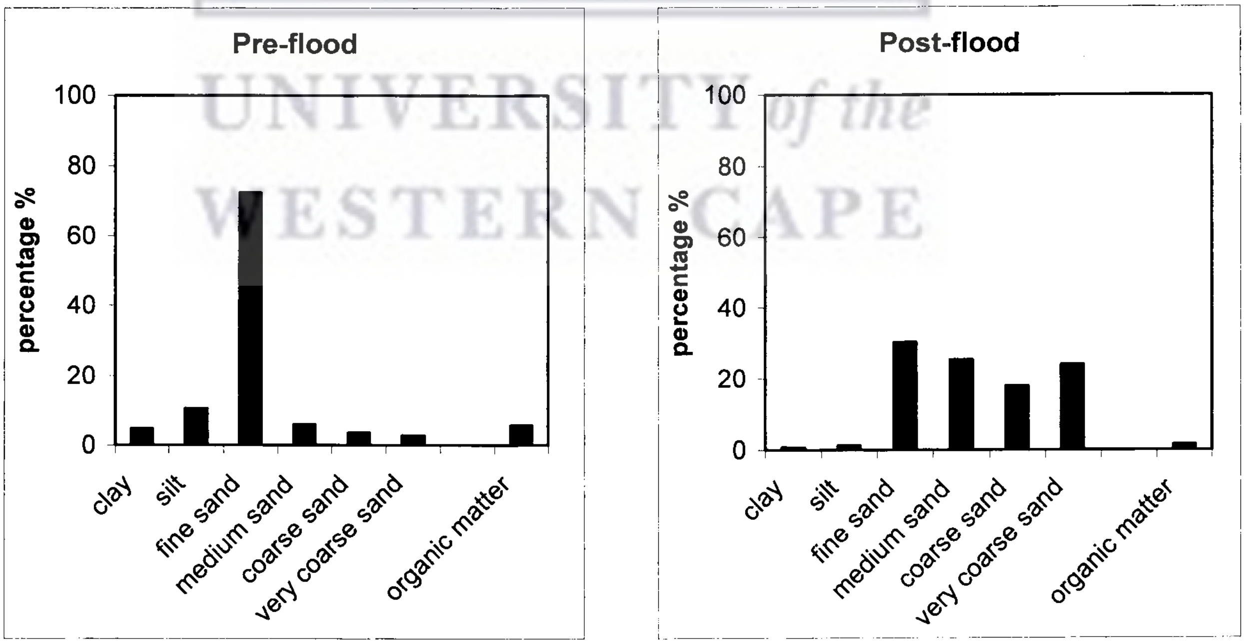

Figure 55. Pre-and post-flood sediment and organic matter results for sample 10.2

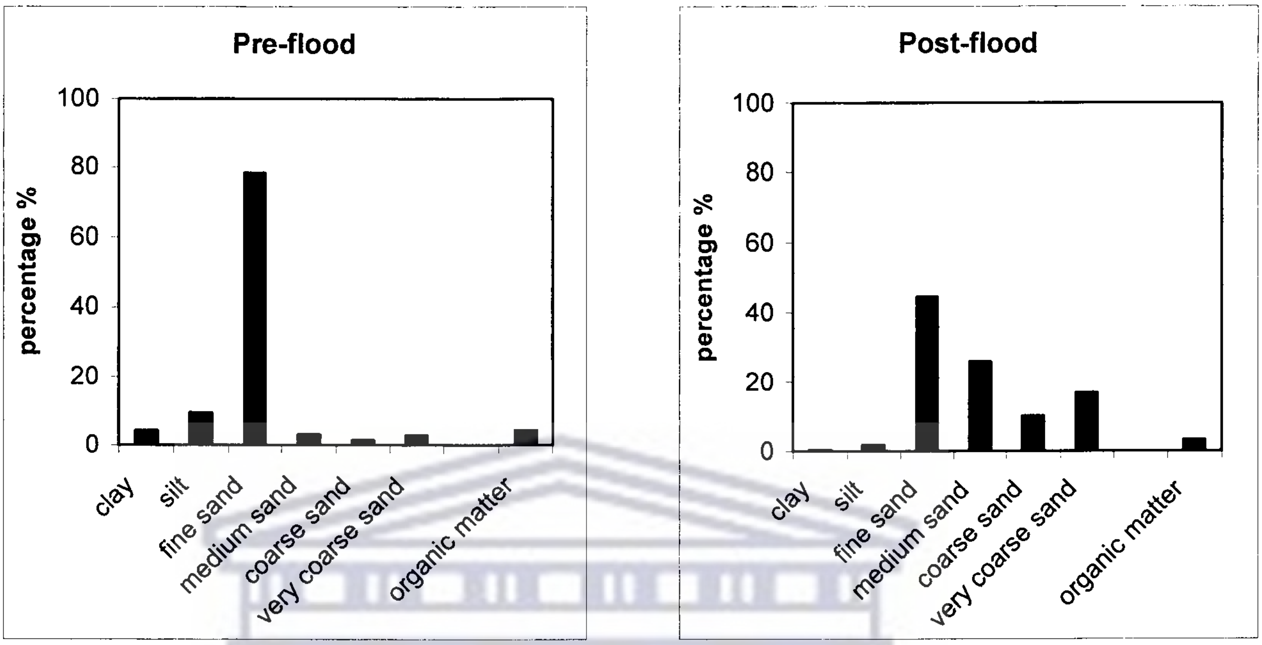

Figure 56. Pre-and post-flood sediment and organic matter results for sample 10.3

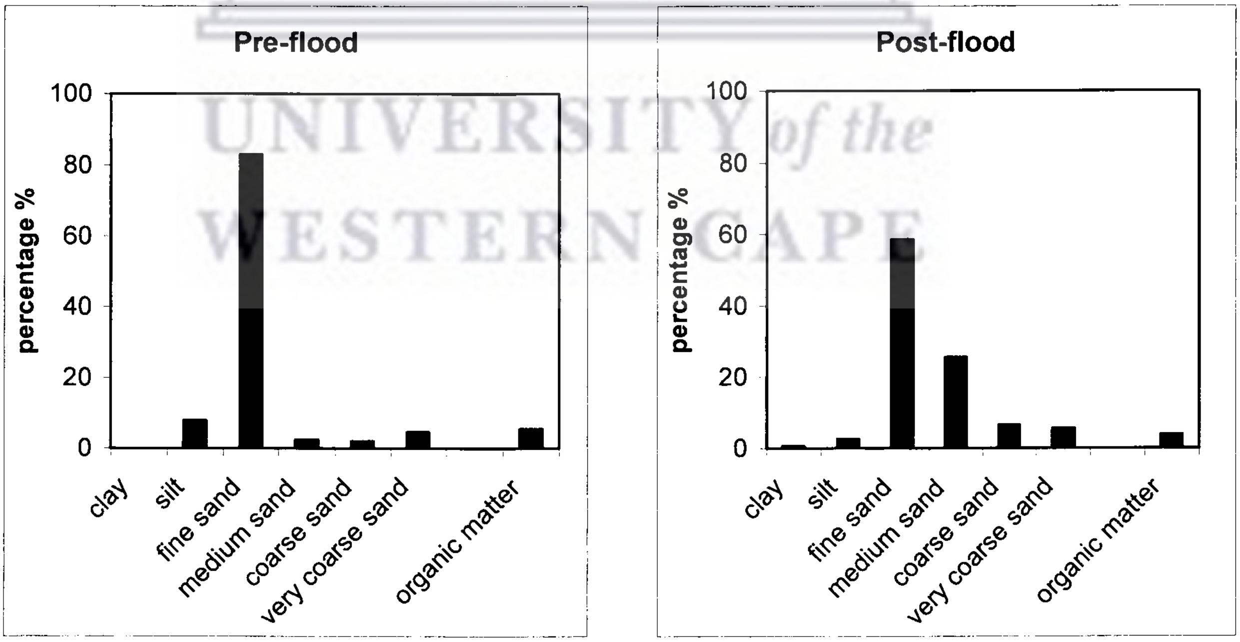

Figure 57. Pre-and post-flood sediment and organic matter results for sample 10.4

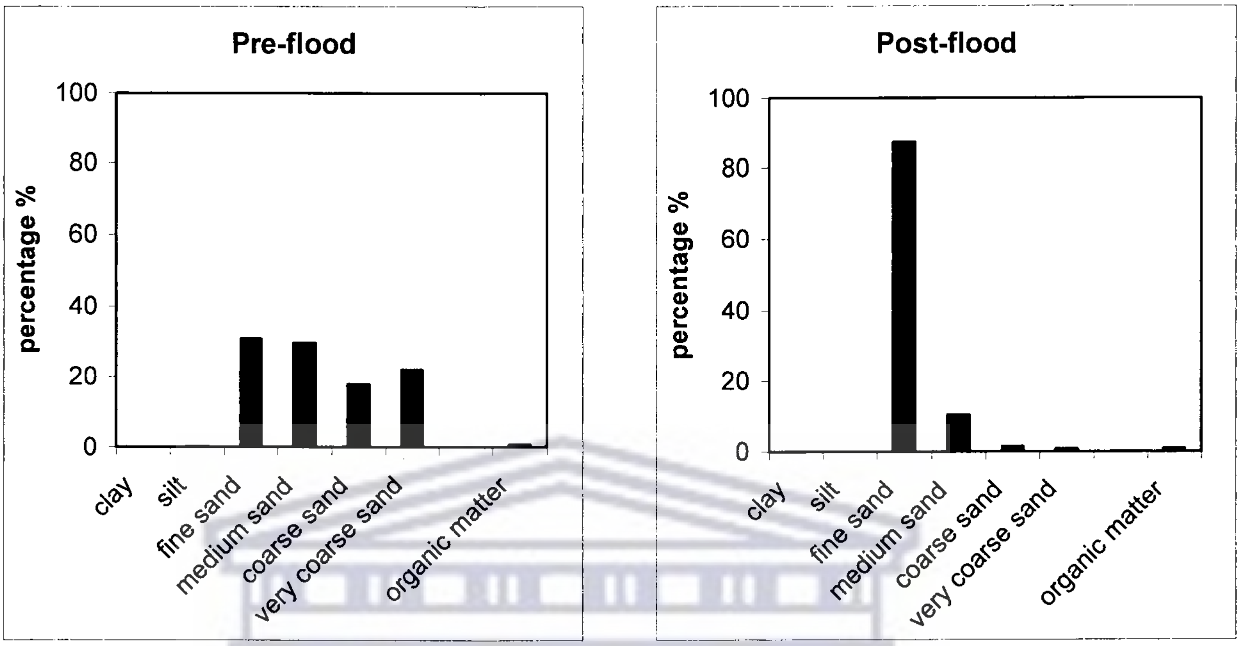

Figure 58. Pre-and post-flood sediment and organic matter results for sample 10.5

Post-flood results

The samples for transect 1.1 and 1.5 taken after the winter floods showed similar results to those taken in May 2001. Although the fine sand showed a considerable decrease in sample 1.3 the general trend still remained. In 1.1 the fine sand increased to 63% but decreased in 1.2 to 20%, in 1.4 to 45% and in 1.5 to 47%. The medium sand fraction increased from the left to right bank with 22% (1.1), 40% (1.2) 31% (1.3), 35% (1.4) and 30% (1.5). The two centre samples, 1.2 and 1.3, showed higher percentages of coarse sand at 19% while 1.1, 1.4 and 1.5 showed only 9%, 11% and 10% respectively. The same trend was shown by the very coarse sand fraction where 1.2 contained 21% and 1.3 contained 30%. Sample 1.1 contained 8%, 1.4 contained 9% and 1.5 contained 13%. Very low organic matter percentages occurred with 2% (1.1, 1.3 and 1.4) and 1% (1.2 and 1.5). No clay occurred throughout the transect and only 2% of silt was found in 1.1.

In transect 8, sample 8.5 showed the highest percentage of fine sand at 76%. In 8.1, 42% occurred, 8.2 and 8.3, 55% occurred and the least amount occurred in 8.4 at 31%. The medium sand remained more constant throughout except 8.5, which contained 13%. Samples 8.1, 8.2, 8.3 and 8.4 contained 21%, 19%, 20% and 23% respectively. The coarse sand fraction showed 13% (8.1), 10% (8.2), 11% (8.3), 12% (8.4) and 3% (8.5). The very coarse sand followed the same distribution with 8.1 (20%), 8.2 and 8.3 (11%), 8.4 (34%) and 8.5 (7%). Organic matter content was low throughout with 8.1 (6%), 8.2 (4%), 8.3 (5%), 8.4 (2%) and 8.5 (3%). Clay occurred at 8.1, 8.2 and 8.3 at 0.7% and silt occurred at 8.1 (3%), 8.2 (2%), 8.3, 8.4 and 8.5 at less than 1%.

In transect 10 the samples closer to the right bank, 10.3 (45%), 10.4 (59%) and 10.5 (87%) contained significant amounts of fine sand especially at 10.5. In 10.1 and 10.2 only 26% and 30% occurred respectively. The medium sand fraction remained similar with 37% (10.1) and 26% (10.2, 10.3 and 10.4). Only 10.5 contained much less at 11%. The coarse sand showed a decrease from the left to right bank with 19% at 10.1, 18% at 10.2, 10% at 10.3, 7% at 10.4 and 2% at 10.5. A similar trend was found with very coarse sand where 17% occurred at 10.1, 24% at 10.2, 17% at 10.3, 6% at 10.4 and 0.8% at 10.5. Organic matter remained low throughout with values below 4%. Silt and clay occurred at 10.2, 10.3 and 10.4, all below 4%.

4.3.3. SEDIMENT DISCUSSION

Pre-flood sediment distribution

A number of factors influence the type and distribution of sediment in estuaries. Some of these include tidal currents and tides, waves, locally generated waves, river discharge, etc. The influences of these factors are determined by the estuary type, which will in turn determine the sediment characteristics (Clifton, 1981). River-dominated estuaries are characterised by fluvial sediment that consists of mainly fine sand (Clifton, 1981; Cooper, 2001a). The Eerste River estuary exhibited river-dominated features and sediment characteristics associated with this morphology type.

The unconsolidated sediment layer found in the centre channel forms when the fine particles are moved in suspension and settles in low energy areas or where slack water occurs. Water remains trapped between these particles during settling so that a soft channel bed is created (Dyer, 1994). The left bank at transect 10 consisted of a dense stand of *Phragmites* reeds. The unconsolidated layers extended from the centre of the channel to the reed bank at transect 10. Fine sand therefore dominates throughout the transect except for sample 10.5 at the right bank side, where the coarser sand fraction showed an increase. A possible reason for this could be that higher flow velocities occurred in that region as coarser material move with the maximum current (Dyer, 1994). Summary tables comparing the pre-and post-flood sediment characteristics for transects 1, 8 and 10 are shown in Tables 5, 6 and 7 respectively.

In transect 8 a similar distribution of sand occurred although the medium sand showed an increase on the left bank side in sample 8.1. The left bank at transect 8.1 consisted of unvegetated beach material and at high tide, overwash would occur and the coarser sand would be deposited in the estuary. Transect 1 was located closest to the estuary mouth and this could explain the increase in the coarser sand fractions.

The percentages of organic matter show similar trends for transect 10, 8 and 1. Sediments from the shallow areas along the edge of the estuary (10.1, 10.5, 8.1, 8.5, 1.1, 1.5) show low levels of organic matter relative to other areas. The highest amounts are found in the centre channels, namely 10.2, 10.3, 10.4, 8.2, 8.3 and 8.4, which were also the deepest channel sections at the time. This suggests that deposition occurred in these deep areas and resulted in higher levels of organic matter. This trend is also displayed in transect 1 although much lower levels of organic matter occurred, except at 1.2. The percentages of silt and clay also increased in the deeper channel sections and decreased along the edge of the estuary.

Post-flood sediment distribution

After the winter floods the estuary had a change in morphology as previously discussed. The tidal influence resulted in the development of flood and ebb dominant channels in the estuary, where sediment would be transported inland with the dominant flood current and seaward in the ebb channel (Dyer, 2000).

In transect 10 an overall decrease in fine sediment occurred with an increase in the coarser material, except at 10.5 where the fine sediment showed a significant increase. The increase in the coarser sediment especially at 10.1 and 10.2, which was located on a dry sandbank during low tide, was transported from upstream during the flood and deposited when the water levels became lower. The areas of coarse sediment may also indicate the direction of flow during the flood peak (Cooper, 1993). If flow was concentrated at the left bank side it could explain the occurrence of the high percentage of fine sediment on the right bank side at 10.5 and 8.5 where lower flow velocities occurred and resulted in settling of fine sediment.

The transects in the upper reaches are also ebb dominated, which results in generally lower current velocities and deposition (Dyer, 1994). This is shown in samples 8.1, 8.2 and 8.3 where fine sand increased together with minimal amounts of silt and clay. The amounts of clay present in the samples may also have been transported from upstream. The increase in organic matter at 8.1 also indicates that deposition occurred and the decrease in samples 8.2, 8.3 and 8.4 indicates the removal of sediment.

Transect 1 would mostly be affected by the incoming tides due to its location. Fine sand had decreased throughout the transect and the coarser sand increased. This occurs due to the transport of coarser material from the seaward side during the flood tide (Lindsay *et al*., 1996). As the ebb channel shallows towards the sea the flood and ebb channels will integrate and sediment will be transported across the ebb channel (Dyer, 1994). Marine sand also enters the estuary from continual barrier overwash during storm surges and high tides (Reinson, 1992). This occurred often in the Eerste estuary as shown in Figures 18 and 19. Only sample 1.1 showed an increase in fine sediment and silt content, which could indicate the ebb channel. The low percentages of organic matter throughout transect 1 could be explained by the increased transport of marine sand into the estuary.

The erosive power of a river increases with an increase in discharge and therefore the most dramatic changes will occur during times of flood. This is also true in terms of sediment transport. Floods accomplish more sediment erosion and deposition than would otherwise occur during fair-weather conditions over months or even years. Flooding is therefore important for the occurrence of channel scouring and sediment transport through estuaries (Cooper *et al.*, 1990; Cooper, 1993).

Spatial estuarine sediment distribution

Sediment patterns vary for different estuaries occurring in different environments (Dyer, 1994). The Eerste River estuary is a bar-built lagoonal estuary and is situated on a wave-dominated coast. It therefore displays a tripartite facies zonation. Other wave-dominated estuaries in South Africa such as the Nahoon, Gqunube and Kwelera show the same spatial sediment distribution as was documented by Reddering and Esterhuysen (1987).

In the upper reaches the estuary is characterised by fluvial sediment, mainly alluvial sands and gravels, which are poorly sorted. The reason being that the sediment could be supplied from a variety of sources such as riverbanks or floodplains. This section of the estuary is therefore considered to be the most complex. The lagoonal area or central basin has relatively deeper water depths compared to other sections in the estuary and the energy current conditions are lower. As a result they become settling environments and consists of both fine sand and mud. The mud is dark grey to black in colour and contains organic matter and shell fragments in certain areas. The third zone is a high-energy marine environment where marine sand is transported into the estuary by waves and tides. As the sediment is of marine origin it is often shelly quartzitic, coarse sand (Reinson, 1992; Kench, 1999). The supratidal bar/spit separating the lagoon from the sea also consists of marine sand.

Table 5. Summary table comparing the pre-and post-flood sediment characteristics for transect 1

	Pre-flood (%)					**Post-flood (%)**				
	1.1	**1.2**	**1.3**	**1.4**	**1.5**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
Clay	0	2	0	0	0	0	0	0	0	0
Silt	0.03	22	0.4	0	0.009	2	0.2	0	0.04	0.03
Fine sand	45	32	63	69	70	63	20	20	45	47
Medium sand	24	18	19	24	20	22	40	31	35	30
Coarse sand	11	13	5	5	4	9	19	19	11	10
Very coarse sand	20	23	11	2	6	8	21	30	9	13
Organic matter	1.4	9	2.2	2	2.2	2	1	2	2	1

Table 6. Summary table comparing the pre-and post-flood sediment characteristics for transect 8

	Pre-flood (%)					Post-flood (%)				
	8.1	**8.2**	**8.3**	**8.4**	**8.5**	**8.1**	**8.2**	**8.3**	**8.4**	**8.5**
Clay	0	0	0	0	0	0.7	0.7	0.7	0	0
Silt	0	5	7	14	0.3	3	2	0.6	0.6	0.05
Fine sand	53	60	60	43	63	42	55	55	31	76
Medium sand	32	12	12	10	12	21	19	20	23	13
Coarse sand	6	6	6	12	5	13	10	11	12	3
Very coarse sand	8	8	9	18	15	20	11	11	34	7
Organic matter	1.3	15	6	11	1	6	4	5	2	3

Table 7. Summary table comparing the pre-and post-flood sediment characteristics for transect 10

	Pre-flood (%)					Post-flood (%)				
	10.1	**10.2**	**10.3**	**10.4**	**10.5**	**10.1**	**10.2**	**10.3**	**10.4**	**10.5**
Clay	0	5	4	0	0	0	0.7	0.4	0.7	0
Silt	0	11	9	8	0.27	0	1	1	3	0
Fine sand	72	72	78	83	31	26	30	45	59	87
Medium sand	16	6	3	3	30	37	26	26	26	11
Coarse sand	5	4	2	2	18	19	18	10	7	2
Very coarse sand	7	3	3	5	22	17	24	17	6	0.8
Organic matter	1.3	6	5	6	0.8	2	2	3	4	0.98

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

Geomorphologically, estuaries vary to a great extent due to antecedent topography, fluvial and marine sediment supply (Cooper, 2001a). Fluvial discharge determines whether an estuary remains permanently open or seasonally closed and therefore plays a significant role in estuarine morphology. The volume of river discharge also determines the size of the tidal prism in open estuaries, e.g. river-dominated estuaries will exhibit a very small or no tidal prism whereas tide-dominated estuaries have large tidal prisms that maintain their inlets (Reinson, 1992).

Estuaries often show changes to their morphology when their hydrological characteristics are changed, e.g. due to human impact or over a shorter time period due to flood events. This will result in changes in the sediment type and distribution. Estuaries usually act as sediment sinks and therefore become progressively filled and shallower over a long time period (Cooper, 2001a). However, during times of flooding scouring occur and causes large volumes of sediment to be removed from the estuary within a relatively short time period.

The historical mapping illustrated the long-term changes in the morphology of the Eerste River estuary. The maps showed the response of the river channel and estuary to the changes that occurred in the catchment over a period of 62 years. During 1938-1977 limited development occurred in the catchment and this was reflected in the river and estuarine environments. The estuary maintained a seasonally closed morphology and breached the sand barrier with winter rainfall. During 1988-2000 increased urbanisation and developments resulted in a change in estuary morphology due to increased river flows as a result of treated sewage effluent and stormwater runoff. It resulted in river mouth conditions with limited estuarine functions, which caused eventual ecological degradation (Morant, 1991). Another result was rapid westward migration, which caused extensive dune destruction. After the winter floods the barrier decreased in width, which meant that a narrower barrier separated a broader river due to increased flows. The mouth migrated back to its easterly position due to breaching of a narrow section of the barrier. A new morphology was displayed as extensive tidal penetration occurred with considerable changes in water level between high and low tides. A tidal intrusion front or plunge line could also be seen as high tide was reached.

The cross-sectional profiles showed extensive differences between the pre-and post-flood surveys. The effects of the tides are clearly illustrated in the November (post-flood) survey where a main flow channel occurred within the actual estuary channel during low tides. On the meander bend most of the erosion was expected to occur on the outer bend and deposition on the inner bend. However, the cross-sections located on the bend showed that erosion also occurred on the right bank side, which was the inner bend. The downstream cross-sections, which were located within a straight channel, retained their shape and deposition mostly occurred. Erosion in the form of undercutting was shown at certain areas of the banks where sparse or no vegetation was found. A large amount of bed scour did occur during the flood, as was shown by changes in some cross-sections, but the channel was rapidly filled with sediment supplied from sources upstream.

The estuarine sediment showed a general increase in coarse sediment in the cross-sections located further upstream after the flood. The samples located closest to the right bank showed high percentages of fine sand and coarser material occurred in the center and on the left bank side. Fine sediment was deposited in low velocity settling areas and coarser sediment required higher transport velocities. The distribution of the sediment therefore indicates the flow direction of the flood peak. The cross-sections located closest to the mouth showed an increase in coarse material due to the transport of marine sediment into the estuary on the flood tide.

Organic matter percentages showed a similar trend for all the cross-sections before the flood. In the shallow areas along the edge of the estuary low levels occurred relative to other areas. The highest amounts were found in the center channels, which were also the deepest sections at the time. The percentages found after the flood showed a general decrease throughout. The spatial estuarine sediment distribution was shown as being tripartite with fluvial sediment in the upper reaches, fine sand and mud in the lagoonal section and marine sand in the mouth area.

The Eerste River estuary has proved to be a very dynamic system. The present study documents the geomorphological changes over a summer and winter period, and hence a longer-term observation would contribute to our understanding of the geomorphological functioning of Western Cape estuaries. A more extensive study on the sediment characteristics could prove useful in determining where and how deposition takes place and what lies beneath this material. Further studies will be necessary to determine whether the estuary will migrate westwards during the next winter or whether it will remain more or less stable. This will also determine if the estuary will maintain its tidal penetration and be classified as a true estuary or whether it will revert back to a river mouth. Similar studies on other Western Cape estuaries are needed to determine if this behaviour is unique to the Eerste estuary or if its behaviour could be classified as typical.

REFERENCES

Allanson, B.R. and Read, G.H.L., 1995: Further comment on the response of Eastern Cape Province estuaries to variable fresh-water inflows, *South African Journal of Aquatic Science*, 21 (1/2), 56-70.

Atkins, G. R., 1970: Winds and current patterns in False Bay, *Transactions of the Royal Society of South Africa*, 39(2), 138-148.

Clifton, C. E., 1981: Estuarine deposits: In: Scholle, A. P. and Spearing, D. (eds). *Sandstone depositional environments*, Tulsa Okla: American Association of Petroleum Geologists, 170-189.

Cooper, J. A. G., 1993: Sedimentation in a river-dominated estuary, *Sedimentology*, 40, 979-1017.

Cooper, J. A. G., 1994: Sedimentary processes in the river-dominated Mvoti estuary, South Africa, *Geomorphology*, 9, 271-300.

Cooper, J. A. G., 2001a: Geomorphological variability among microtidal estuaries from the wave-dominated South African coast, *Geomorphology*, 40, 99-122.

Cooper, J. A. G., 2001b: The role of extreme floods in estuary-coastal behaviour: Contrasts between river-and tide-dominated microtidal estuaries, *Sedimentary Geology*, in press.

Cooper, J. A. G., Mason, T. R., Reddering, J. S. V. and Illenberger, W. K., 1990: Geomorphological effects of catastrophic flooding on a small subtropical estuary, *Earth Surface Processes and Landforms*, 15, 25-41.

Dyer, K. R., 1994: Estuarine sediment transport and deposition, In: Pye, K. (eds). *Sediment transport and depositional processes*, Blackwell Scientific Publications, London, 193-217.

Dyer, K. R., 2000: *Estuaries: A physical introduction*, John Wiley & Sons Ltd, England.

Grindley, J. R., 1982: Estuaries of the Cape: Part 11: Synopses of available information on individual systems, Rep. No.16 Eerste (CSW 6). Heydorn, A. E. F. and Grindley, J. R. (eds). Stellenbosch, *CSIR Research Report 415*, 51pp.

Gross, M. G. and Gross, E., 1996: *Oceanography: A view of earth*, Prentice-Hall International (UK), London.

Grundlingh, M. L. and Largier, J. L., 1991: Physical oceanography of False Bay: A Review, *Transactions of the Royal Society of South Africa*, 47(4/5), 387-400.

Harrison, T. D., 1998: A preliminary survey of the coastal river systems of False Bay, South-West coast of South Africa, with particular reference to the fish fauna, *Transactions of the Royal Society of South Africa,* 53(1), 1-31.

Huizinga, P., Taljaard, S. and Van Niekerk, L., 2001: The effects of water abstraction on the estuaries of the Eerste and Lourens Rivers, CSIR Report, ENS-S-C2001-007.

Ingmanson, D.E. and Wallace, W.J., 1989: *Oceanography: An introduction*, Wadsworth Publishing Company, Inc., USA.

Jury, M., 1991: The weather of False Bay, *Transactions of the Royal Society of South Africa*, 47(4/5), 401-417.

Kench, P.S., 1999: Geomorphology of Australian estuaries: Review and prospect, *Australian Journal of Ecology*, 24, 367-380.

Lane, S. N., Richards, K. S. and Chandler, J. H., 1996: Discharge and sediment supply controls on erosion and deposition in a dynamic alluvial channel, *Geomorphology*, 15, 1-15.

Largier, J.L. and Slinger, J.H., 1991: Circulation in highly stratified Southern African estuaries, *South African Journal of Aquatic Science*, 17 (1/2), 103-115.

Largier, J.L. and Taljaard, S., 1991: The dynamics of tidal intrusion, retention, and removal of sea-water in a bar-built estuary, *Estuarine, Coastal and Shelf Science*, 33, 325-338.

Lindsay, P., Mason, T. R., Pillay, S. and Wright, C. I., 1996: Sedimentology and dynamics of the Mfolozi estuary, north Kwazulu-Natal, South Africa, *South African Journal of Geology*, 99(3), 327-336.

Luger, M., 1994: Kuils River, Western Cape, *Environmental Planning and Management*, 5(5), 4-7, 9, 11, and 13.

Morant, P. D., 1991: The estuaries of False Bay, *Transactions of the Royal Society of South Africa*, 47(4,5), 629-640.

Ninham Shand, 1993: Western Cape System Analyses, Water Quality, Volume 1: General.

Ninham Shand, 1999: Kuils River Moss, Volume 1: Final report, Report No. 2913/8070.

O'Callaghan, M,: 1990: The ecology of the False Bay estuarine environments, Cape, South Africa. 2. Changes during the last Fifty years, *Bothalia*, 20(1), 105-121.

Pendón, J. G., Morales, J. A., Borrego, J., Jimenez, I. and Lopez, M., 1998: Evolution of estuarine facies in a tidal channel environment, SW Spain: evidence for a change from tide-to wave-domination, *Marine Geology*, 147, 43-62.

Pethick, J., 1984: *An introduction to coastal geomorphology*, Edward Arnold Ltd, Great Britain.

Ramm, A. E. L., 1990: Application of the community degradation index to South African estuaries, *Water Resources*, 24(3), 383-389.

Reddering, J.S.V. and Esterhuysen, K., 1987: The effects of river floods on sediment dispersal in small estuaries: a case study from East London, *South African Journal of Geology*, 90(4), 458-470.

Reddering, J.S.V. and Rust, I.C., 1990: Historical and sedimentary characteristics of Southern African estuaries, *South African Journal of Science* 86, 425-428.

Reddering, J.S.V., 1983: An inlet sequence produced by migration of a small microtidal inlet against longshore drift: the Keurbooms Inlet, South Africa, Sedimentology, 30, 201-218.

Reddering, J.S.V., 1988: Coastal and catchment basin controls on estuary morphology of the south-eastern Cape coast, *South African Journal of Science,* 84, 154-157.

Reinson, G. E., 1992: Transgressive barrier island and estuarine systems. In: Walker, R. G. and James, N. P. (eds). *Facies Models: Response to sea level change*, Love Printing Service Ltd., Stittsville, Ontario, 179-194.

Richard, A. and Davies, J. R., 1992: *Depositional systems: An introduction to the sedimentology and stratigraphy*, Prentice-Hall, Inc., New Jersey.

Rowell, D. L., 1994: *Soil Science: Methods and applications*, Longman Group, UK.

Schroeder, W. W., Dinnel, S. P. and Wiseman, W. J., 1990: Salinity stratification in a river-dominated estuary, *Estuaries*, 13(2), 145-154.

Schumann, E.H. and Pearce, M. W., 1997: Fresh-water inflow and estuarine variability in the Gamtoos estuary, South Africa, *Estuaries*, 20 (1), 124-133.

Seaman, M.T. and van As, J.G., 1998: The environmental status of the Orange River mouth as reflected by the fish community, Water Research Commission Report No. 505/1/98.

Slinger, J. H. and Taljaard, S., 1994: Preliminary investigation of seasonality in the Berg River estuary, *Water SA*, 20(4), 279-288.

Söhnge, A. P. G., 1991: Alluvial history of the Eerste River, Stellenbosch, *South African Journal of Geology*, 94(4), 299-312.

Wainman, G. R., Polito, A. and Nelson, G., 1987: Winds and subsurface currents in the False Bay region, South Africa, *South African Journal of Marine Science*, 5, 337-346.

Whitfield, A. K., 1992: A characterization of Southern African estuarine systems, *South African Journal of Aquatic Science*, 18(1/2), 89-103.

Whitfield, A. K., 1994: An estuary-association classification for the fishes of Southern Africa, *South African Journal of Science*, 90, 411-416.

Wiseman, K. A. and Simpson, J., 1989: Degradation of the Eerste River system: Legal and administrative perspectives, *South African Journal of Aquatic Science*, 16(2). 282-299.

Wiseman, K. A. and Sowman, M. R., 1992: An evaluation of the potential for restoring degraded estuaries in South Africa, *Water SA*, 18 (1), 13-19.

Wright, A. and Conrad, J., 1995: The Cape Flats aquifer: Current Status, CSIR Report No. 11/95.