UNIVERSITY OF NATAL

POST-DAM SEDIMENT DYNAMICS BELOW THE INANDA DAM AT THE MGENI ESTUARY, KWAZULU NATAL (SOUTH AFRICA).

by

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PREFACE

The work described in this thesis was carried out in the Department of Life and Environmental Sciences, University of Natal, Durban from August 2000 to October 2002, under the supervision of Professor Gerry G. Garland.

This thesis represents the original work by the author and has not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others, it is duly acknowledged in the text.

ABSTRACT

The Inanda Dam, situated some 32 to 35km upstream of the Mgeni River estuary on the Indian Ocean 5 km north of Durban, was constructed between 1984 and 1989. This impoundment deprived the downstream section of a great volume of water and sediment supply, initiating significant downstream changes. This situation is compounded by sand winning which directly extracts about 210,000 tonnes of sediment from the Lower Mgeni further depriving the estuary of sediment. A 1997 study predicted that assuming a continuous competent discharge and low contribution of sediments from the tributaries, the channel would gradually scour. Other predictions included a reduction in the total sediments reaching the estuary, continued flushing of existing channel sediments downstream towards the estuary, site-specific channel bed erosion at times of peak water release, gradual build up of sediments near the estuary mouth, gradual fining of bed-load channel and estuarine sediments, and ongoing re-establishment of the central island.

The main aim of this study was thus to investigate downstream changes in the Mgeni river estuary below the Inanda dam with regards to sediments, water discharge and channel morphology from 1997 to test these assertions.

Results show a decrease in competent discharge below the Inanda dam since 1997, resulting in a corresponding decrease in sand and an increase in mud fractions, with the mud content being associated predominantly with heavy minerals. This is reflected in the poorly sorted sediment. The plotting of cross-sectional survey revealed site-specific erosion, as well as estuarine bank failure to be an on-going process, and indicate points of bed scouring and accretion.

A number of reasons have been identified as geomorphological explanations for the changes since 1997. These include among others, a lower hydraulic gradient at the estuary, occasional minor flood events, a weak bank material composition along some portions of the estuarine bank, the Inanda dam , which impounds coarse sediments and large volume of water and increased tidal activity at the Mgeni estuary.

It is concluded that although some of the probable responses predicted in 1997 have happened, sufficient relaxation time may not yet have elapsed for others to become evident.

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"With a multitude of counsellors, there is an accomplishment". This proverb well indicates that this thesis has been successfully realised thanks to the kind and loving support given to me in various ways by well meaning individuals, friends, relatives and organizations. I do particularly feel indebted to and extend my profound gratitude to:

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I will truly commit all of you to my memory for the success of this thesis.

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CHAPTER ONE

INTRODUCTION

1.1 Rivers and Dams

The history of dam construction started as early as 3000BC in the vicinity of modern Jordan, where remains of the earliest dams have been uncovered (Jeffers, 1925; www.irn.org). Since then, many countries have viewed human regulation of rivers with dams as an answer to water and energy shortage and the increase of crop yield. This has engendered their construction in varied proportions, from small earth-bounds to big impoundments like the world's largest, Ghana's Akosombo Dam, covering 8500 square kilometres of land (Davies, 1998). Estimates reveal that there are about 40,000 large dams (150 m from base to crest) worldwide and an additional 800,000 small ones (Davies, 1998). Although important for irrigation, water and energy supply (Lere and Scudder, 1999), they often initiate significant downstream geomorphological impacts, particularly on river discharge characteristics, channel geometry and on sediment characteristics and distribution (Barrow, 1987; Diab and Scott, 1989; Fakir, 2000; Gordon, 1992; Weiss, 1999; Shen, 1998). For example the construction of the Carbora Bassa dam on the Zambezi in Mozambique initiated down cutting meanders downstream and a vast braided network of erosion in the coastal zone as well as the exposure of a central island with substantial tree growth (Davies, 1998). Upon closure of the High Aswan Dam in 1964, two erosional processes were initiated, notably immediate downstream channel scour and general streambed profile changes from Aswan to the Mediterranean Sea (Laurson, 1958). When clear water devoid of sediment is released from a dam, not only does its erosive aggressiveness increase but also its velocity and transport ability. This was the case in the 1930s and 1940s when clean water released from the Hoover Dam scoured material from the river bed to an average depth of 4 to 15 feet, that is about 1.2 to 4.6 m high downstream over a distance of about 14 miles (315.42 km) (Laurson, 1958; www.irn.org). With much of the coarse sediment held behind a dam, downstream sediment sizes and distribution become finer depriving many fish, molluscs and crustaceans of their habitats. In the United States of America and particularly in Northern United States for example (www.irn.org), reductions of sediment and water discharge downstream of dams have resulted in 93% loss of fresh water fauna. This is also true at the Volta estuary in Ghana, where reduction of downstream flows by the Akosombo and Kpong dams has led to the disappearance of the once thriving clam industry at the river's estuary. The alteration of flow by dams is also a major cause of the precipitous decline of sea fisheries in the Gulf of Mexico, the Black and Caspian Seas, California's San Francisco Bay and the Eastern Mediterranean (www.irn.org).

1.2 The Inanda Dam

The Inanda Dam in the KwaZulu-Natal province of South Africa, situated some 32 to 35 km (Archibald et al, 1990 and Moleko, 1997) upstream of the Mgeni River mouth (Figure 1.1), was constructed between 1984 and 1989. This human impoundment cut off a great volume of water and sediment supply to the estuary and the coast. It has been estimated that before the dam, in 1986, the Mgeni river yielded 1.6×10^6 tonnes of sediment annually (Badenhorst and Cooper, 1989). However, the four dams, namely the Midmar, Henley, Nagle and the Inanda, situated on its upper catchment have reduced contemporary yield to the coast (Cooper, 1993). The Department of Water Affairs (1990) indicated that the Dam retains 6.8million tonnes of total sediment per annum and Garland and Moleko (2000) pointed out that of the 0.5×10^6 tonnes pre-dam lower catchment sediment yield per year (Cooper, 1993), the post dam lower catchment yielded only 311,000 to 600,000 tonnes at the time of their study in 2000.

In addition to these negative factors affecting the Mgeni system, sand winning up to 1997 led to the direct extraction of about 210,000 tonnes of sediment annually from the Lower Mgeni, further depriving the estuary of sediment (Moleko, 1997).

This situation is further compounded by a reduction of mean annual discharge at the lower Mgeni from its pre-dam 323 million m^3 to 309 million m^3 (Garland and Moleko, 2000). These reductions in sediment and water supply to the lower Mgeni downstream of the dam have affected the estuarine characteristics.

Apart from these dam effects, the lower Mgeni has also undergone a number of human-induced influences with likely impacts downstream from the Inanda dam. These include bridging and canalisation (Archibald et al, 1990; Cooper, 1993; Moleko, 1997; Singh, 2001). These modifications, as well as frequent recent seasonal minor floods (Eric, pers. comm., 2001) may well have impacted on sediment characteristics and distribution, channel morphology and downstream water flow.

Though previous researchers like Archibald et al (1992), Cooper (1993) and Moleko (1997), investigated post-dam downstream changes in sediment, channel and discharge characteristics, it is opportune to investigate most recent post-dam downstream changes to test a conceptual model developed by Moleko in 1997 (see section 3.4) and to monitor further downstream changes after 1997, since fluvial processes are dynamic, always creating changes in their channels and at estuaries.

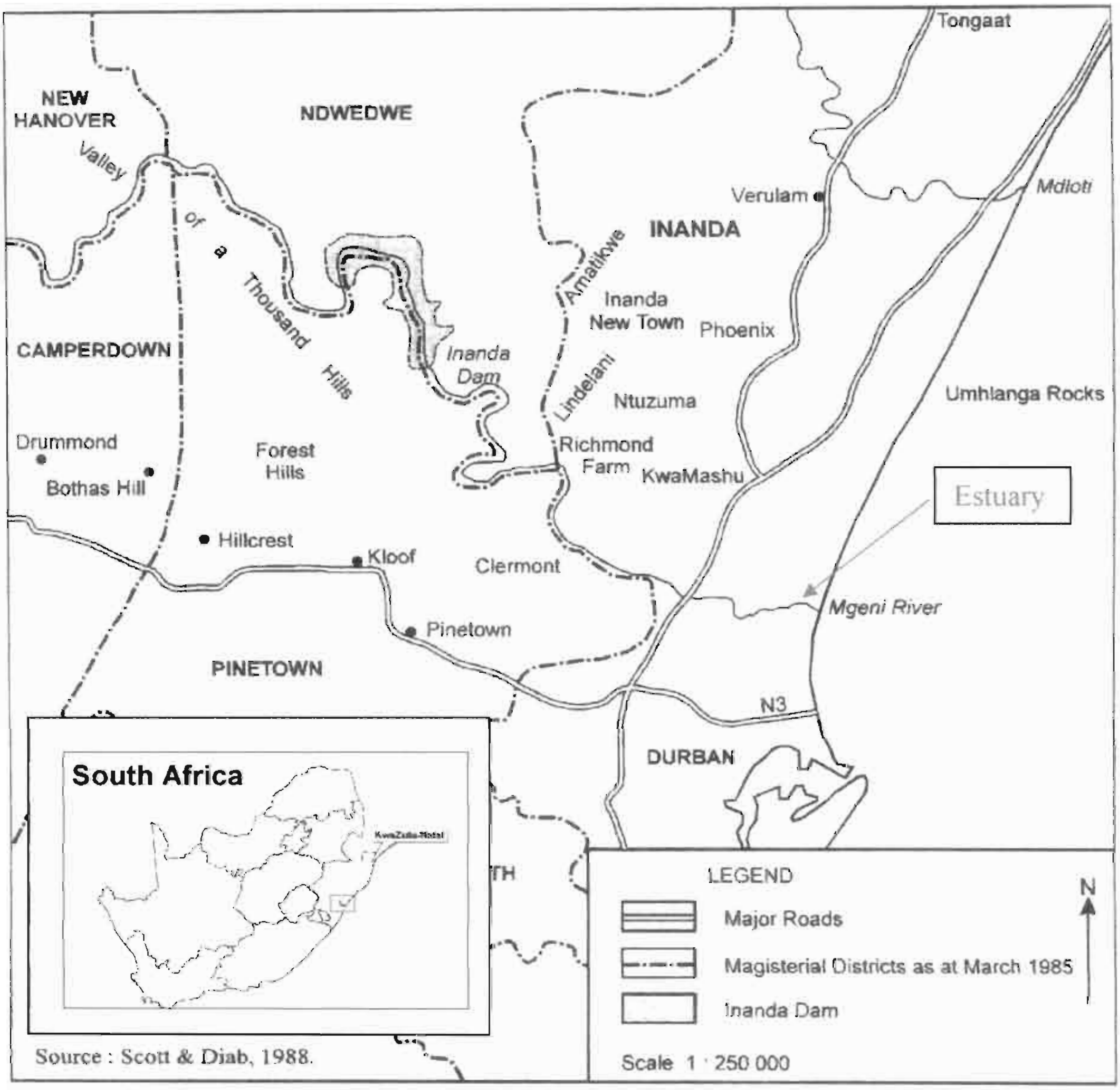


Figure 1.1: Location of the study area. The insert is a map of South Africa highlighting the KwaZulu-Natal province and the Mgeni estuary.
(Source: Modified from Scott and Diab, 1988)

1.3 The Study Area and its Topography

In its wider context, the study area is found inland of the KwaZulu-Natal province in South Africa, and is restricted to the lower catchment immediately below the Inanda Dam (itself situated in rural KwaZulu-Natal in the Valley of the Thousand Hills). Though no actual survey was conducted in the catchment and its tributaries, it is assumed that processes in the lower catchment now largely influence the Mgeni estuary as the dam cuts off the upper catchment. Cooper (1989) describes the Mgeni catchment topography as rugged, rising steeply from the Indian Ocean and culminating to about 3500 m in the Drakensberg and covering a downstream catchment of approximately 395 km^2 (Archibald, et al, 1990; Cooper, 1993). This rugged relief and the dissected hinterland with a hydraulic gradient of between 1:120 and 1:132 (Cooper and Mason, 1987 and Cooper, 1993) corresponds fairly to the youthful stage of the Davisian cycle of erosion (Sparks, 1986) where incision of river bed and transportation of sediments is the order. The lower reach draining into the Indian Ocean has a hydraulic gradient of 1:550, and is a transport/depositional environment. The TIN elevation model provided (Figure 1.2) portrays the general topography of the study area catchment, contrasting the elevated hinterland with the less elevated coastal area.

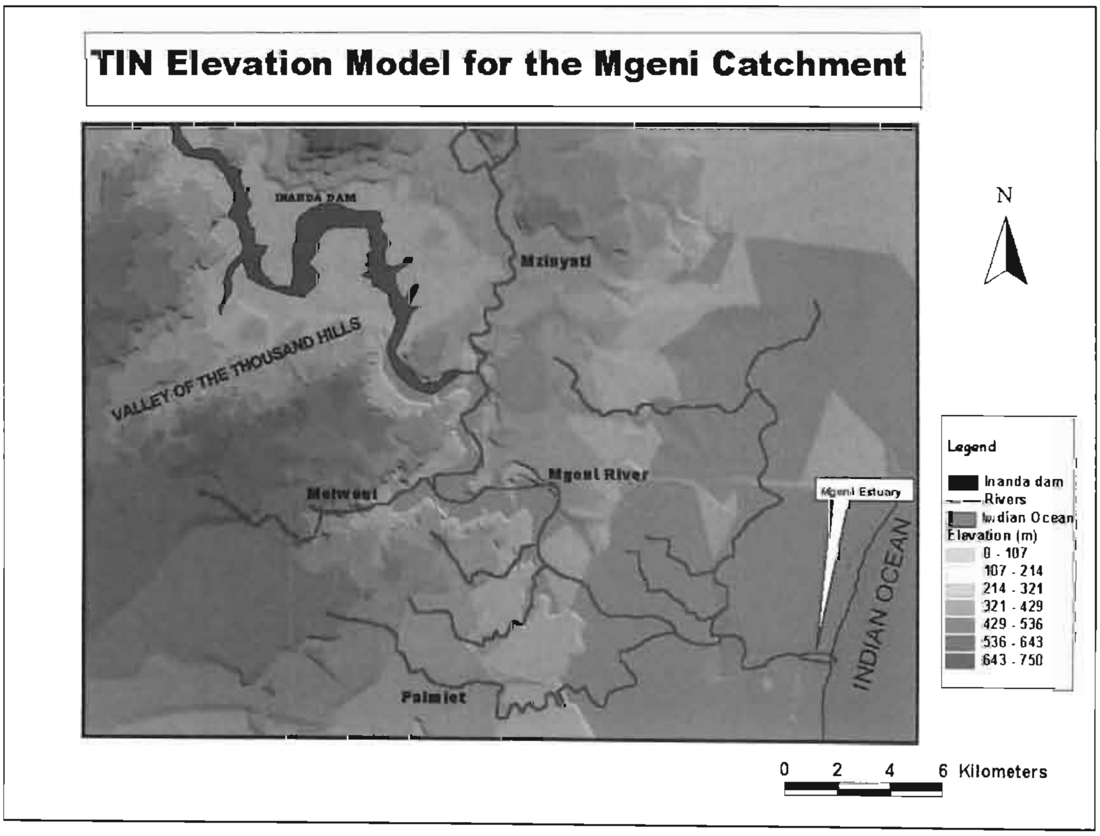


Figure 1.2: An elevation model portraying the general topography of the study area catchment. TIN - Triangulated Irregular Network (Source: Produced by Researcher, October 2002)

Though showing the wider environment influencing the study area, the above TIN model also show the actual location of the study area (the Mgeni estuary), restricted to the lower 2.5 km from the estuarine mouth inland, which is thought to experience tidal salinity fluctuations (Archibald et al, 1990; Badenhorst and Cooper, 1989).

1.3.1 Location and physiography of the Mgeni estuary

The Mgeni estuary is found North of the Durban city at approximately 29°48'S and 31° 02'E in the NE of South Africa (Badenhorst and Cooper, 1989). The study area comprises a longitudinal stretch extending from Connaught Bridge to the estuary mouth adjacent the Indian Ocean (see Figure 1.3a, 3b and 3c below). The North bank of the upper estuarine channel is steep comprising of the more resistant Dwyka Tillite and Pietermaritzburg Shale as opposed to the flat low-lying South bank of alluvial formation (Cooper and Mason, 1987). The channel exhibits a tendency towards braiding over a distance of approximately 1.5km downstream particularly to the Northern bank stretching from Connaught Bridge to Ellis Brown Viaduct. Conversely, the Southern bank is a fairly continuous stream of flow. A groyne to prevent tidal scour has stabilized the Southern estuary mouth and the southward progression of sand spits or long shore drift (Cooper and Mason, 1987; Diab and Scott, 1989; Moleko, 1997). The result has been scour of the northernmost bank of the estuarine mouth from the groyne position (Cooper, 1993). The activity of wave tides producing long-near-shore drift extending southwards constricts the channel outlet causing periodic closure of the channel, hence flooding the lagoon and obligating its opening by the Durban Metropolitan authorities (Cooper and Mason, 1987; Eric, pers. comm., 2001).

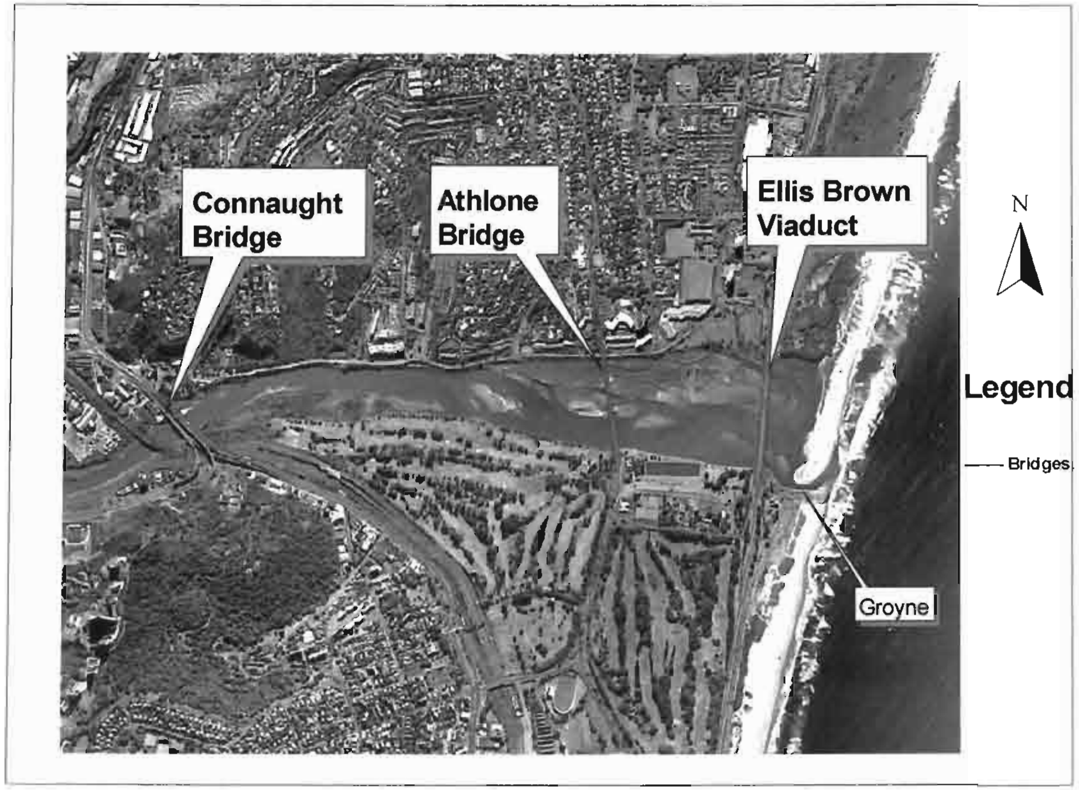


Figure 1.3 (a): A corrected Aerial photo of the study area showing bridges as outstanding benchmarks. Note the braiding network to the North Channel.

Figure 1.3 (b): The Mgeni estuary, looking inland from Athlone Bridge.

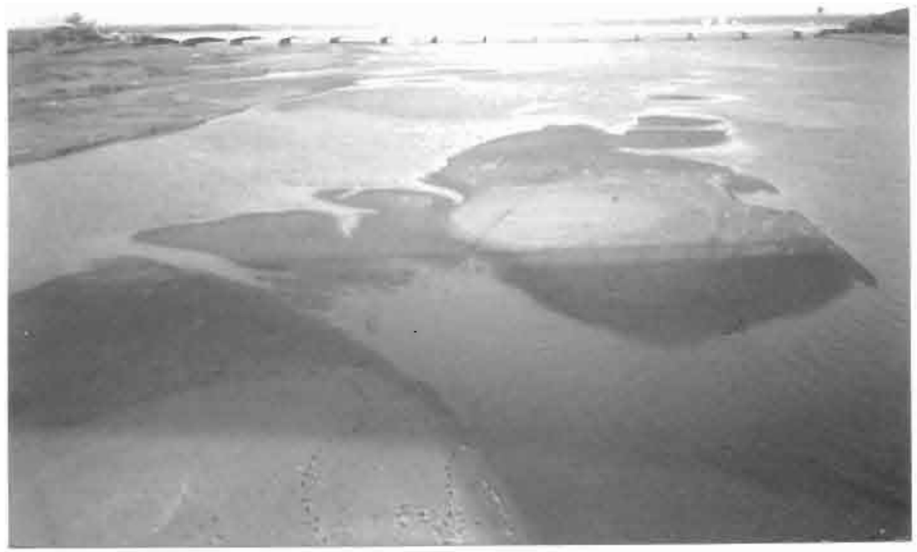


Figure 1.3 (c): The Mgeni estuary seaward from Athlone Bridge

1.3.2 Climate

The study area falls within the regional climatic type of KwaZulu-Natal, which has been described as subtropical with a warm wet summer and a cool dry winter (Badenhorst and Cooper, 1989; Preston-Whyte and Tyson, 2000). Though average annual rainfall is estimated between 900-1000mm with 80% of the rainfall in summer (Cooper, 1993; Tyson, 1987), occasional extremes sometimes result in seasonal flood events especially in summer months. Combined with the steep and dissected hinterland, these floods scour the channel and alter sediment patterns in the Mgeni estuary. Figure 1.4 presents the mean monthly rainfall of four selected stations on the lower catchment below the Inanda dam from 1989 to 1999. Of the ten rainfall stations on the catchment, the four were selected because they are currently operational while the rest closed between 1960 and 1990. Graphs for the four operating stations indicates that October to February is the period with the highest rainfall values and thus the likelihood of being the highest period of flow or even possibly minor flood events which erode and transport sediment to and even out of the estuary.

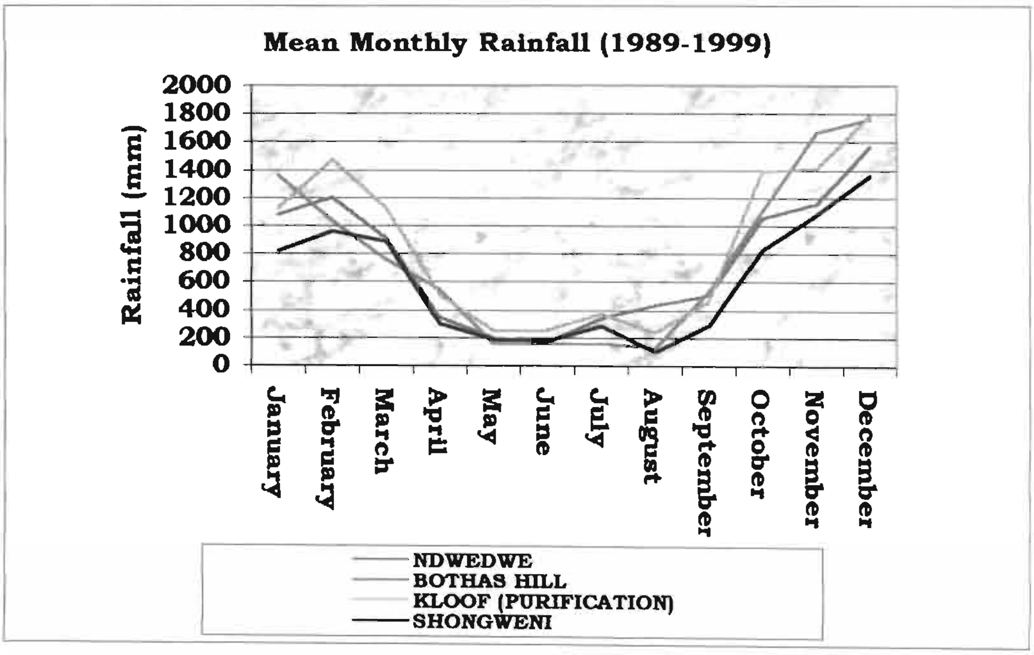


Figure 1.4: Mean monthly rainfall of four selected stations on the lower catchment of the Mgeni River
(Source: Computer Centre for Water Resources, 2001).

A table and graphs showing the average monthly rainfall for the four stations from 1989 to 1999 are found in Appendix 1.1 and 1.2. This rainfall information leads to the reasonable conclusion that except for the periodic regulation of downstream discharge by the upstream dam officials, spring-summer months are responsible for any channel erosion, scouring, transport and deposition of sediment within the Mgeni system.

1.3.3 Geology of the study area

Cooper, (1993) describes the upper catchment geology as fine grained sedimentary rocks intruded by dolerites which give place to deeply weathered proterozoic granite-metamorphic schist, metamorphic Natal Group Sandstone and a gneiss complex in the centre (Scogings, 1997). However from the digitised geological map of the Mgeni catchment (Figure 1.5), the lower section corresponding to the study area reveal that the channel is dominated by alluvium and flanked by resistant diamicite and shale (Dwyka Tillite) which outcrops on the north bank around Connaught Bridge, about 2.4km inland from the estuarine mouth. The southern seaward section and the geological bed formation of the river itself are of Ecca formation (siltstone) flanked at the mouth by unconsolidated sediments – beach sand (Callow, 1994; Cooper, 1987; Whitmore et al, 1999). A detailed geology of the Mgeni catchment is presented in Figure 1.5.

THE GEOLOGY OF THE LOWER MGENI CATCHMENT

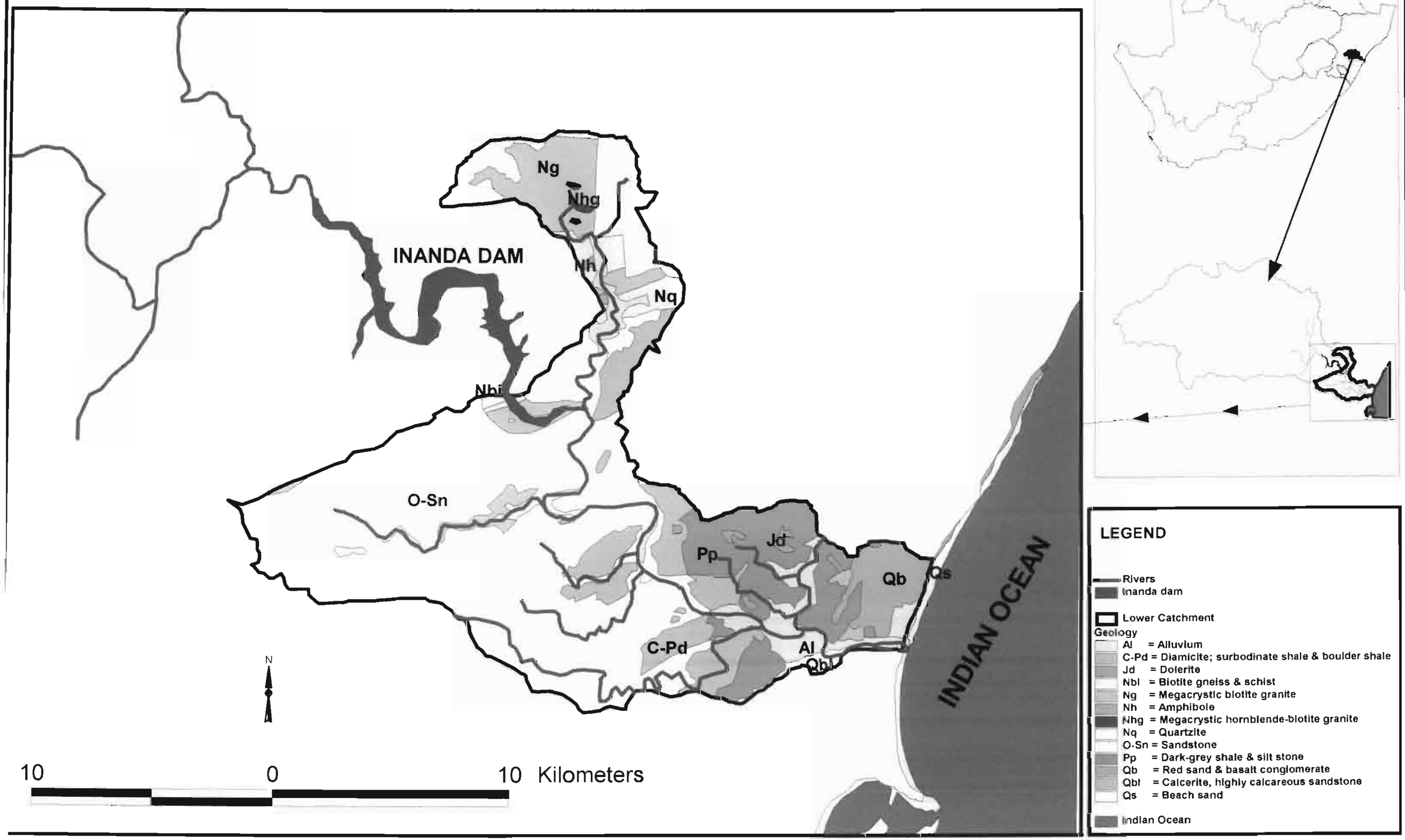


Figure 1.5: Digitised Geology of the Lower Mgeni Catchment (Source 1:250 000 Geological Series, Durban)

Though hemmed by this geological setting, which is a major clue to the provenance of sediment types and mineralogy at the estuary (not part of this study), Cooper (1987) acknowledges that the greatest volume of the estuarine sediment is dominated by quartz and feldspar (Badenhorst and Cooper, 1989) and are derived from the deeply weathered megacrystic granite found at the valley of the Thousand Hills approximately 30-32km upstream from the Mgeni mouth (Figure 1.2).

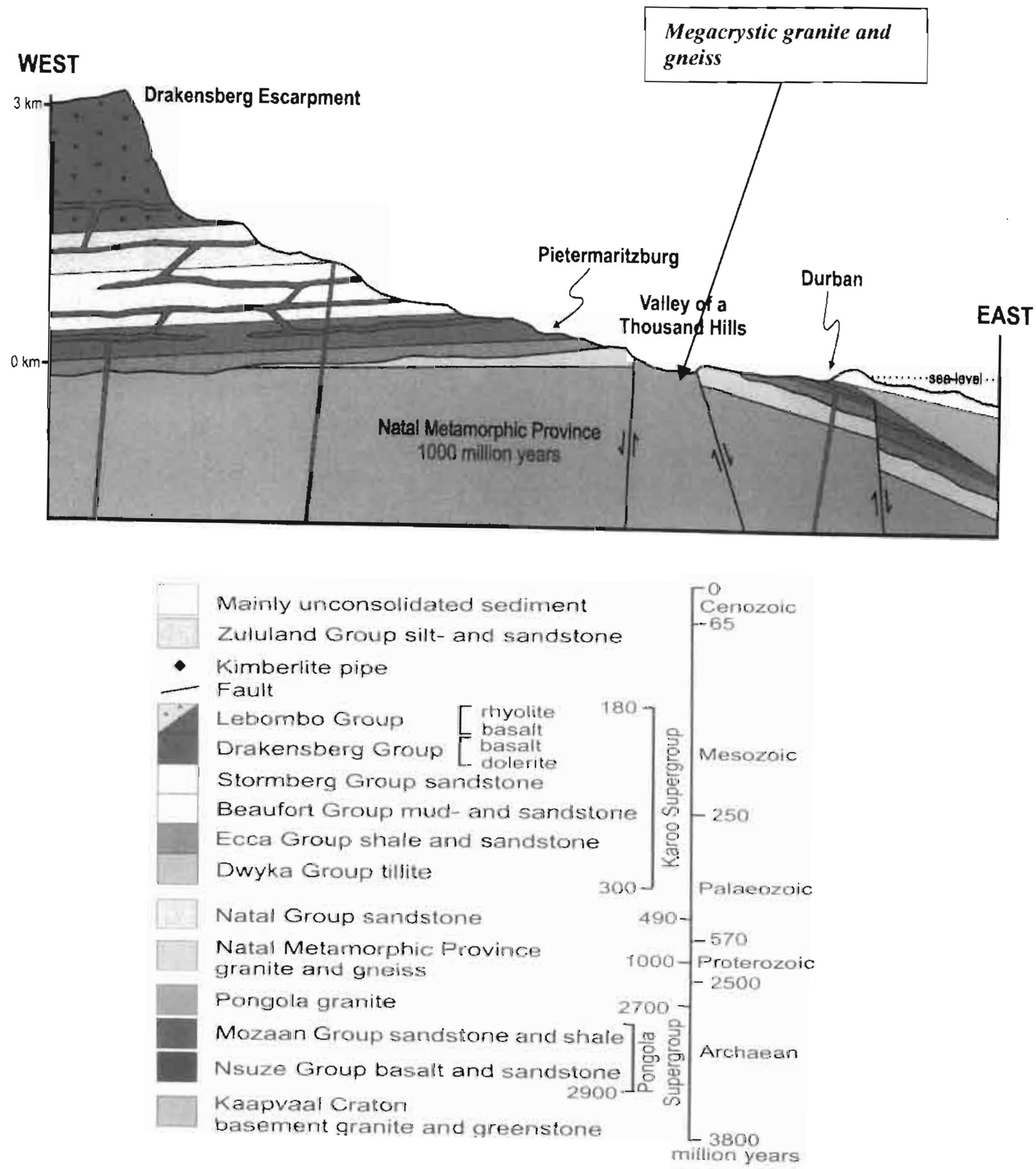


Figure 1.6: A cross-section of the Mgeni geology from the Drakensberg to the Indian Ocean (Source Whitmore et al 1999). Note the Valley of the Thousand Hills where most sediment in the Mgeni emanates

The Natal metamorphic province in Figure 1.6 is made up of granite and gneiss (Whitmore et al. 1999). Since part of this area is found below the Dam and assuming that there has been no change in the lower catchment weathering processes, it would be reasonable to conclude that sediment provenance in the estuary is still partly from the same source noted by Whitmore et al (1999). (The determination of sediment mineralogy and sources is not the part of this study).

1.3.4 Hydrology of the study area

Though the Mgeni catchment occupies a wider area, only the lower catchment below the Inanda dam estimated at 395 km^2 (Archibald et al, 1990; Cooper, 1993) is the target area for this study. This is the case because the drainage networks upstream above the dam empty into the dam itself and is regulated by the dam management through downstream flow release. Thus the hydrological network of the study area is made up of the Mgeni River below the dam as the third order stream following Strahler's method of stream ordering (Gordon et al, 1992; David, 1992), while its lower four tributaries (Moleko, 1997) and numerous smaller river networks are of second and first orders. It was necessary to review this hydrological setting because Moleko (1997) maintained that the four tributaries above the Connaught Bridge inland, namely the Palmiet, Aller, Molweni and Mzinyati, contribute sediment load into the main channel. This hydrological network is also presented in Figure 1.2.

1.4 Statement of The Problem

Since the inception of dam in 1984 to its completion in 1989, there has been growing concern about the effect of the impoundment on downstream discharge and sediment characteristics and distribution as well as on the habitat of estuarine biodiversity at the river's mouth to the Indian Ocean. This prompted a number of researchers, notably Cooper (1993) and Moleko (1997), to investigate and report on the fluvial geomorphology, sediment characteristics and distribution in the Mgeni River below the Inanda dam. Moleko (1997) identified a higher, more competent post-dam discharge, which would be capable of transporting sediment into the estuary and flushing out the estuarine sediment into the sea and thus altering the morphology of the estuarine channel. He showed that the estuary was dominated by sand with low mud and gravel fractions, the opposite of the pre-dam situation where mud and gravel were the dominant fractions in the estuary. Moleko showed that previous pre-dam environmental impact studies by Diab and Scott (1988) predicting silting up of the estuary had at that stage not happened and that the estuary had witnessed no net sediment accretion or erosion, one of the possible reason being stated that the lower tributaries were contributing less sediment into the estuary. He acknowledged the gradual recovery of the riverine and estuarine channel morphology from the 1987 flood. This later aspect corresponds to Cooper's (1993) concept that a channel will undergo a progressive readjustment after a major disturbance. However Moleko (1997) blamed most of morphological changes on the Inanda Dam, which holds coarse sediments and a large volume of water behind its wall. In an attempt to predict the fate of the estuary, he developed a conceptual model of change for the estuary, which included a future scour of sediment in the estuary, a recovery of the central island, site specific erosion and gradual fining of bed-load channel and estuarine. Additionally, since 1997, exceptional rainfall has caused flood discharges to occur on two occasions in 1999 (Mervin, pers. com, 2000). It is believed that this intervening natural event must have affected the estuarine characteristics. The impacts of these natural events, alongside Moleko's conceptual model now merit investigation.

1.5 Aim and Objectives of the Study

The main aim of this study is to investigate downstream changes in the Mgeni river estuary below the Inanda dam with regard to sediments, river flow and channel morphology from 1997 to 2000 and to test Moleko's conceptual model. To achieve this aim, it was necessary to work towards the following objectives:

- Establish present cross-sectional profiles of the river and estuarine channel between Connaught Bridge and Ellis Brown Viaduct.
- Analyse and map the present texture and distribution of sediments, including heavy mineral content in the Mgeni estuary between Connaught Bridge and Ellis Brown Viaduct.
- Explain any changes according to current theories of fluvial and estuarine geomorphology.

1.6 Nature and Hypothesis of the Study

This research is a quantitative, predominantly positivistic work, which deals with the collection, analysis and interpretation of empirical data. It falls under the domain of fluvial and estuarine geomorphology in physical geography and considers the effects of modified river flow on the stream flow, sediment characteristics and distribution, and channel dynamics.

The null hypothesis is that there has been no change in sediment characteristics and channel morphology of the Mgeni River. The investigation of this hypothesis was guided by a number of key research questions including: what has happened to the regime of the flow since 1997? Have sediment characteristics been modified? Has there been any significant change to the river channel profile? Has there been any accumulation of sediment at the estuary?

1.7 Summary

Chapter one has presented a brief historical background of dams in general and particularly of the study area as well as the aims and objectives of the study, providing a sense of direction to this thesis. The proceeding chapters will be structured as follows: Chapter Two is an overall literature review on dam impacts around the world, Three will focus on previous literature on the Mgeni estuary, Four is the methods and techniques employed in this study, Five presents the results of the 2000 findings, Six compares the 2000 and the 1997 results, Seven interprets the resulting changes according to current themes in fluvial geomorphology and Eight concludes with a general appraisal of Moleko's (1997) Model and a possible future trend for the Mgeni system.

CHAPTER TWO
DAMS AND ESTUARIES-A REVIEW OF LITERATURE

2.1 Introduction

To effectively understand post-dam changes below the Inanda dam, it is important to review the world scenario and past case studies of dam impacts on downstream discharge, estuaries and tidal activity. This chapter is dedicated to a literature review on these aspects.

2.2 Downstream Effects of Large Dams on Rivers and River Processes

Studies reveal that the impoundment of a water body by a dam has negative downstream ecological consequences specifically on species habitat, fauna, flora and downstream riparian agriculture (Barrow, 1987; Dixon, 1989; www.irn.org). Past studies have proven that the impoundment of a river detains sediments in the dam, reducing sediment supply downstream and initiating bank scour and down cutting (Barrow, 1978; Binger, 1978; Dixon et al 1989; Mitsch; Gosselink 1993). This can be well understood by considering some fluvial theories and functional equations, which enhances better understanding of dam impacts on hydraulic and channel geometry. Some of these theories, frequently mentioned in hydrological literature are the Manning Equation and stream power (Gordon et al, 1992; Maidment 1992; Mitsch and Gosselink, 1993; Morgan, 1995; Morisawa, 1968; White, 1984). They associate the rate of streambed, bank erosion as well as sediment entrainment and transport with stream velocity, volume of discharge, channel slope, roughness and hydraulic slope. The Manning Equation states that velocity is directly proportional to hydraulic radius and the channel slope but inversely proportional to channel roughness. It further states that discharge is directly proportional to cross-sectional area of a stream, its hydraulic radius and the channel slope but inversely proportional to channel roughness. Equation wise:

$$V = \frac{1}{n} R^{2/3} S^{1/2}$$

Or

$$Q = \frac{1}{n} A R^{2/3} S^{1/2}$$

Where V = Mean channel velocity (m sec^{-1})

Q = Discharge (m^3 sec^{-1})

R = Hydraulic radius (m)

S = Slope of the energy line or channel slope

A = Cross-sectional area of stream

n = Manning's coefficient of roughness or roughness factor. It varies between 0.02 for straight earth canals and 0.112 for very sluggish streams with high vegetation growth.

Note: Values for n are found in Mitsch and Gosselink (1993) & Morisawa (1968).

The importance of understanding this equation lies in the fact that the reduction of water depth and wetted perimeter (factors of hydraulic radius) as a result of water retention by a dam will definitely affect velocity as suggested by the equation. Flow reduction in the formal channel will effectively reduce the cross-sectional area. These prevailing conditions are compounded where an estuary is situated in an area of reduced channel gradient (slope) with increased roughness marked by the presence of sand bars, in-channel and marginal vegetation, variation in discharge as well as any channel irregularity. One would therefore expect a high frictional drag, reduced stream competence (ability of river to entrain and transport sediment) at the Mgeni estuary, where some of these factors hold.

However some authors stress that the effectiveness of these factors on downstream channel dynamics further depends on flow quality, bank and bed material type as well as channel configuration and alignment (Gordon, 1992; Hemphill and Brameley, 1989, Hey et al, 1982; Thorne, 1998). In relation to flow quality for example, it has been established that clean water releases devoid of sediment from dams tends to satisfy their "hunger" for sediment load by scouring sediment downstream, causing rapid channel degradation below the dam (Binger, 1978; Laursen, 1958). This was evident during the release of clean water from the Aswam high dam in Egypt in 1964 and from the Hoover, Parker and imperial dams in the US. This implies that for the Mgeni river channel, the release of water by dam officials would initiate some downstream sediment erosion and transportation just below the dam towards the estuary.

While the above is true with the release of clean water from a dam, Binger (1978) maintains that even in steady flow conditions, lateral erosion of the stream bank will undermine and carve off materials above the water line. This phenomenon, known as nick point erosion or undercutting

(Gordon, 1992; Thorne, 1998) was identified during this study at the estuarine channel (Figure 5.11a and b). In addition to these negative impacts, reduced river flow may also lead to the emergence of sand bars and their stabilization either by armouring (Thorne, 1998) or colonization by a protective vegetative cover (Cooper, 1993). This is the case in the Mgeni estuary, where the development of sand bars has gradually been colonized by various vegetation species since the impoundment in 1989. These sand bars adjoining the north bank are probably responsible for the deviation of flow to the south bank leading to bed scour; banks undercut and collapse hence gradual bank-line retreat.

Moreover, bank erosion is also a function of channel turbulence and bank saturation during high flows resulting to sloughing due to excessive pore water pressure (Laursen, 1958). This adds impetus to the understanding of the processes at the Mgeni estuary. For example, previous studies testify to the occurrence of erosion in the estuary during periods of minor or major flood events when discharge and velocity are high. This is supported by Statham (1977) who noted that sediment concentration and transport rate rises with discharge and vice versa, and that rivers sort sediments by transporting material below a threshold grain size, leaving coarser and better sorted material behind. Thus with progress downstream, a decline in grain size is expected. Monkhouse (1965) and Pye (1984) have identified one reason for this as change in slope. Sediment distribution of the Mgeni system as discussed in chapter five support these theories especially at the estuary where the hydraulic gradient is definitely lower than upstream (Cooper, 1987; Cooper, 1993).

2.3 Estuaries

An estuary has been defined "a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water from inland drainage" (Cooper, 1987; Dyer, 1979). Though other definitions exist, (Davis, 1994), this definition is preferred in the context of this study because it underscores the link between inland drainage and the sea, clearly evident at the Mgeni estuary. These extremely dynamic environments constantly change in response to natural and anthropogenic forces affecting the sediment budget. This is especially true when upstream dams impound and decrease the amount of sediments reaching the estuary (French, 1997). Estuarine sedimentation is largely attributed to yields from fluvial catchments, but net bedload and suspended sediments can be directed upstream by high tidal flows unless upset by fluvial flood discharges (Chapel et al, 1994). Based on the dominant source of hydrology, two types of estuaries have been broadly identified, namely tidal and river-dominated estuaries (Cooper, 1993). In the latter form any upstream interference with flow will significantly affect the supply of fresh water and sediment to the estuary. The Mgeni estuary is a river-dominated estuary (Cooper, 1993), which means almost all of its sediment originates from the catchment and its channel and not from the Indian Ocean. An estuary will remain open where the transport of sediments is not sufficient to fill the funnel shaped mouth or where the tidal currents are strong enough for a continuous removal of sediments (Mangel et al, 1990). This is not the case with the Mgeni estuary, which suffers from periodic closure due to the southward progression of long-shore drift against the stabilized southern mouth but also due to inadequate flow to flush sediments from the mouth into the Indian Ocean considering that much of the water is held behind the Inanda dam.

Other ways of classifying an estuary are based on the degree of mixture between saline seawater and inland fresh river water resulting either in a stratified, partially or fully mixed estuary (Cooper, 1987; Davies, 1994; Dyer, 1979; Pye, 1994). It has not been possible to identify in which categories the Mgeni estuary falls as it is not very critical for this study.

2.4 Dams, Tides and Sediment Distribution

Tides have been defined as the periodic rise and fall in the sea level accompanied by tidal current (inflow and outflow) of water onto the coastline or into an outlet (Davis, 1994; Monkhouse, 1965). Various tides have been identified and their ranges documented (French, 1997; Pye, 1994). Monkhouse (1965) notes that the Indian Ocean and thus the Mgeni estuary experiences a semi diurnal tide, with a maximum spring tidal range of 2.6m at Durban and a minimum of about 2m (Cooper, 1987). This situates the estuary and the adjoining coastline between the microtidal and mesotidal estuarine type discussed in Bird (1984), Cooper (1987) and Davies (1964). The semi-diurnal tides identified by Monkhouse (1965) are two high tides and two lows within 24hours: high tide between 0-6hours and 12-18hours, and low tide between 6-12hours and 18-24hours. This phenomenon was observed and photographed on the 8th of September 2000 in the study area as represented in Figure 2.2 (a) and (b) below.

Figure 2.2 (a) The Mgeni estuary at high tide (b) The Mgeni estuary at low tide

(Source: Researcher, September 2000)

As these tides flood into an estuarine channel (flood tide) or ebb down the channel into the sea (ebb tide) during a tidal cycle, they produce currents which transport sediments into and out of the estuary - a process referred to by Bowman (1988) as "sediment flux". The result is an alteration of the estuarine fresh water composition and at times scours the estuary mouth (Bird, 1984; Davis, 1994). Monkhouse (1965) indicates that a tidal scour may be experienced at the mouth of a bottlenecked estuary. However this is not the case with the Mgeni estuary because of engineered protection, except northward from the groyne (Cooper, 1987). Nevertheless channel migration (Bruun, 1978) caused by ebb tidal current is a frequent phenomenon in the estuary. In normal situations where a river is unregulated by an upstream dam, fluvial discharge pushes back tidal advance, limiting the effect of tides on an estuary (Chapel et al, 1994). The upstream existence of a dam considerably reduces flow, leading to the advance of tidal prism over a greater distance with a greater effect of saline water in the estuarine system. The incoming flood tidal currents from the sea bring along both bed load and suspended sediments, which meet with fluvial sediments, which fill estuaries. This explains why estuaries have been referred to as sediment sinks (Davis, 1994; Pethick, 1984). Mud is transported in estuaries as suspended load, and sand as bedload in the process of rolling or saltation (Knighton, 1984; Monkhouse, 1965; Morgan and Briggs 1977; Sparks 1989). However, in low-energy estuaries with sluggish currents, fine sediments accumulate letting only a fraction out during ebb tides. This flood-ebb movement results in the re-circulation of sediments effectively limiting the inland penetration of sea-derived sand, leading to the gradation of grain size from coarse sand near the mouth, silt in the middle and mud at the upper inland end of the estuary. Remarkable during flood and ebb tide are turbidity movements and the redistribution of mud in an estuary, with a notable area of deposition and accretion being intertidal mud flats (Pethick, 1984).

Though tidal response to the upstream Inanda dam was not included in this study because it is considered a subject for further investigation in a full thesis, it is probable that the effect of tides is now greater in the estuary than before the dam.

2.5 Summary

An overview of the above literature sheds light on a number of aspects, notably the effects of reduced river flow on downstream processes, estuaries, tidal response to dam constructions and their combined effect on sediment distribution in an estuary. This provides a background for understanding the expected changes in the Mgeni estuary as it continues to respond to the upstream Inanda dam.

CHAPTER THREE

THE MGENI ESTUARY- AN OVERVIEW OF PREVIOUS STUDIES.

3.1 Introduction

The Mgeni estuary is situated on a wave dominated east coast of South Africa and occupies narrow bedrock confined alluvial valley. Though a river dominated estuary (Cooper, 1993), it is partially blocked at its outlet by an elongated sand barrier. On the south bank of the Mgeni River outlet is a groyne protecting the outlet against wave action and interrupting the deposition of longshore drift transported by the north-bound longshore current. This reduces the chances of the outlet closing permanently. Prior to the construction of the Inanda Dam located upstream of the river, the estuary was permanently open, with water flushing in and out. The dam held back large quantities of water transforming the estuary to a temporarily open-closed estuary (Whitfield, 2000). The occasional temporal blockage of the estuarine mouth is blamed on the reduction of water volume reaching the estuary (due to retention by the upstream dam) and on the progressive elongation of the barrier at its mouth, prompting its re-opening by officials of Durban Cooperation (Archibald et al. 1990; Eric, 2001, pers. com).

3.2 Previous Work on the Mgeni Estuary and Gaps in Research

Long before the construction of the Inanda Dam till the present, the lower Mgeni catchment area and the Mgeni estuary has and continues to be a point of focus to researchers. Begg (1978, 1984) wrote on the ecology of estuaries of KwaZulu-Natal. However, these studies were prior to the construction of the Inanda Dam. The proposal to construct the Dam in the 1980s lured many papers from institutions, researchers and organizations on possible downstream consequences. Nicholson (1984) submitted a crude preliminary report on the possible impact of the Inanda dam on the estuary emphasizing on the maintenance of the estuarine mouth's configuration. Four years later, this report was criticized by Archibald et al (1988) for perceived flaws. However, the latter dwelt mainly on the dam impact on water quality. This was also the case with subsequent reports (CSIR, 1989, 1990). Though Archibald and others (1990) attempted to predict post-dam estuarine sedimentation, these were merely speculations and recommendations based on simulated sedimentological scenarios. Cooper et al (1989) and Cooper (1987) carried out a survey at the Mgeni estuary but this dealt with the estuarine pre-flood, pre-dam geomorphology, sediment dispersal pattern and the consequences of the 1987 floods at the time when the Inanda dam was still under construction. However, the results of that study are useful are to this study when compared with the post-dam situation. Diab and Scott (1989) forecasted the social and estuarine post-dam impacts and Ninela (2000) is currently investigating social impacts on those displaced by the Inanda dam. Nevertheless, as is evident from the above reports, emphasis has been either on the estuarine status quo or predicting the possible effects of the dam after its construction.

An interesting piece of literature relating to the dam was that of CSIR (1984). Having noted that tidal and fluvial flows flush an estuary mouth while longshore and fluvial sediment transport block estuarine mouths, it was concluded that the effect of a dam on the Mgeni estuary would focus on the estuary mouth. This explains why emphasis on the operating policy of the dam was to maintain the pre-dam hydraulics, which is to keep the estuarine mouth open. To achieve this objective, it was recommended that simulated floods of $25m^3sec^{-1}$ for 48 hours once per month be released from December to April to keep the estuary open and to scour any sediments accumulating in the estuary. Based on the variation rates of monthly evaporation below the dam, lowest between October and April and highest between May and September, it was also recommended that minimum perennial flow rates of $0{,}005m^3sec^{-1}$ from October to April and $0.012m^3sec^{-1}$ from May to September be released among others to maintain an aesthetically pleasing, continuous river flow downstream the dam (CSIR, 1984).

After the dam's construction, the Mgeni catchment geology (Scoring, 1997 and Thompson, 1995) as well as aspects of heavy minerals in Natal estuaries (Callow, 1994) was investigated. However, these works are generalised and make no mention of channel, hydraulic (river flow), sediment and tidal dynamics in the Mgeni estuary. Cooper (1993) commented mostly on the behaviour of river-dominated estuaries using the Mgeni as an example after which he conceptualised a general model of estuarine channel recovery after a major disturbance, for example a flood event. This is subject to further investigation and is not included in this study. CSIR (1992) concluded that due to the impoundment, the estuarine mouth closes at neap tides (low flow or low tide), that the groyne at the mouth would reduce suspended sediment washed into the mouth, that in-channel island formations will maximise freshwater discharge by concentrating flow in deeper channels. The recommendation of this study was for ongoing monitoring – part of what this study seeks to accomplish.

Singh (2001), dealt mostly with modelling stream flow and sediment yield in the lower Mgeni catchment. Hydrologically, he identified a season of "high" flow ranging from 1155 m^3sec^{-1} to 2735 m^3sec^{-1} (April to September) and of "low" flow, 483 m^3sec^{-1} to 1747 m^3sec^{-1} for the remaining months. According to his simulated stream flow results, mean annual volume of flow for the total lower Mgeni catchment is 22 278.5 million m^3 exceeding the annual volume of 18.5

million m^3 required for the functioning of the riverine and estuarine ecology (DWAF, 1990). Singh further maintained that the annual production of sediment in the lower Mgeni sub-catchment is 10 855.1 tons per annum with sediment yield rate of 73.8 $tons/km^{-2}yr^{-1}$. He attributed the presence of silt in the estuary primarily to the likely reduction of stream flow velocity, poor farming practices and other human practices between the Inanda dam and the Mgeni estuary that contribute sediment to the estuary. According to him, the combined effects of these have been the smothering of organisms living under the estuarine bottom, increased turbidity and the development of sand bars across the mouth of the Mgeni. He credited the latter more to decrease in stream flow due to the upstream dam.

Ecologically, Singh maintains that reduction in stream flow would not only increase salinity level in the estuary but would significantly affect the floral and fauna communities of the Mgeni River Park at the upper reach of the estuary and the Beachwood white, red and black mangroves (*Avicennia marina, Rhizophora and Bruguuiera gymnorrhiza*), two ecological niches which are corridors linking the natural areas within Durban. Referring to Preston-Whyte (1991), he indicated that marine species that utilise the estuary for breeding and as nurseries, including fish that are of food and commercial value and birds that feed at the estuary would be affected. However, in his study, he did not include a detail evaluation of channel morphology as well as the flow and sediment dynamics below the dam and at the Mgeni estuary.

Relating to the post-dam period, Moleko (1997) investigated these gaps in previous research and the conclusions reached were that, contrary to the pre-dam predictions, there had been no net estuarine accretion or degradation, that estuarine sediment had been redistributed and that the sediment calibre had become finer since dam closure. However he developed a model of change for the estuary (Section 3.4), which relates to Cooper's model for general channel recovery after a disturbing event (Section 3.3).

3.3 Cooper's Conceptual Model of Post Flood Channel Adjustment.

Cooper, 1993 theorised that during floods, lateral channel confinement promotes vertical erosion of bed material leading to deposition of eroded material as an ephemeral delta in the sea. After floods, the river gradient is restored within a few months through rapid fluvial deposition and formation of a shallow braided channel. Over an extended period (approximately 70 years) the estuarine banks and bars are stabilized by vegetation and mud deposition. Subsequent down cutting in the marginal areas transforms the channel to an anastomosing pattern which presents a stable morphology, adjusting to the normal range of hydrodynamic conditions. In relation to the

Mgeni estuary, Cooper points out that in a river dominated estuary anastomosing like the Mgeni, sedimentary processes follow a cyclical pattern dominated by almost instantaneous flood impacts and long term post channel adjustment as typified in the Figure 3.2.

Figure 3.2A portrays a mature or stable state with cohesive banks and channels in which tidal exchange produces semi-diurnal salinity and water level fluctuation. Flood tidal currents deposit a small flood tidal delta, which is eroded during moderate floods but reforms subsequently. On the other hand ebb tidal deposition is inhibited by wave action while the barrier at the mouth is stable. There is a central island of sand bars stabilized by vegetation and dividing the channel into two. Channel scour is primarily vertical but bedload supply to the coast is minimal.

Figure 3.2B shows a flood episode during which the channel witnesses both vertical and lateral erosion and sediment is flushed out of the estuary destroying the equilibrium. The river mouth is completely eroded and a submerged delta is deposited offshore.

Figure 3.2C is the beginning of post-flood recovery stage during which salinity is re-established in the estuary encouraging the settling of suspended load. The barrier at the mouth begins to form by over washing of the emerged formerly submerged delta and it's progradation by longshore drift. The deposition of fluvial fine-grained sand from upstream causes shallowing and uncohesive sand banks, which promote braiding.

In the long term (Figure 3.2D); braided bars are stabilized with vegetation, which in turn promote intertidal mud deposition. This stabilizes the banks and induces down cutting and deposition on the central sand banks leading to their coalescence into a central island (Figure 3.2E and F). The cycle is completed as the central island and the banks are firmly stabilized leading to a return of the pre- flood conditions as in Figure 3.2A.

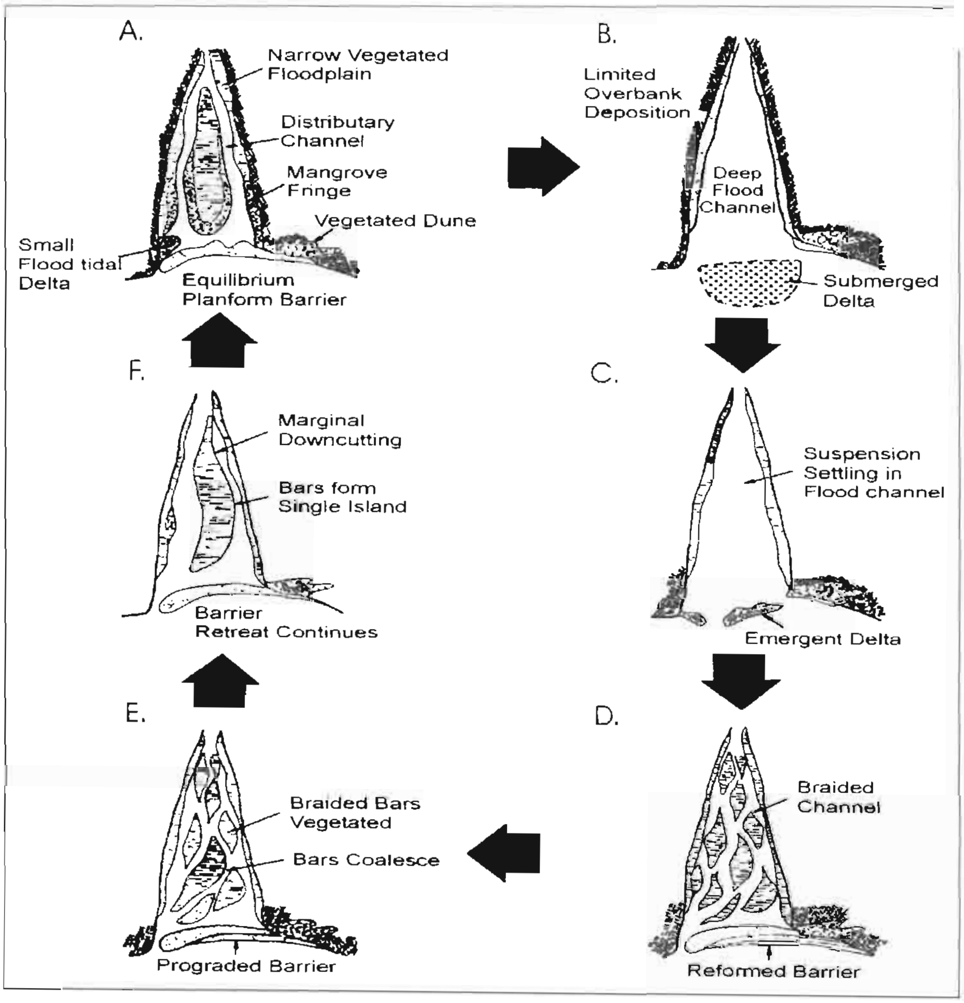


Figure 3.1: Cooper's conceptual model of channel readjustment (Source: Cooper, 1993)

3.4 Moleko's 1997 Model

When a system is disturbed there is a tendency towards equilibrium or recovery (Cooper, 1993; Gordon et al. 1982 and Anderson et al. 1981). Moleko (1997) identified the 1987 floods and the closure of the Inanda Dam in 1989 as two major events that disturbed the Mgeni system. On the basis of this, and together with his own results, he developed a conceptual model of change for the estuary. The main points of this model are:

a) In the future, the channel will scour gradually due to low contribution of sediments from the tributaries and upstream trapping of catchment-derived material assuming a continuous competent discharge.
b) The recovery of the central island is in process.
c) A massive reduction in the quantity of coarse and fine sediments in the estuary will occur.
d) There will be continued flushing of existing channel sediments downstream towards the estuary, without replacement from upstream sources.
e) Site-specific channel bed erosion will occur at times of peak water release.
f) There will be approximate volume equilibrium at the main sediment sink-the estuary-until such a time as sediment stored in the channel has all been flushed through the system.
g) A gradual build up of sediments near the estuary mouth until an exceptionally high discharge event capable of moving material through the opening and out to the sea against tidal and coastal currents occurs.
h) There will be gradual fining of bed-load channel and estuarine sediments due to the retention of coarse sediments in the system behind the Inada Dam, poor coarse sediment contribution from the main tributaries below the dam and continued extraction of this fraction by sand winning activities.
i) If the same water release policy is maintained, then a gradual reduction in fluvial sediment volume of the estuary once channel flushing is completed, in sections near the mouth. This could be balanced to some degree by incoming material transported by tidal and coastal currents.

A summary of the above model is represented in figure 3.2.

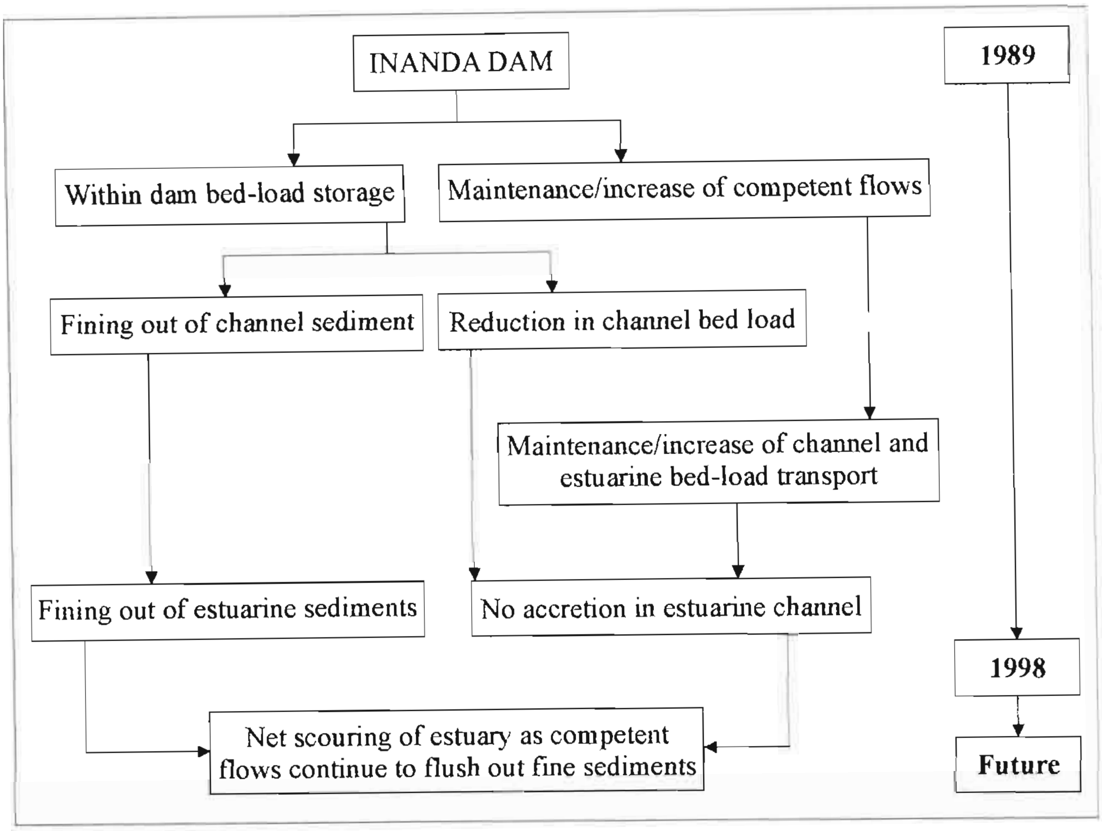


Figure 3.2: Summary of Moleko's Conceptual Model (Source: Moleko, 1997)

Garland and Moleko (2000) noted that steps (a) to (f) were well under way then and that step (g) would begin shortly. In addition to the above model, Cooper (1993) and Moleko (1997) predicted that the channel is marching to a new stage of equilibrium. While Cooper specifically mentions the time and the final form of the equilibrium, Garland and Moleko (2000) rather assert that the time needed for the lower Mgeni to reach final equilibrium with the new controlling variables of sediment fractions, discharge and human influence is unclear, hinting that it is not possible to predict the final equilibrium form of the channel with confidence.

Cooper's conceptual model of general channel recovery and more specifically, Moleko's conceptual model of change for the Mgeni estuary are the benchmarks or key concepts under investigation by this study.

3.5 Summary

This section has drawn attention to Cooper's (1993) and Moleko's (1997) Models which outline a process of change for the Mgeni estuary in response to a flood event and especially to the Inanda dam. The latter, Moleko's Model is key to this study and is the concept to be tested in the light of recent findings.

CHAPTER FOUR

METHODOLOGY AND STUDY TECHNIQUES

4.1 Introduction

A number of techniques were employed to collect and analyse data in relation to sediment, downstream dam discharge and channel morphology. Most of these fall within the framework of empirical quantitative data collection and analysis evoked by the positivistic school of scientific thought (Johnstone, 1983; Robinson, 1998). These include comparative study of 1985-1999 aerial and orthophotos observation, field observation, sediment sampling, channel cross-sectional surveys, laboratory analysis, and interpretation of the results.

4.2 Hydrological Data

Theories of fluvial geomorphology reveal that sediment erosion and transport are partly, a function of discharge (Gordon et al, 1992; Maidment 1992; Mitsch and Gosselink, 1993; Morgan, 1995; Morisawa, 1968; White, 1984). To determine the influence of dam discharge on channel dynamics and sediment transportation and distribution, data on the volume of monthly maximum daily release of water from the Inanda dam, 1998 to 2000 was obtained from the water utility company, Mgeni Water, Pietermaritzburg. Dam discharge was selected as it has been used in previous studies (Cooper, 1984 and 1987; Moleko, 1997) to characterise the hydrology of the Mgeni. From the acquired data, the mean monthly maximum daily discharge, (that is, the daily maximum discharge for each month of the year from 1998 to 2000) was calculated. This has been preferred because it gives a better picture of dam discharge over a number of years, and was used in Moleko's (1997) prior study.

4.3 Bed Sediment Sampling and Analysis

This section describes bedload sediments sampling procedure and laboratory analysis as well as the technique employed in heavy mineral separation.

4.3.1 Sampling procedure

Methods of sampling bed sediments have been described by Gordon et al (1992) and Maidment (1992), and include sampling along a cross section at set intervals and at various reaches following the long profile of a river. Of these sampling methods, pit-type was preferred in this study for its accuracy and relative ease of collection.

Guided by the foregoing literature, sediments at the Mgeni estuary were collected along transects in the estuarine channel. The distance between transects was determined by distance calculations from an orthophoto pre-marked with the 1997 transects positions. Tracing them in the field resulted in a difference in distance between the 1997 and 2000 transects not further than 30m away from the new positions (Figure 4.1). Sample points along these transects were then surveyed using the dumpy level for accuracy of distance apart, which are approximately 5 to 6m. The reasons for sampling close to Moleko's (1997) positions have been to enable a fair comparison between the 1997 and 2000 situation and to determine the nature of change between the said periods. These sampling positions have been mapped using appropriate GIS softwares notably, Atlas GIS and ArcView 3.2a - refer to figure 4.1.

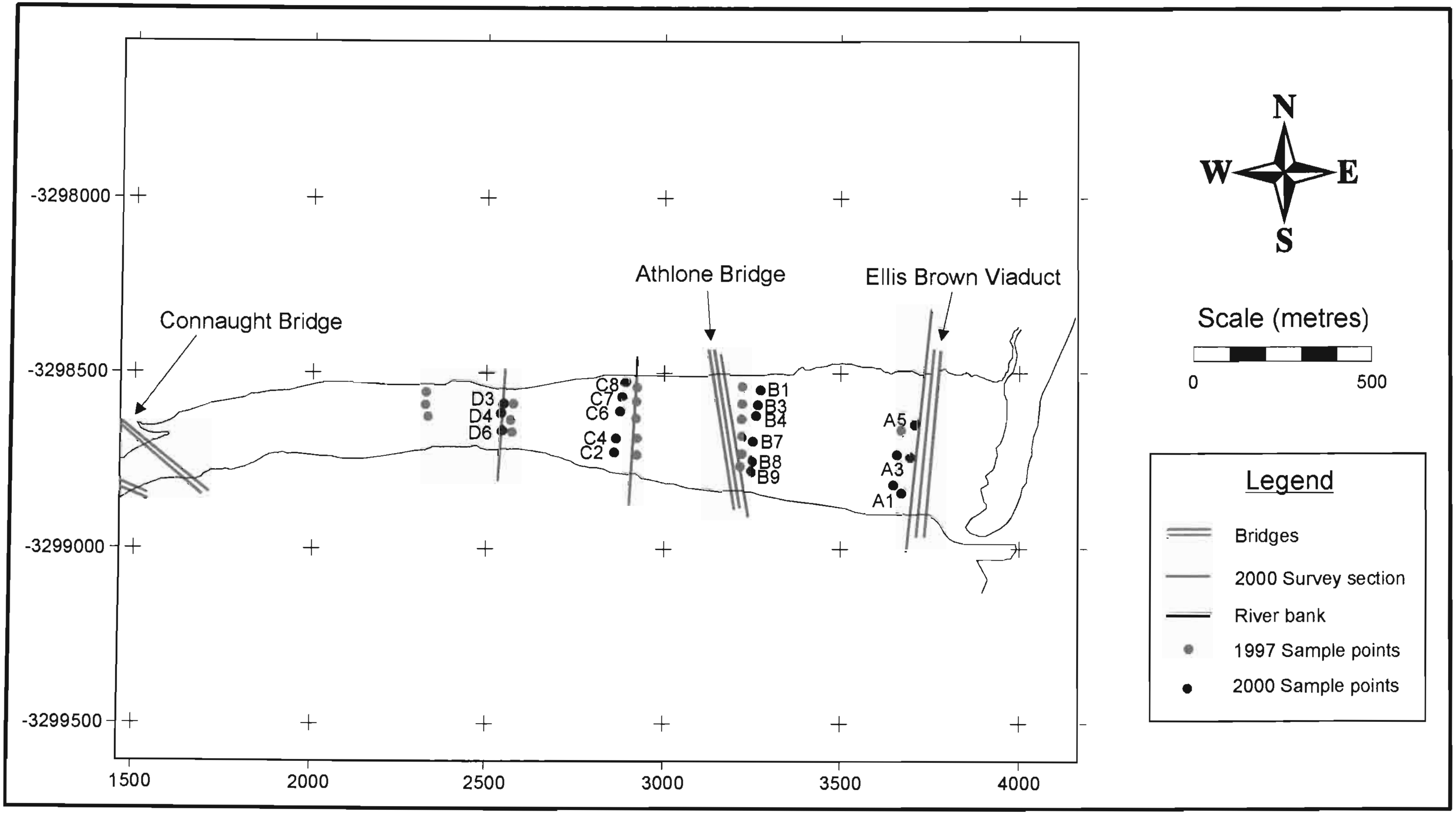


Figure 4.1: Sample Points and Survey Sections from the 2000 Study

4.3.2 Laboratory analysis

In the scientific method, the collection of empirical data is one thing but the laboratory analysis is the other, both of which lead to results and interpretation of the findings. This section presents the laboratory analysis of sediments and their characteristics.

4.3.2.1 Bedload sediment analysis

Analysis of bedload is in the laboratory using selected methods, which include dry sieving, pipette analysis or settling tube analysis and wet sieving (Gordon et al, 1992; Linholm 1987; Morgan and Briggs 1977). Of these sieving methods, dry sieving was chosen for this study because of the great quantity of coarse sediments in the collected samples. First, all samples were air-dried and sieved individually following the standard dry sieving procedure as suggested by Dyer (1986), Gordon et al (1992), Linholm (1987), Morgan and Briggs (1977). Following this procedure, each sample was passed through a stack of sieves and agitated for 10minutes (Mange et al, 1992) over an automatic electric agitator. The topmost sieve for gravel was selected to represent the gravel size of 2mm whiles the last (catching pan) representing the critical mud size was 0.0625mm. Percentages of the total were calculated and the percentage finer than (Dyer, 1986 and Gordon, 1992) was determined for the construction of cumulative particle size distribution curves using the semi-logarithmic graph paper (see Appendix 4.1).

4.3.2.2 Heavy mineral separation

The study of heavy minerals is considered valuable in constructing the structural histories of both the basin and tectonic hinterlands and may contain messages encoded in the assemblages that could help in determining among others, their source, sedimentary transport paths, mapping sedimentary dispersal patterns, correlating sand bodies and locating economic deposits (Mange et al 1992). Even so, this study focuses on determining sediment characteristics and the percentage of heavy minerals in the Mgeni Estuary as one of its objectives. It helps characterise the nature of Mgeni sediments and is hoped that this study will establish the basis for subsequent researchers to further investigate other heavy mineral parameters as indicated above by Mange et al (1992).

Chelin (1998) and Mange (1992) have described the sampling methodology of heavy minerals (not applicable to this study because the minerals were already in the sampled sediments) as well as their process of separation and analysis including laboratory sieving, dense liquid separation and the presentation of results. Because heavy minerals tend to sink in dense liquids (Luepke, 1984) due to their high specific density in comparison to their light counterparts, which remain in suspension, these authors suggest a number of dense liquids to be used for heavy mineral separation. Of all the dense liquids, bromoform (tribromoethane) was used due to its effectiveness. Many chemicals have been suggested for washing the bromoform off the heavy minerals after separation (Mange et al. 1992). However, acetone, which is frequently used because of its low toxicity, was the preferred washing liquid for the heavy minerals in this study.

For the Mgeni estuary, the technique employed was a combination of the standard heavy liquid fractionation using the gravity settling method as described by Chelin (1998) and Mange et al (1992). The Centrifuge method was not used since the resultant frequencies of individual heavy minerals are the same when any of the two methods are used and the more so as the equipment for centrifuging was not available. Of the two types of gravity settling methods, the pipette method was preferred over the funnel separating method due to its accuracy and safety from the health risk presented by the dense liquid, bromoform. According to the procedure outlined by Chelin (1998), a sediment quantity of about 50 g was poured into a separating Adrian pipette containing about 200 ml of bromoform. This mixture was then agitated by hand-shaking and left on a retort stand for the heavy minerals to settle for 3-5 minutes, after which they were released, washed with acetone and dried in the oven at a temperature of 110^{0}c. Each sample was then weighed and their percentages in each sediment sample were calculated (Appendix 4.4). The results were analysed and mapped in micro-soft excel and ArcView GIS (Figure 5.8, 5.9 and 5.10 a and b).

4.4 Statistical Analysis of Sediment Grain Sizes

The analyses of particle size distributions are commonly used for both descriptive and inferential purposes (Morgan and Briggs 1977). They involve the calculation of diagnostic values, known as size parameters and include measures of central tendency, namely the mean, mode and median (Dyer, 1986; Friedman et al, 1978; Pethick, 1984; Selley 2000; Leeder 1982).

The mean particle size is the best measure of average grain size (Tucker 1988) and a much superior estimator of the whole distribution than either the mode or the median (Leeder, 1982). The median was determined directly from the percentage finer than curves by taking the value of the Phi (mesh or particle size) for each sample intersected by 50% cumulative percentage finer than. It is a good indicator of where half of the sediment particle size classes in an estuary or river are either finer or coarser than that particle size. The percentage finer than has been recommended over the simple calculation of sediment size percentage in each sample (Dyer, 1986; Gordon et al 1992, Morgan and Briggs 1977). The advantage is that it facilitates better comparisons between different samples and in determining the median from the 50th percentile. Using the percentage finer than results, graphs were constructed (Appendix 4.1) from which the median particle for each sample was determined and compared with those of 1997 to identify and map changes in median size sediment distribution. To achieve this objective, the 2000 median grain size results were tested against the 1997 median sizes using the Chi-square test and the Student t test, confirming the null hypothesis (section 1.6).

The value of the most frequently occurring particle size is the mode and is situated at the peak of a simple frequency curve (Leeder, 1982; Lindholm 1987; Morgan and Briggs 1977; Tucker 1988). The modal grain size for each sample was obtained by extracting the particle size with the highest percentage on a distribution table and for the entire estuary by averaging these grain sizes with the highest percentage frequency. Measures of dispersion like skewness, sorting and kurtosis were calculated from cumulative percentage finer than curves using the method outlined in Morgan and Briggs (1977) and also discussed by Dyer (1986), Friedman et al (1978), Leeder (1982), Pethick (1984) and Selley (2000).

For the Mgeni, preference was given to Morgan and Briggs' (1977) conventions due to their usage of a greater number of percentiles for accuracy. Their equations for the parameters are:

$$\textbf{Skewness} = \frac{\phi84 - \phi50}{\phi84 - \phi16} - \frac{\phi50 - \phi10}{\phi90 - \phi10}$$

$$\textbf{Sorting} = \frac{\phi90 + \phi80 + \phi70 - \phi30 - \phi20 - \phi10}{5.3}$$

$$\textbf{Kurtosis} = \frac{\phi90 - \phi10}{1.9(\phi75 - \phi25)}$$

Where, $\phi10, \phi25, etc$ = phi or grain size at 10, 25 percentiles etc.

1.9 and 5.3 = Constants

(Source: Morgan and Briggs, 1977)

In determining the above parameters, averages of each grain size category (gravel, sand and mud) were calculated section by section. Skewness measures the symmetry or asymmetry of a distribution, alternately the tendency of all the grains to belong to one class of particle size (Leeder 1982, Selley 2000). As for sorting or standard deviation this refers to the spread of values around the mean and effectively measures the degree of scatter or uniformity of particle size distribution. Kurtosis is the measure of peakedness of grain size distribution and is related to both sorting and normality or non-normality of the distribution (Dyer, 1986; Morgan and Briggs 1977; Tucker 1988)

4.5 Channel Cross Sections

Data for constructing the 2000 cross-sectional profiles at various channel reaches was obtained from SRK Consulting (Engineers and Scientists). A comparison of their survey sections with Moleko's (1997) led to the selection of those closest to the 1997 profiles. Except for section B (Figure 5.2) - about 95m apart, the selected profiles were never further than 35m displaced from Moleko's (1997) originals. Using ArcView GIS software, the actual coordinates of each section endpoints were determined (Appendix 4.2 and 4.3 presents details of the cross-sectional end points and their coordinates). Survey values within the end points were recalibrated to start with zero so as to match the 1997 data. It was then possible to construct graphs of the 2000 channel cross-sections (Figure 5.2). These graphs have been used to compare the morphology of channel form between 1997 and 2000 (Figure 5.15a-d). To determine the quantity of sediment changes, the profiles were converted to JPEG format in Micro-soft Photo Editor and exported to MapInfo Professional where they were georeferenced and digitised as polygons for determining the approximate loss of sediments in square meters. Using the last end point for the 2000 profile and the corresponding 1997 profile end point to close the polygons resulted in excluding some portions of the 1997 cross section, which were longer than the 2000 end point. This discrepancy results from the channel configuration, which is narrower along the 2000 cross sectional profiles and probably because the 1997 sections were not entirely perpendicular to the river course, thus an apparent increase in profile lengths.

4.6 Maps and Graphics

Maps and graphics have been employed as visual representation of some aspects and findings related to the Mgeni estuary. To achieve this objective, various software packages have been used. These include ArcView 3.2a, ER Mapper, Atlas GIS and MapInfo Professional. Most graphs portraying some of the results have been plotted in Microsoft excel.

4.7 Bank Erosion

Evidence of bank erosion at the Mgeni estuary was obtained through sequential observation. comparison and interpretation of the 1985, 1997 and 1999 aerial photographs. This was accompanied by repeated physical observation of the estuarine bank from 2000 to 2001.

4.8 Summary

This chapter has described the methods and techniques in the field, in the laboratory and on desktop. These include sampling, laboratory and statistical analysis, cross-sectional survey, the production of graphics and maps using specialised computer programmes, field as well as aerial photos observation and interpretation. Together these have produced the results that are presented in Chapter Five.

CHAPTER FIVE

RESULTS OF THE 2000 INVESTIGATION

5.1 Introduction

This section contains the results of the 2000 study in relation to sediment characteristics and distribution, channel form, hydrological flow and tidal flux.

5.2 Hydrological Flow

The daily release of water from the Inanda dam by the dam management and the contribution from tributaries below the dam has an impact on the stream competence to erode and carry load. Discharge statistics obtained from the water utility company, Umgeni Water. Pietermaritzburg for 1998-2000 (Table 5.1) has been graphically presented (Figure 5.1) to shed light on flows and discharge dynamics over the years.

Table 5.1: Monthly maximum daily average flow rate (m^3 sec^{-1})

Month	1998 - 2000
January	21.5
February	27.7
March	19.5
April	15.1
May	6.0
June	2.4
July	2.2
August	1.5
September	1.6
October	1.4
November	3.8
December	16.5

(Data source: Umgeni Water 2001)

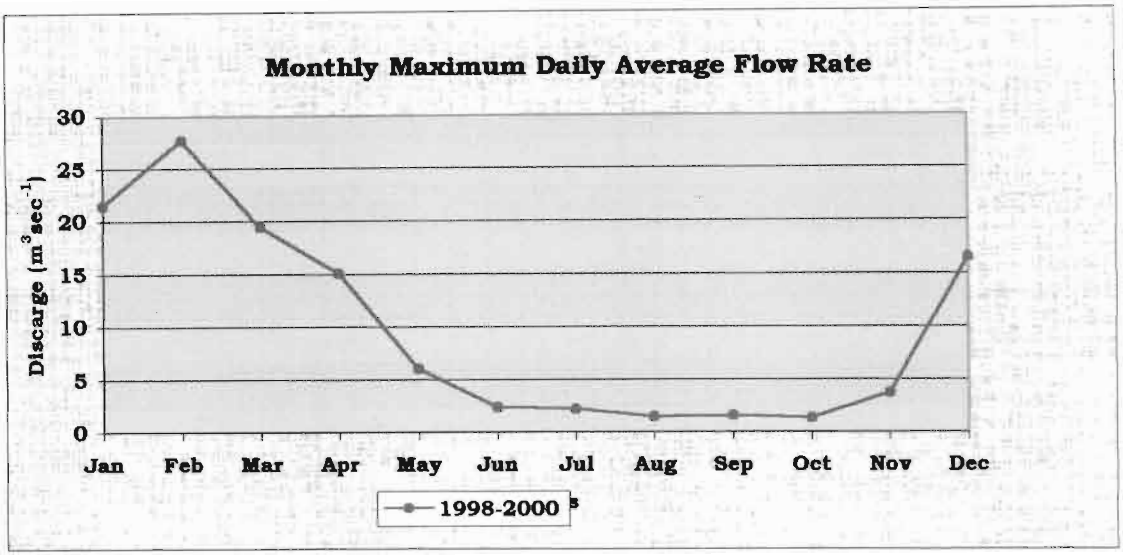


Figure 5.1: Monthly maximum average daily rates of the lower Mgeni River, 1998-2000 (Data source: Umgeni Water 2001)

The above hydrograph from 1998-2000 shows that the summer month of February is the period with peak discharge of water below the dam (27 m^3sec^{-1}), followed by January, March, December and April ranging approximately between 16 and 21m^3sec^{-1}. May to November witnessed the lowest discharge ranging from 1.5 to 6.5 m^3sec^{-1}. This flow record seems to conform to the pattern of rainfall in the lower Mgeni catchment as presented in Appendices1.1 and 1.2, portraying mean monthly rainfall for four stations in the lower Mgeni catchment. To this can be added base flow (Gordon et al, 1992), which during the filling of the dam in 1989, was estimated at 2m^3sec^{-1} to 4m^3sec^{-1} below the dam (CSIR, 1992). The discharge data suggest that sediment erosion; transport and deposition downstream at the estuary are higher during summer and lower during winter. However this strongly depends on the critical stream power or shear stress capable of entraining and transporting sediments to the Mgeni estuary.

5.3 Channel Cross Section

The present channel geometry was determined by constructing profiles of the 2000 cross-sectional survey data acquired from SRK Consulting (Engineers and Scientists) using the Micro-Soft Excel programme and corrected in Corel Draw. Together with the insert indicating the 2000 survey sections, these profiles, (Figure 5.2) relates to a stretch of the estuary between Ellis Brown Viaduct and approximately 1200m upstream from Athlone Bridge.

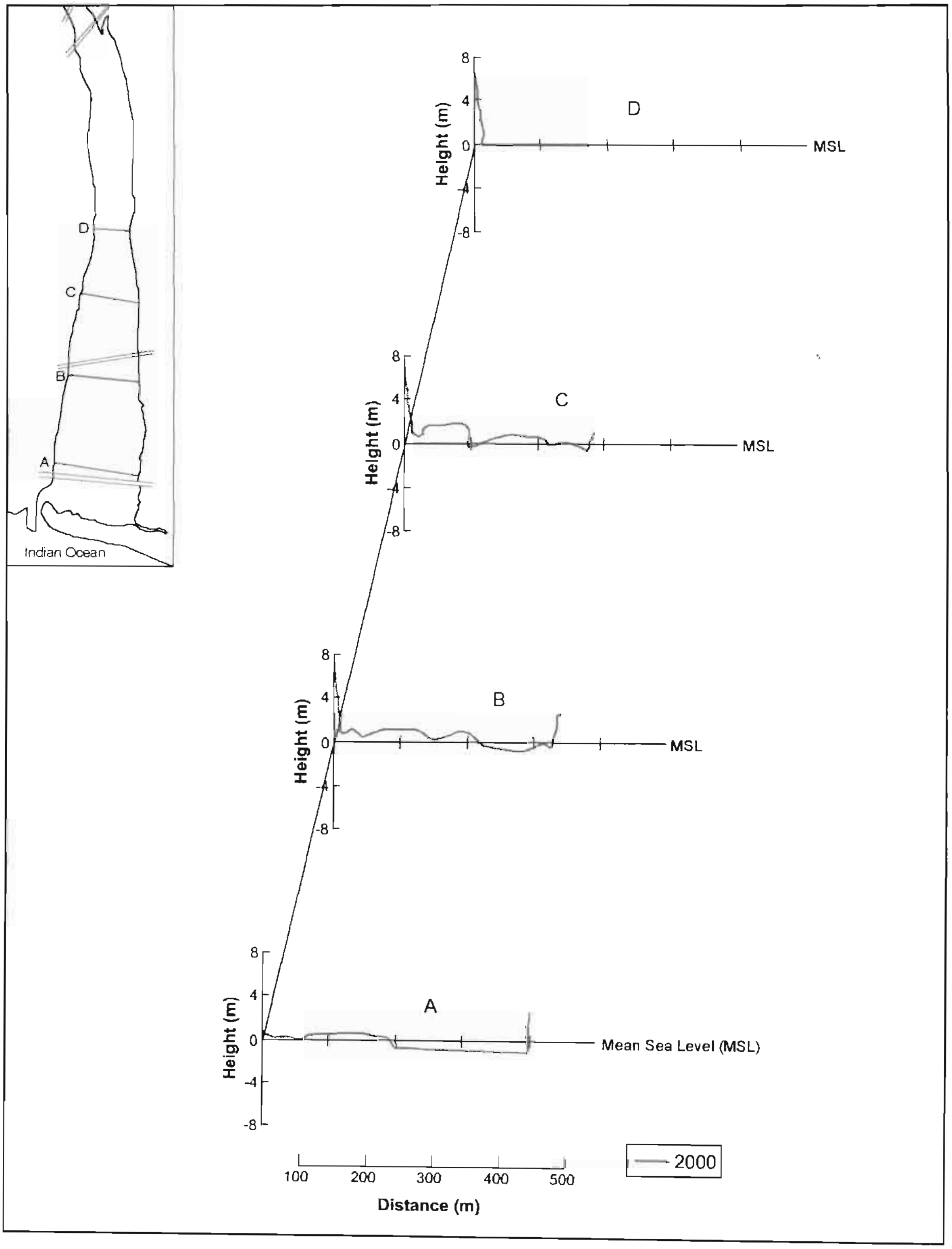


Figure 5.2: 2000 channel cross-sectional profiles
(Data source: SKR Consulting (Engineers and Scientists))

The profiles are located at depths fluctuating from about <1 m to 3.7 m below mean tide level, with the maximum being about 3.7 m south of Athlone Bridge on the south bank.

5.4 Sediment Characteristics

Sediment characteristics refer to particle grain size distribution, parametric measures (skewness, sorting, kurtosis) of sediments and the mineral characteristics of sediment in the Mgeni estuary.

5.4.1 Particle size distribution

Particle size distribution in a river is proportional to stream competence, velocity, and roughness; and to channel gradient (Cooke at al, 1977; Gordon et al, 1992; Maidment, 1992; Mitsch and Gosselink, 1993; Morgan, 1995). For the Mgeni estuary, this implies that coarser particles would be found where the river velocity is high enough and capable of transporting larger grain size particles as opposed to areas of low velocity, dominated by fine grain sediments. Moreover, mapping the distribution of particle size in the estuary provides a basis for understanding estuarine current movement, tidal fluctuations and sediment migration and redistribution over the years (Bruun, 1978). This corresponds to one of the objectives of this study, to determine sediment dynamics in the estuary and to verify Moleko's (1997) hypothesis that there will be a gradual fining of sediment in the estuary due to the impoundment of coarse sediment in the upstream dam. To test this concept, the percentage fraction for mud, sand and gravel or grain size classes of each sample was mapped in ArcView GIS using a grid spatial resolution of 5m and the results are presented in Figures 5.3 (a) to (c).

The distribution of gravel in the estuary (Figure 5.3a) indicates that the gravel fraction, which contributes 5-10% of sediments, is found in the middle reaches at about 53 m and 300 m south and north of Athlone Bridge respectively. Sand dominates (90-100%) the upper reaches, occupies 60–90% of the middle reaches especially to the south bank and 55-60% of a small patch just north of Ellis Brown Viaduct (Figure 5.3b). Mud (Figure 5.3c) occupies approximately 10-45% of the channel's north bank between Ellis Brown Viaduct and Athlone Bridge and a portion of the south bank as well as a small portion north of Athlone Bridge adjacent to the north bank.

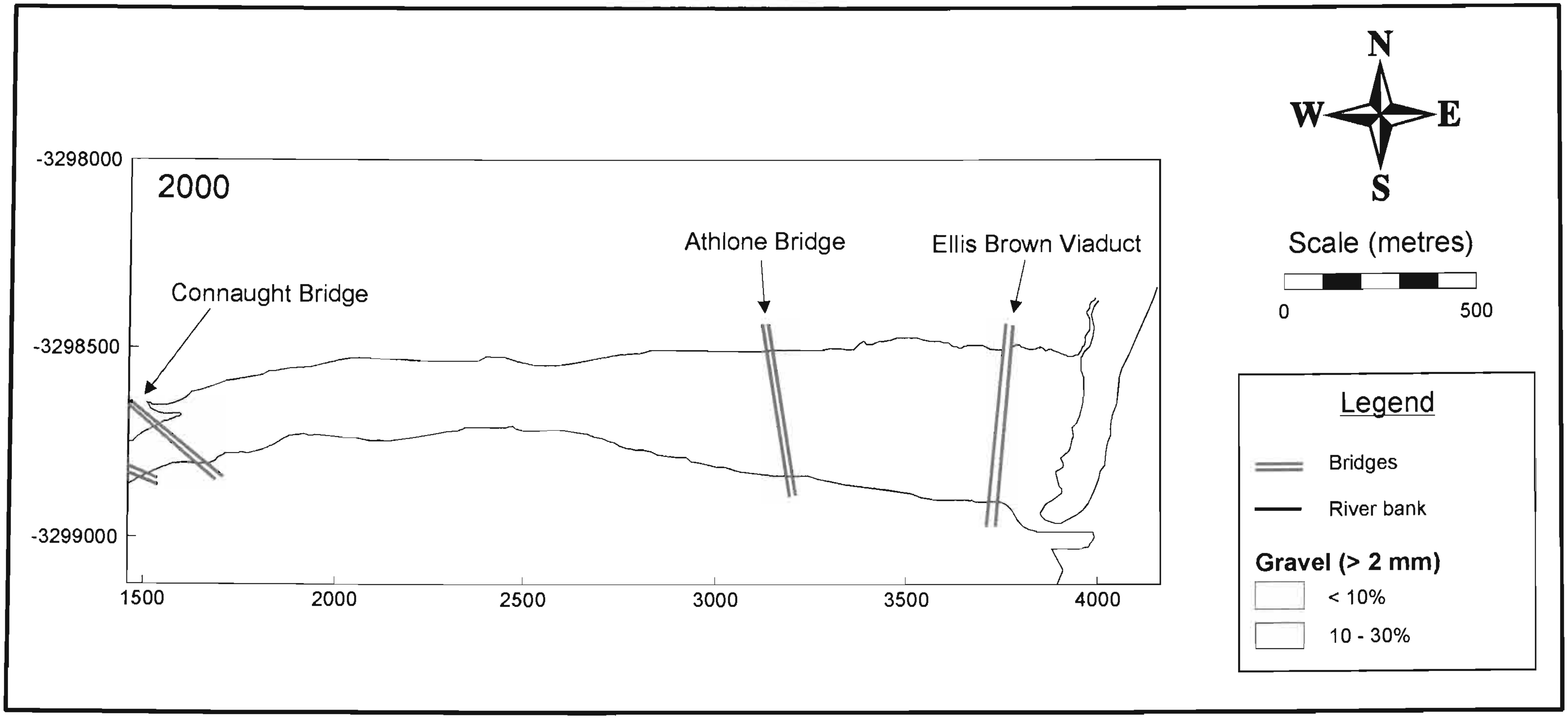


Figure 5.3(a): The distribution of gravel in the Mgeni estuary, 2000.

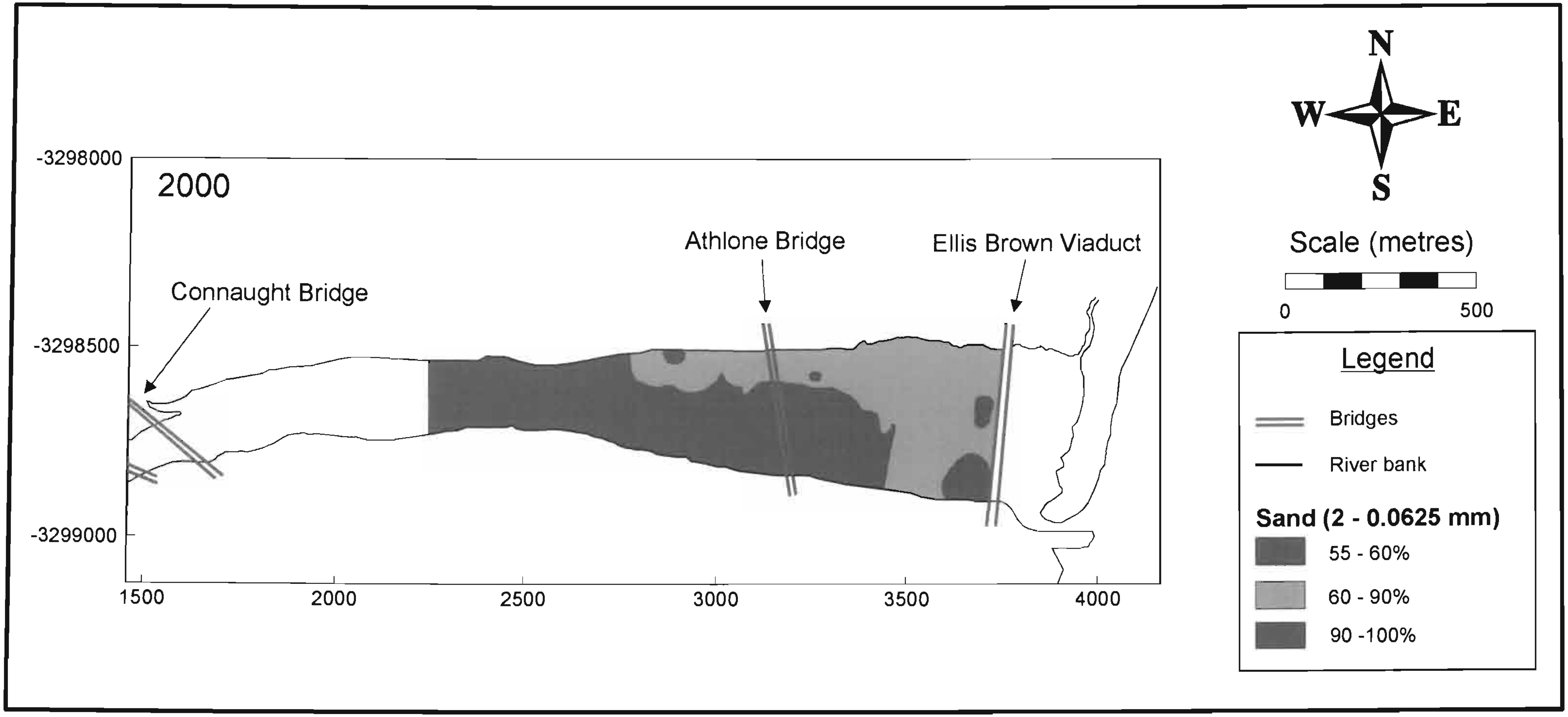


Figure 5.3(b): The distribution of sand in the Mgeni estuary, 2000.

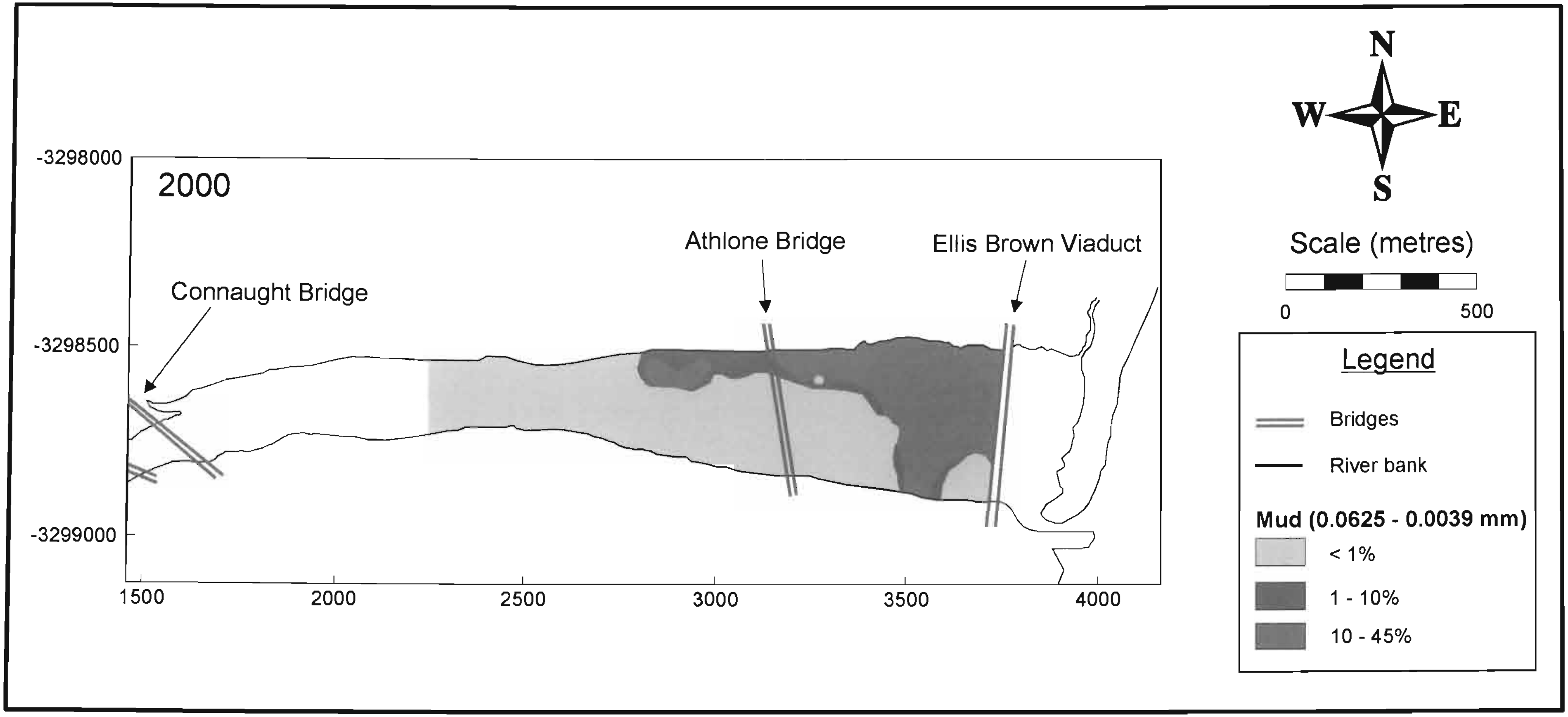
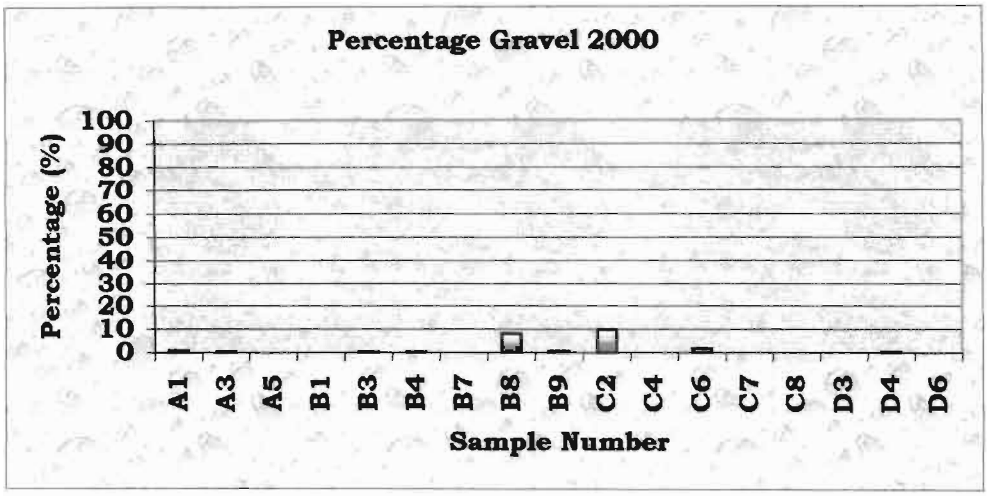
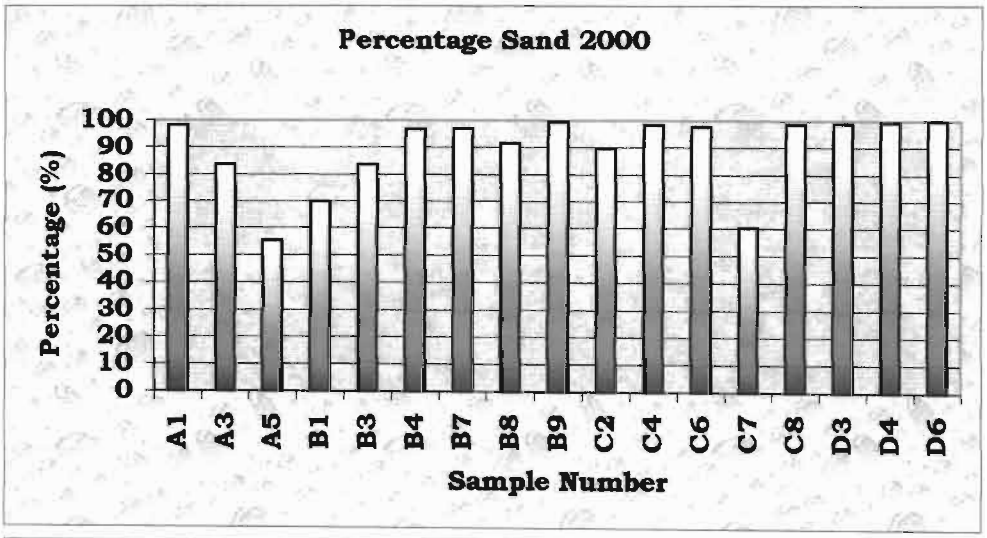


Figure 5.3(c): The distribution of mud in the Mgeni estuary, 2000.

Graphically, the percentage distribution of sediment in the Mgeni estuary for 2000 year is presented thus:





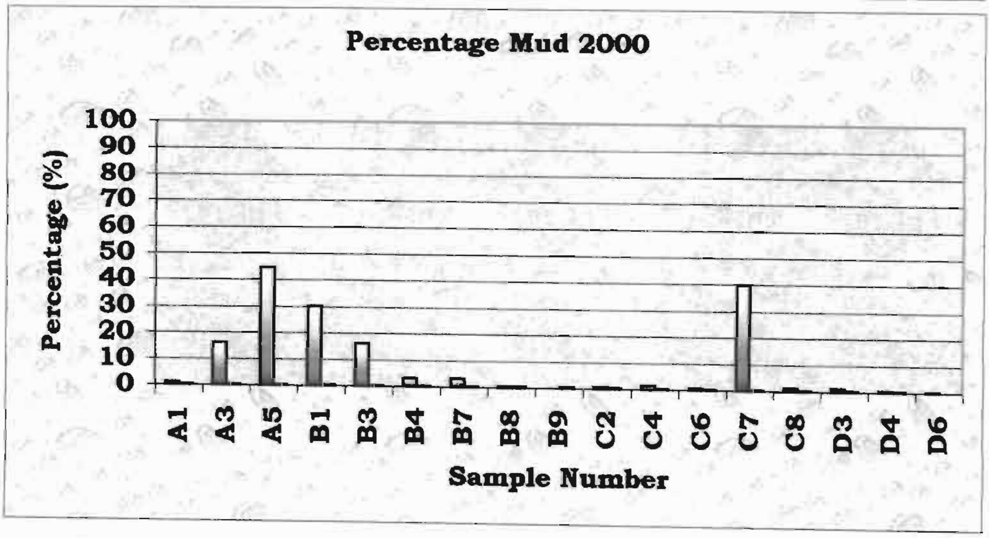


Figure 5.4: Percentage distribution of sediment grain size class in the Mgeni Estuary, 2000.

(Data source: 2000 sampling results)

The above histograms (Figure 5.4) harmonises with the spatial distribution of sediment grain size class in the Mgeni estuary (Figures 5.3 a-c). The topmost graph shows that the highest concentration of gravel is in sample B8 and C2 along the second and third reaches (see sampling positions, Figure 4.1). Sand dominates in the estuary especially at the upper reaches as represented by the fourth reach, D4 and D6 with almost 100% sand; while mud dominates the lower reaches especially to the north bank as represented in A3, A5, B2 located along the first and second reaches (A and B). There is a small patch of mud inland at reach 3 to the north bank (C7). This sediment grain size distribution reflects how reduction of flow velocity and volume due to the Inanda dam has redistributed sediment in the estuary, with sand dominating the upper reaches and mud at the lower reaches.

The median grain size distribution in the estuary, Figure 5.5 (also represented in Appendix 5.1a) shows the estuary is dominated by fine to medium size sediments.

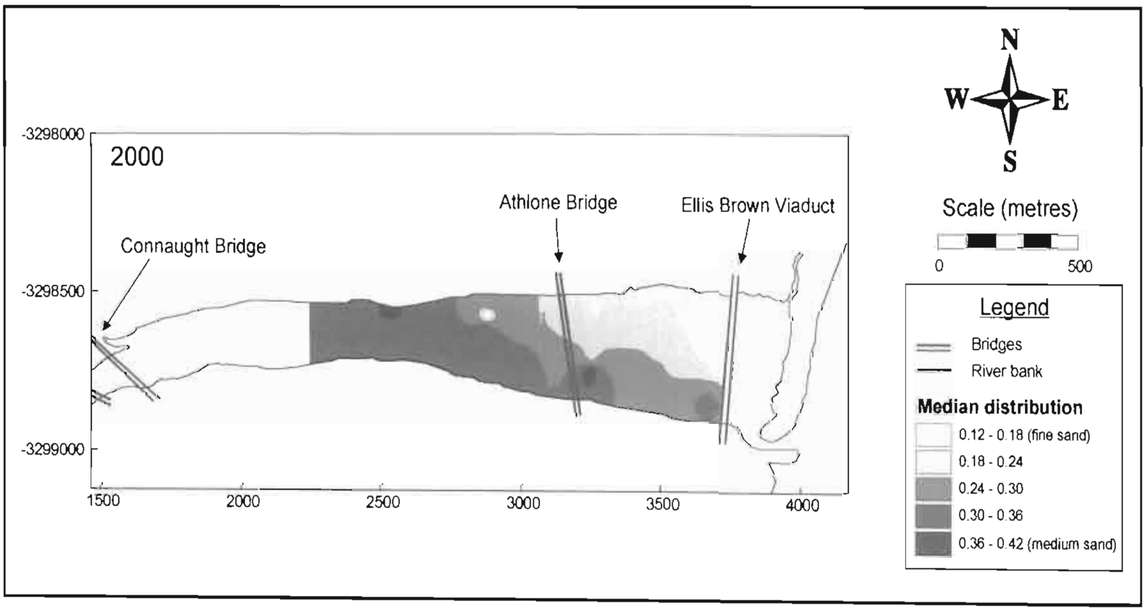


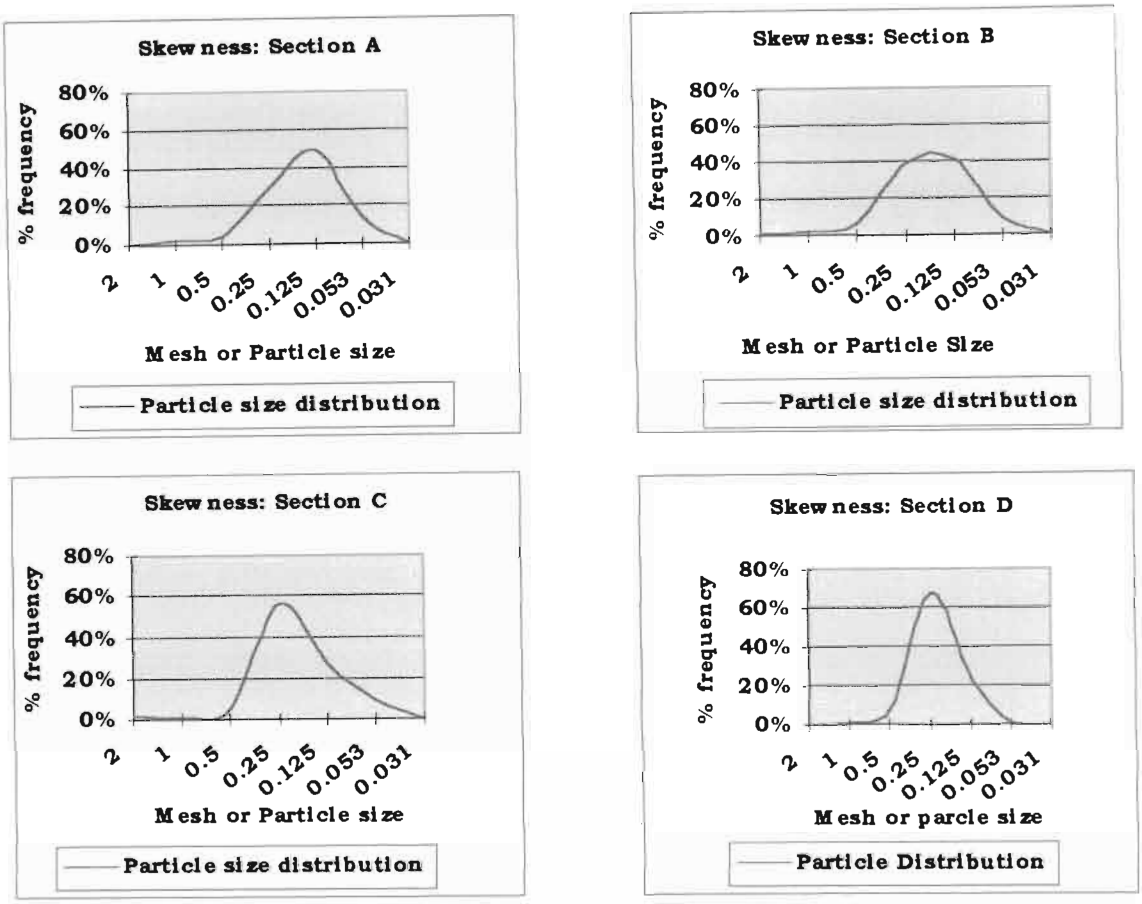
Figure 5.5: Median grain size distribution in the Mgeni Estuary, 2000
(Data source: 2000 sampling results)

The highest median, 0.42 is situated along transect B to the south bank just south of Athlone Bridge. This is also the site for the concentration of medium size sediments. A3 and A5 forms the concentration of fine sediments to the north channel just north of Ellis Brown Viaduct, while B1 and C7 are smaller concentration of fine sediments to the south and north of Athlone Bridge. A section-by-section median grain size distribution reveals averages of 0.23, 0.27, 0.30 and 0.33 mm for sections A, B, C and D respectively (Appendix 5.1b). The median size in the entire estuary is 0.28 mm, supposedly situated approximately between section B and C just north of Athlone Bridge and indicates the predominance of medium to fine sand in the Mgeni estuary.

5.4.2 Skewness, sorting and kurtosis

To ascertain the overall granulometric distribution of particle size in the estuary, recourse was made to measures of central tendency (the mean, mode and median), measure of dispersion of grain size distributions particularly skewness and sorting - otherwise known as standard deviation (Friedman et al, 1978; Selley, 2000 and Leeder, 1982), as well as the tendency towards concentration or peakedness of grain size distribution referred to as kurtosis (Tucker, 1988) - details in section 4.4.

These measures of central tendency have been calculated for the Mgeni estuary and the statistics are included in Appendix 5.1a and b showing the spread of these parameters in each sample, transect by transect and in the estuarine system. The statistics reveal that the mean, median and modal grain sizes in the Mgeni estuary are 0.29, 0.28 and 0.20 mm respectively. These calculated figures indicate for example that half of the sediment in the estuary is greater than the median, 0.28 mm and half is less than this grain size. The most frequently occurring grain size in the estuary is 0.20 mm (mode) and the typical grain size in the estuary is represented by the mean grain size, 0.29 mm. However the most dominant grain size, the mode for each section reflects differently. For example it is much finer (0.17 mm) at the lower reaches close to the Mgeni mouth than 0.23 and 0.25 mm at the upper reaches inland. This pattern replicates for the mean and the median, which are also finer towards the mouth than upstream. Appendix 5.1 b.
All Four surveyed transects display a positive skew with B and C being strongly fine skewed (0.34 and 0.31) while A and D are fined skewed (0.24 and 0.20). These parameters are graphically represented in Figure 5.6 A-D below. Values for the graphs were derived from the mean frequency distribution of each particle sizes in all samples transect - by - transect in the estuary.



Figures 5.6 (A-D): Skewness, section by section at the Mgeni Estuary
(Data source: 2000 sampling results)

All four transects are poorly sorted ranging from 1.07-1.57, signifying the predominance of fine deposits and the inability of flow to sort the sediment during transportation and/ or deposition. This is indicative of and correlates with the reduced discharge below the Inanda Dam (refer to table 5.1). Calculated kurtosis transect by transect show a leptokurtic curve for transect A, B and D (1.35, 1.29, 1.21), and a very leptokurtic distribution for C (2.58). This means the distribution of particle sizes are well sorted in the centre than the tail and indicate a higher peaked distribution than the normal, where sediment distribution is straddled into half between fine and coarse sediments.

Though a section by section presentation of the above graphical parameters may give a fair picture of hydraulic behaviour and sediment dynamics in the estuary, it is the average of each parameter for all four surveyed transects that presents a convincing result for the entire Mgeni estuary as Figure 5.7 below shows.

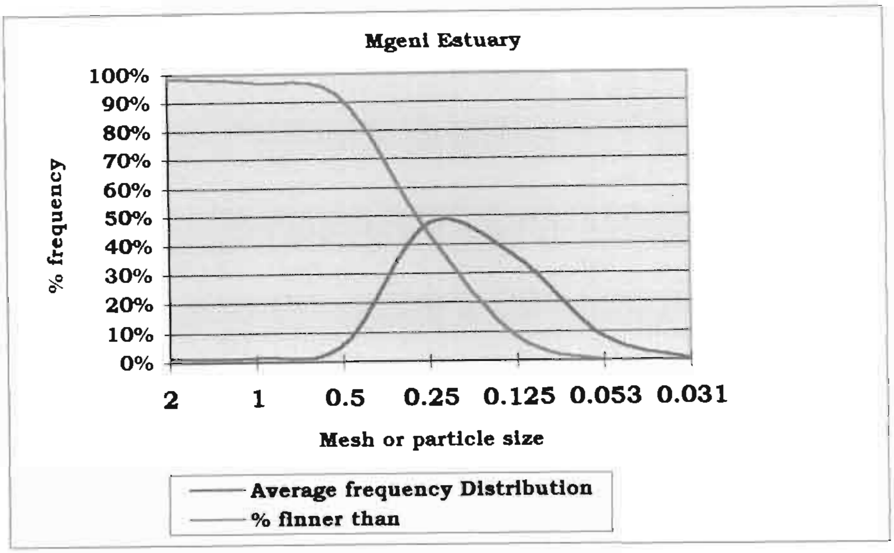


Figure 5.7: Estimated skewness for the entire estuary

(Data source: 2000 sampling results)

The above-summarised presentation of grain size parameters for the Mgeni estuary (see also Appendix 5b) indicates that sediment distribution in the estuary is skewed towards the fine tail signifying an excess of medium to fine sand (0.29). It is poorly sorted (1.46) with a very leptokurtic distribution (1.67).

5.4.3 Mineral characterisation of sediments

To help characterise the mineralogical composition of the sediments, a selected number of samples were subjected to heavy mineral separation following the procedure described in section 4.3.2.2. The percentage fraction of light and heavy minerals in each sample was determined and is tabulated in Appendix 4.4. These results have been compared in Excel and are graphically presented in Figures 5.8 and 5.9 below.

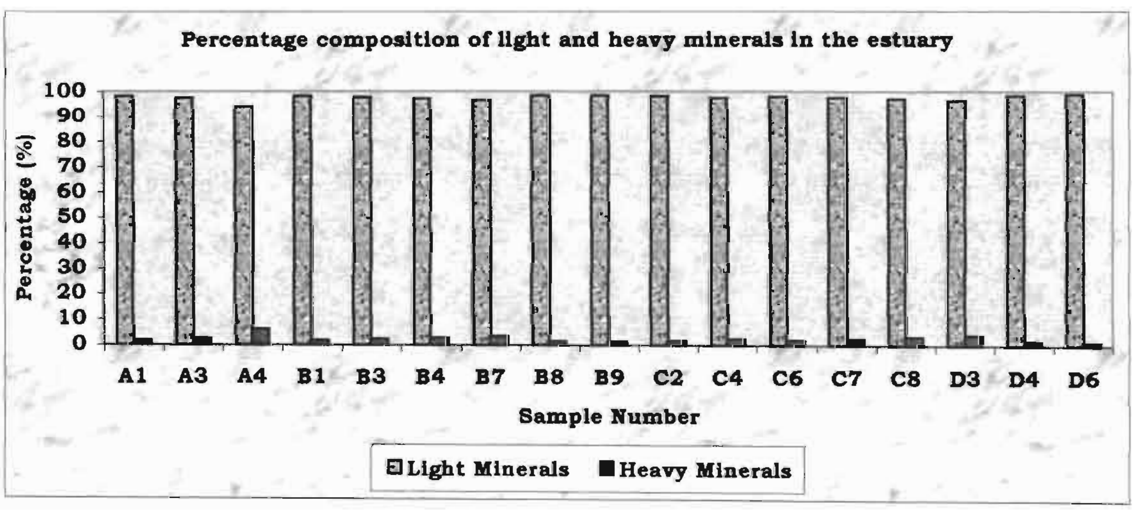


Figure 5.8: Percentage composition of light and heavy minerals in each sample

(Data source: 2000 sampling results)

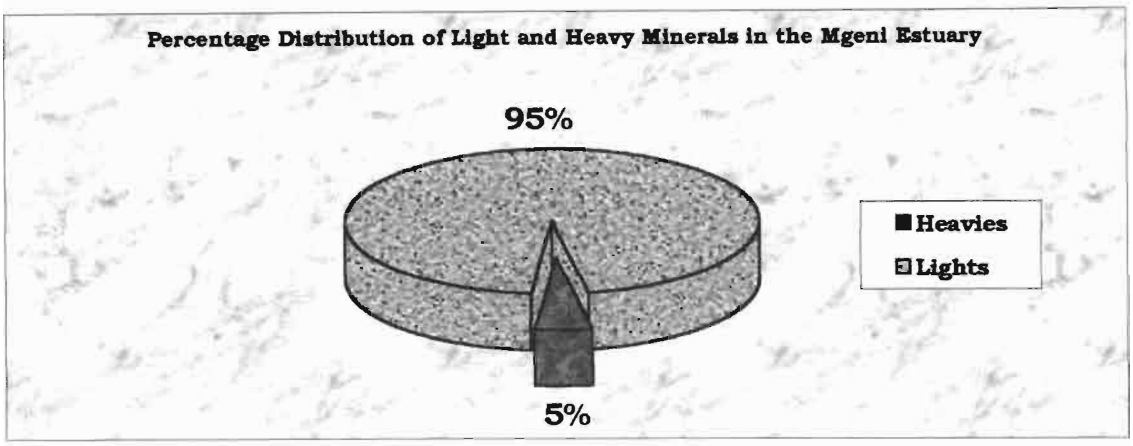


Figure 5.9: Percentage distribution of light and heavy minerals in the Mgeni Estuary (Data source: 2000 sampling results)

The above two figures portray the dominance of light minerals firstly in all samples and then in the Mgeni estuary. Figure 5.9 indicates that about 5% of the total sediment load in the estuary is composed of heavy minerals as opposed to 95% of light minerals. Using ArcView Spatial Analyst, it was possible to map the spatial distribution of these minerals in the estuary and to show their association with sediment (Figures 5.10 a and b). The results show a strong relationship between sediment grain sizes and the minerals.

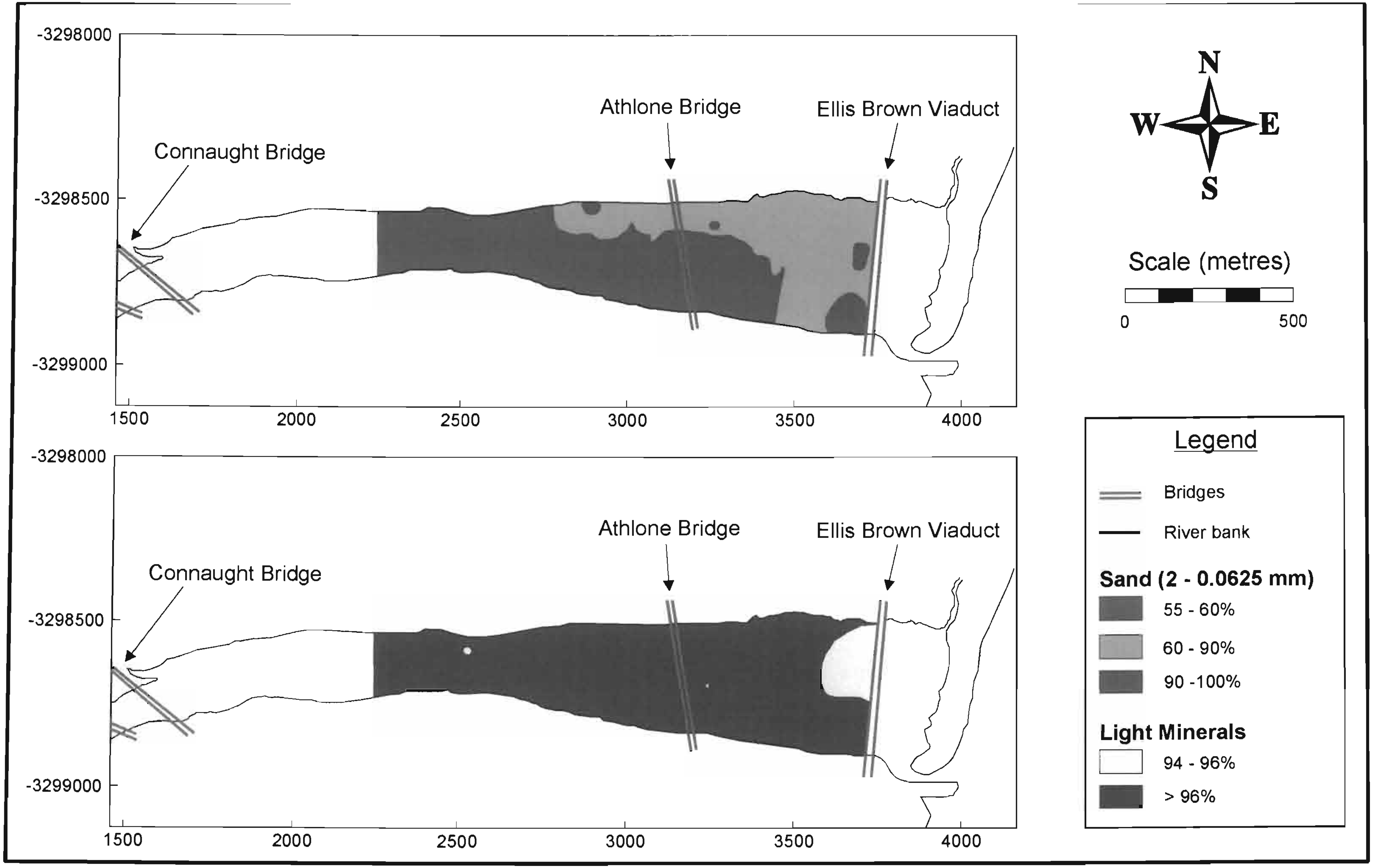


Figure 5.10(a): Spatial distribution of light minerals and their relationship with sand (Data source: 2000 sampling results).

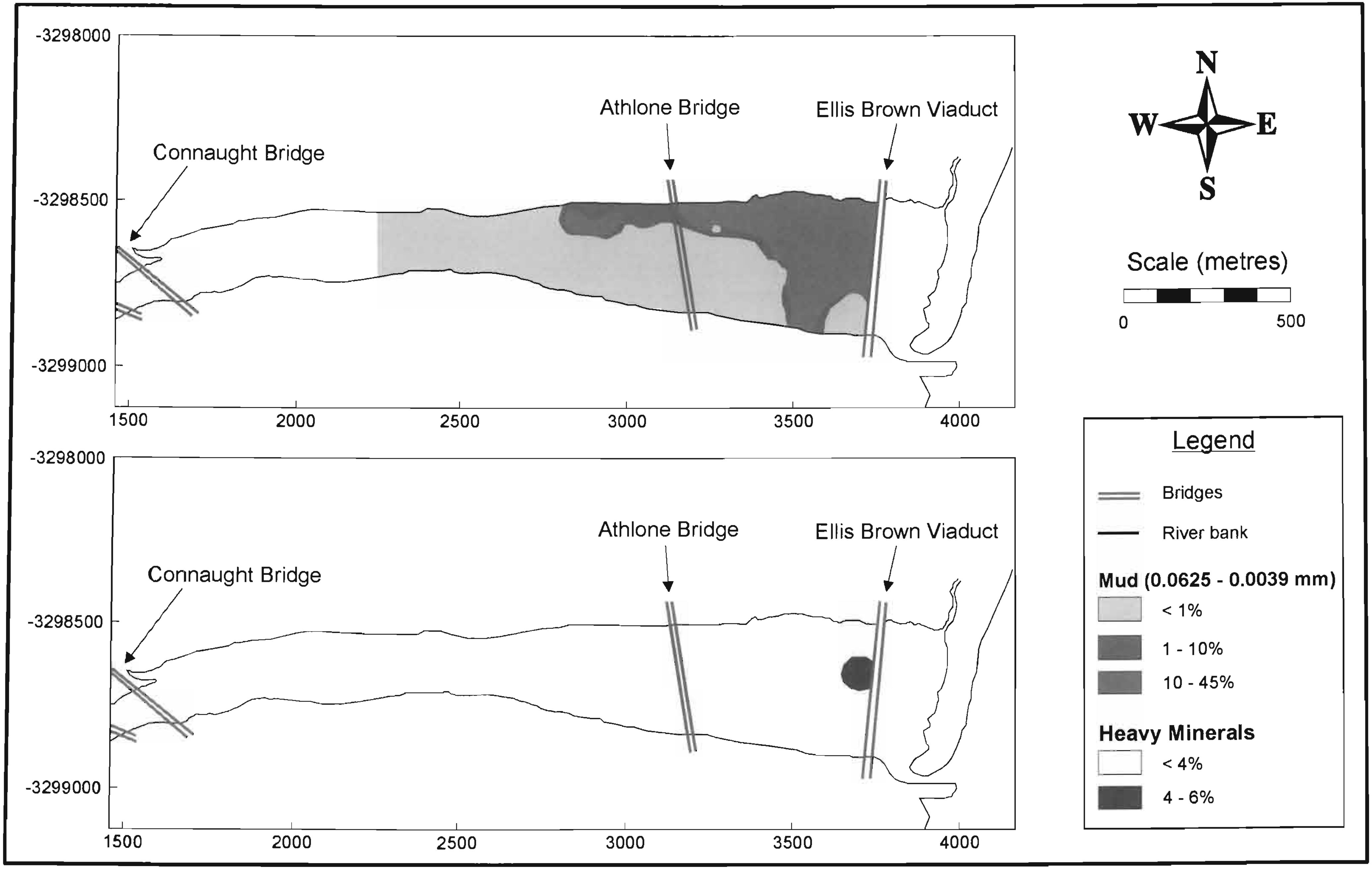


Figure 5.10(b): Spatial distribution of heavy minerals and their relationship with mud (Data source: 2000 sampling results).

As Figure 5.10a above show, there is a high concentration of light minerals in sand and gravel while heavy minerals are highly concentrated in mud. This behavioural pattern of minerals in relation to sediment grain sizes confirms Rubey's (1993) hypothesis that heavy minerals tend to concentrate in fine and much finer grained sediments.

5.5 Evidence of Bank Erosion

It is believed that reduced flow in the estuarine channel is cutting through sections of the Mgeni estuary resulting in bank failure. This conclusion has been reached following a number of site observations at the estuarine channel bank, where visual evidence of site-specific bank erosion at specific points (Figure 5.11 a and b) were identified, though not close to the surveyed cross-section positions.

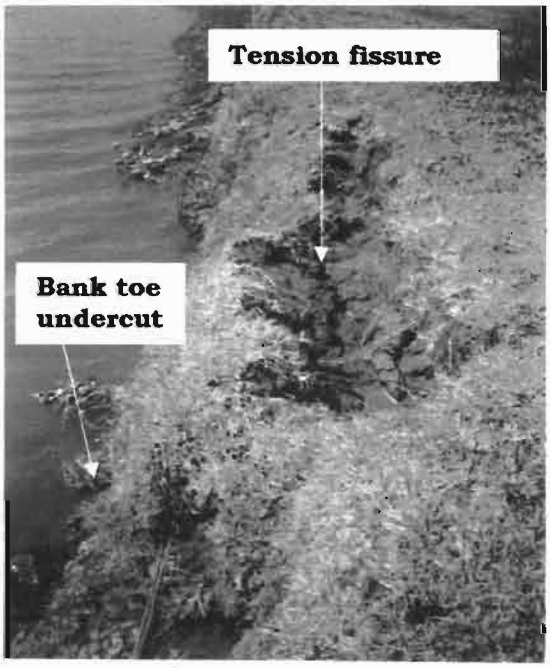


Figure 5.11 (a): Bank toe undercut and fissurisation - July 2000

Figure 5.11(b): Bank failure - July 2000 (Source: Researcher)

The scene in figure 5.11a and b above, captured at the Mgeni estuary in July 2000 is referred to as cantilever failure (Thorne, 1998). Its mechanism of failure is illustrated in the researcher's own model below (Figure 5.14).

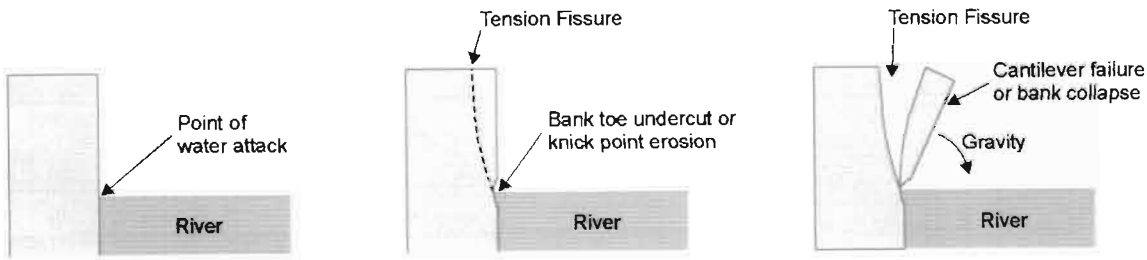


Figure 5.12: A model of bank under-cut or knick point erosion and cantilever failure in the estuarine channel (Source: Researcher)

Generally, in relation to the above model, water attacks and cut into the estuarine bank at half-full stage. As the process continues, the over-hanging material pulls apart from the bank due to tension fissures caused by gravity. Further undercutting leads to failure of the over-hanging material. Bank failure at half-full flow stage as observed at the Mgeni estuary is proof that rivers and estuaries are dynamic systems (Worster, 1985), and that reduced flow is contributing to bank toe under cut and collapse.

5.6 Summary

Having analysed the data of the 2000 survey (Chapter Four), the results shows dam release is higher in summer and lower in winter, that channel cross-sectional profiles are located at depths varying from 1 to about 4 metres. There is a dominance of fine to medium size sediment in the estuary; there is evidence of bank erosion mostly on the lower south bank and a 95% dominance of light minerals in comparison to 5% heavy minerals in the estuary. How would such results compare with the 1997 results? This question is answered in Chapter Six.

CHAPTER SIX

A COMPARISON OF MOLEKO'S (1997) AND THE 2000 RESULTS

6.1 Introduction

Moleko, (1997) conceptualised a model of change (section 3.4) for the Mgeni estuary in response to the existence of the upstream Inanda dam. To test this model with the 2000 results, it was mandatory to compare downstream flow (hydrology), channel cross-sections and sediment characteristics for the two periods of study.

6.2 Hydrology

River flow is a critical factor in the erosion and transportation of sediments. Moleko (1997) concluded that frequent competent discharges at the time of his study were flushing sediments out of the estuary into the ocean, predicting that this might lead to estuarine channel scour. Had this happened, this would have fulfilled among others the objectives of the recommended water release policy from the Inanda Dam (CSIR, 1984; 1992), namely to keep the estuary mouth open and to scour out any sediment that had accumulated in the estuary. To test Moleko's (1997) hypothesis, it was necessary to compare dam discharge over three periods (Table 6.1 and Figure 6.1), 1960-1989 (pre-dam), 1990-1997 (immediate post-dam) and (further post-dam 1998-2000), which would also contribute in determining the trend of discharge below the Inanda dam and the likely impact on the erosion, transportation and sedimentation.

Table 6.1: Comparison of monthly maximum daily average flow rate ($m^3 sec^{-1}$)

Months	1960-1981	1990-1997	1998-2000
January	41.6	47	21.5
February	49	72.2	27.7
March	46.1	69	19.5
April	30.4	40.6	15.1
May	19.9	9.1	6.0
June	4.7	4.6	2.4
July	7.4	18.9	2.2
August	5.4	30.6	1.5
September	11.4	6.8	1.6
October	22.3	7.3	1.4
November	21.7	11.3	3.8
December	37.4	38.2	16.5

(Data source: CCWR, 2000; Moleko, 1997 & Umgeni water 2001)

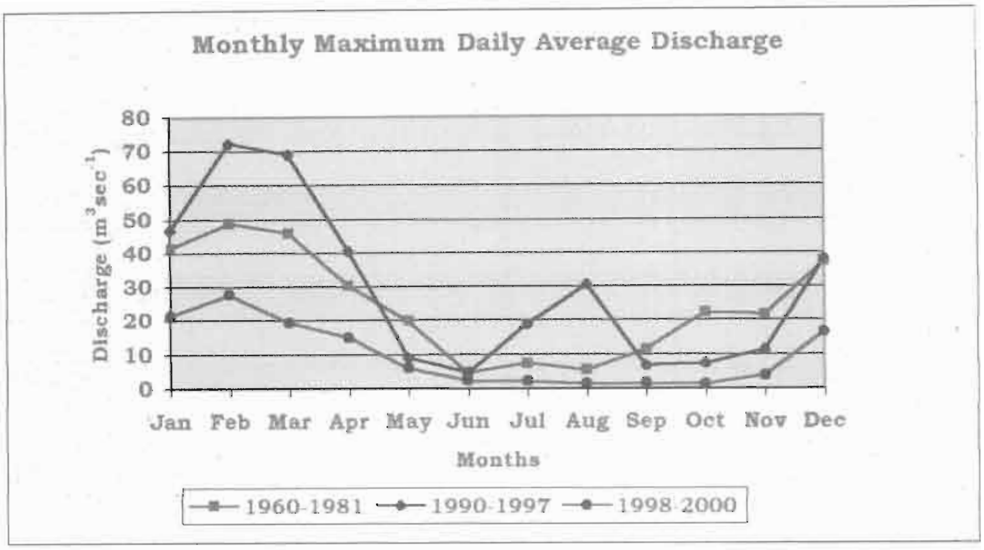


Figure 6.1: Comparison of Monthly Maximum Daily Average Flow, 1960-2000 (Data source: CCWR, 2000; Moleko, 1997 & Umgeni water 2001)

The graph and table above shows there has been a massive change in the downstream water release policy by dam management. For example, Table 6.1 indicates that there has been a drop in monthly maximum daily average flow from January to December during the 1998 – 2000 period in comparison to 1997 and pre-dam discharge scenario. This is evident in the graph (Figure 6.1), where the 1998-2000 downstream dam release lies below the 1960-1981 and 1990-1997 graphs. The disparity is so great that except for the month of February, the present release policy falls far short of the 25 m^3sec^{-1} monthly release from December-April as one of the estuary's management objectives recommended by CSIR before the dam (1984, 1992), aimed at maintaining an open channel and to flush out accumulated sediments in the estuary. In fact put together, monthly maximum average daily flow has reduced by 33.5% what it was in 1997.

6.3 Channel Cross Sections

To determine whether there has been any channel scour as predicted by Moleko in 1997, the 2000 cross-sections (Section 5.3) where imposed on the 1997 profiles as presented in Figures 6.2 (a) to (d). Although not possible to compute actual sediment volumes, it was determined that sediment, equivalent to a cross-sectional area of about 623.8 m^2 has been flushed from the lower reach at transect A, north of Ellis Brown Viaduct. Transects B to D witnessed accretions ranging from 91.6, 192.6 and 609.5 m^2 at specific portions while losing 26, 158 and 26.2 m^2 worth of material along other portions of the profiles.

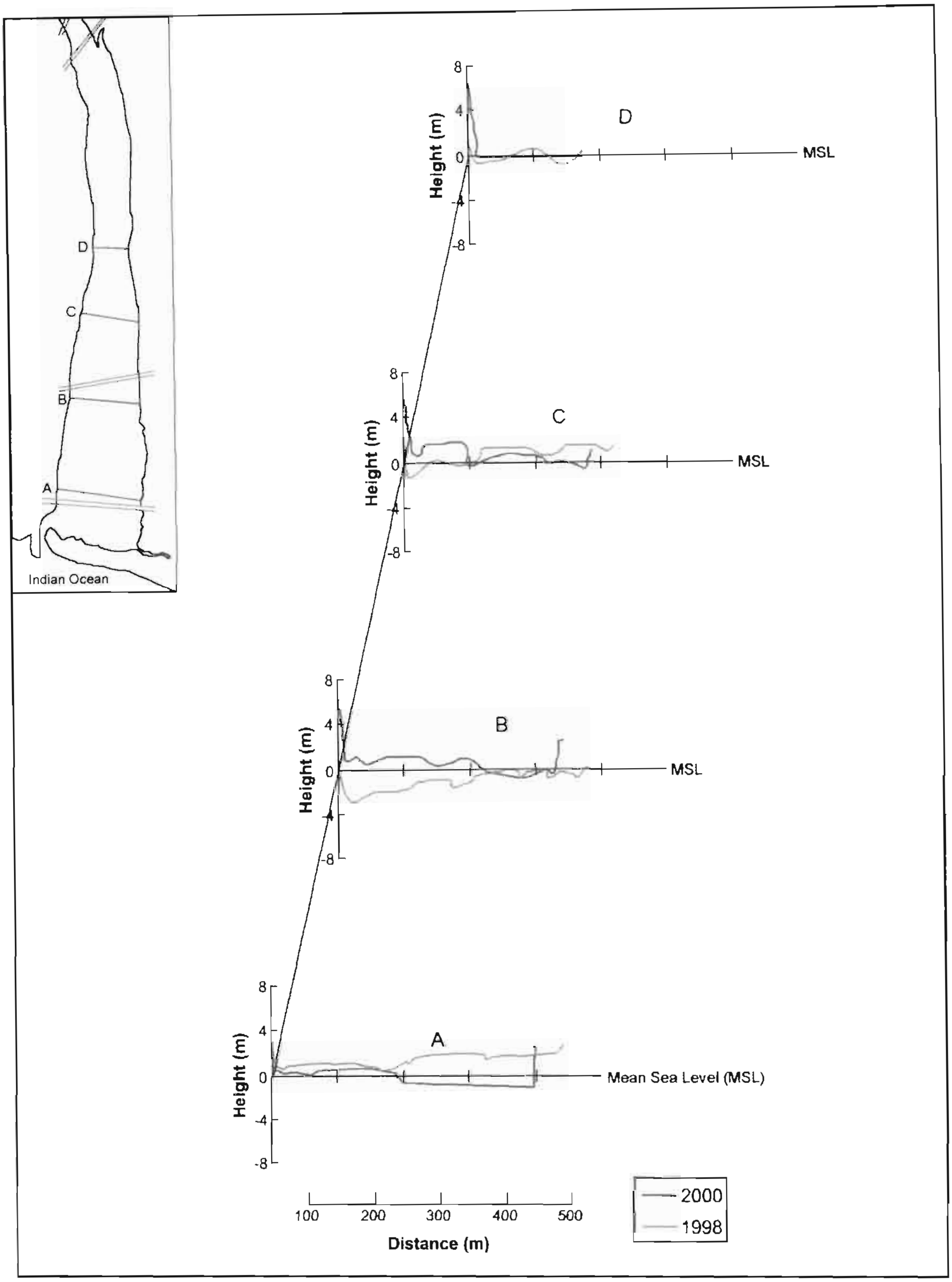


Figure 6.2: Channel cross-sectional change from 1997-2000
(Data source: Moleko, 1997 and SKR Consulting (Engineers and Scientists))

However, put together it is estimated that there has been a slight net accretion of about 59.7 m^2 of sediment in estuarine bed. This contrasts with Moleko's predictions that the channel will not accrete. Although neither the locations of the cross sections nor the sample positions correspond precisely to those of Moleko's (1997) study, the variations never exceed 0.5% of the total estuarine length, allowing valid comparison between the two data sets. Nevertheless, the fact that not all channel profiles give evidence of erosion confirms one of the 1997 claims that there would be site-specific erosion in the estuary.

6.4 Sediment Characteristics and Re-distribution

Mapped results of particle size analysis were compared with Moleko's (1997) results (Figure 6.3 a to c). Generally, the comparison seems to follow the 1997 pattern with fine to medium sand still dominating the estuary. However, except for gravel and sand, there is a remarkable increase in the spatial coverage of mud content at the lower reaches. The three sediment sub components have witnessed a notable redistribution in the estuary. There has been a reduction of gravel in the estuary (Figure 6.3a), by about 20%. In Figure 6.3 (b), more than 90% (>90%) of sand now completely dominates inland of the estuary while the estuarine mouth, which was occupied in 1997 by >90% of sand has witnessed a significant reduction to between 60-90%.

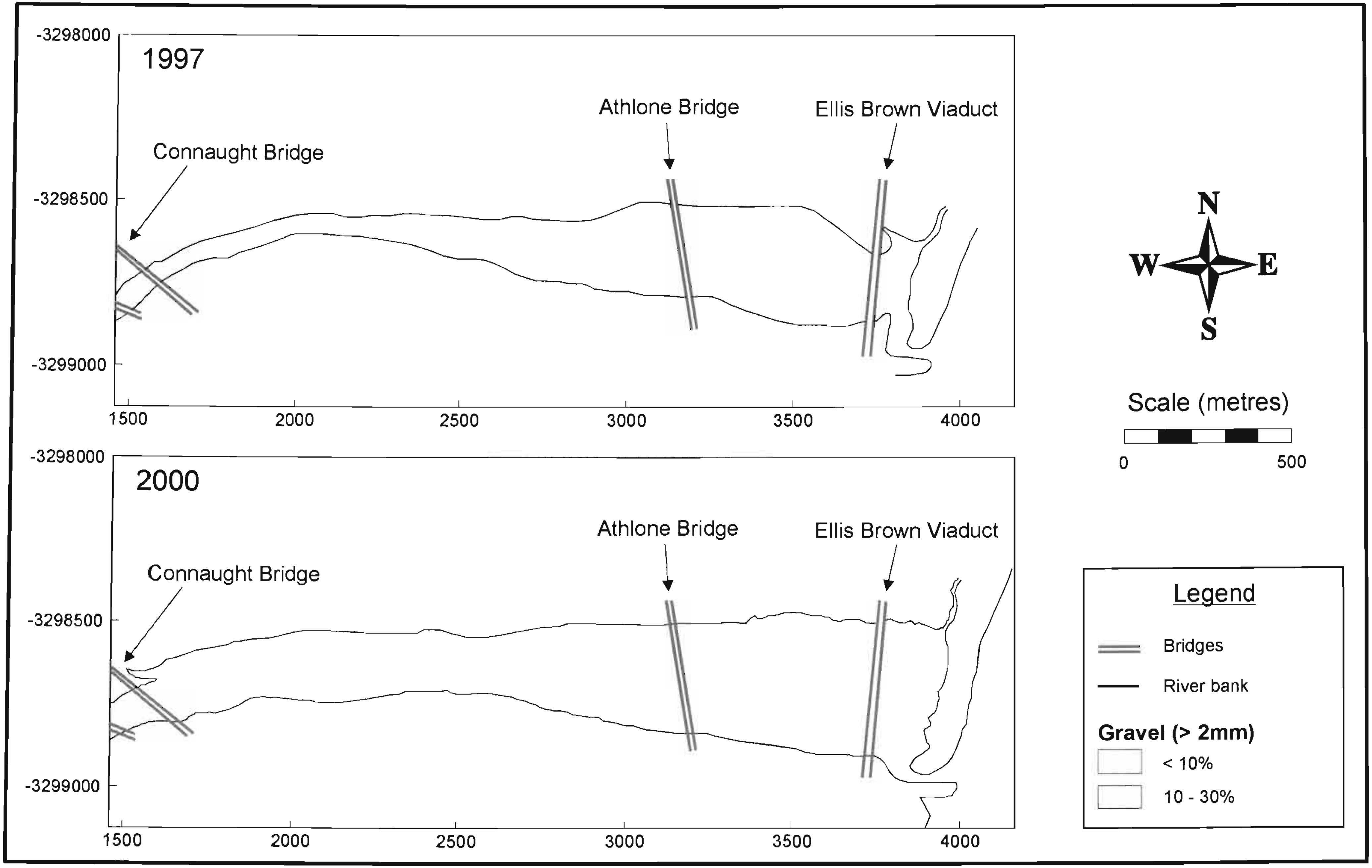


Figure 6.3(a): Gravel re-distribution and dynamics in the Mgeni estuary, 1997-2000 (Data source: Moleko 1997 and 2000 sampling results).

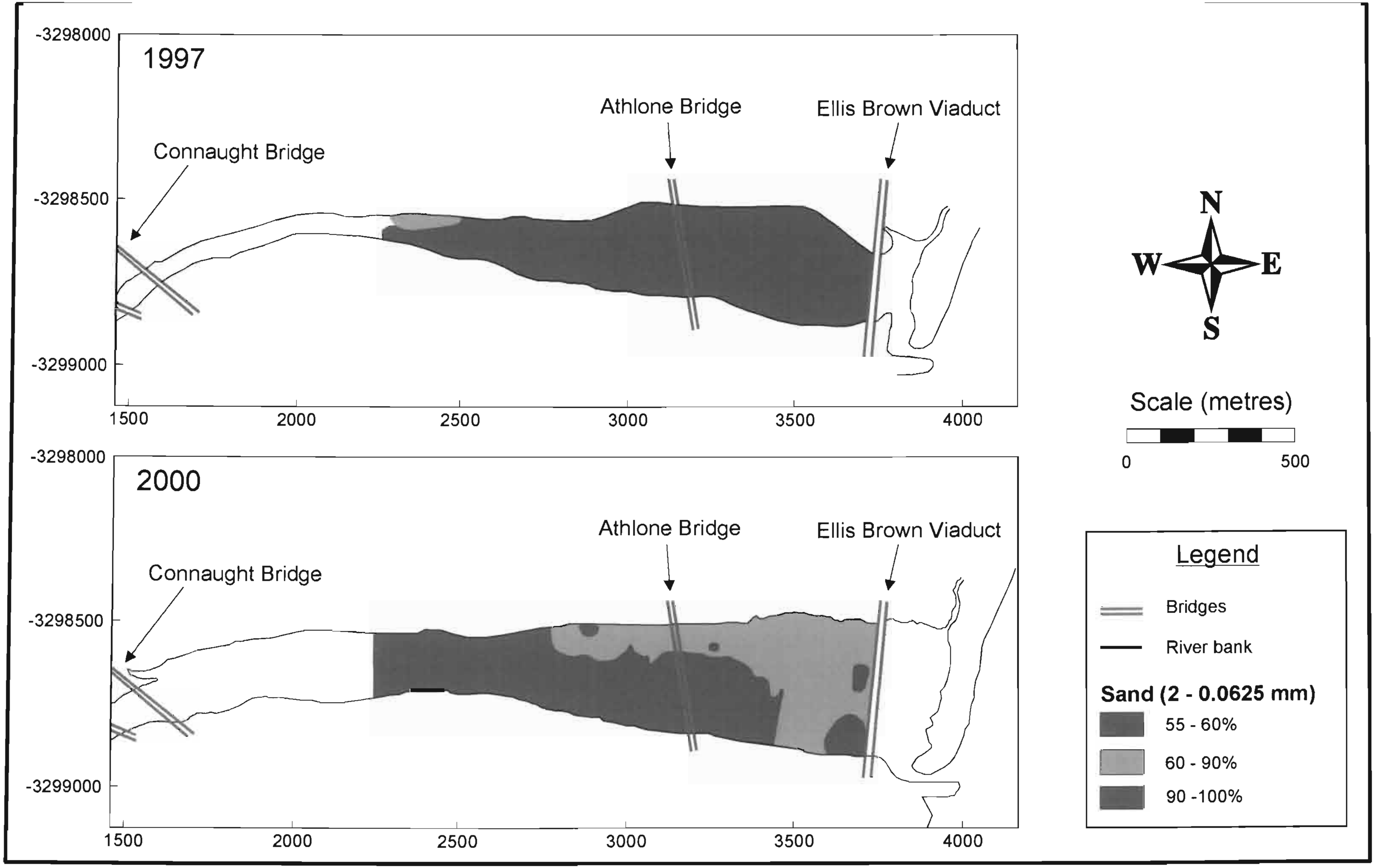


Figure 6.3(b): Sand re-distribution and dynamics in the Mgeni estuary, 1997-2000 (Data source: Moleko 1997 and 2000 sampling results).

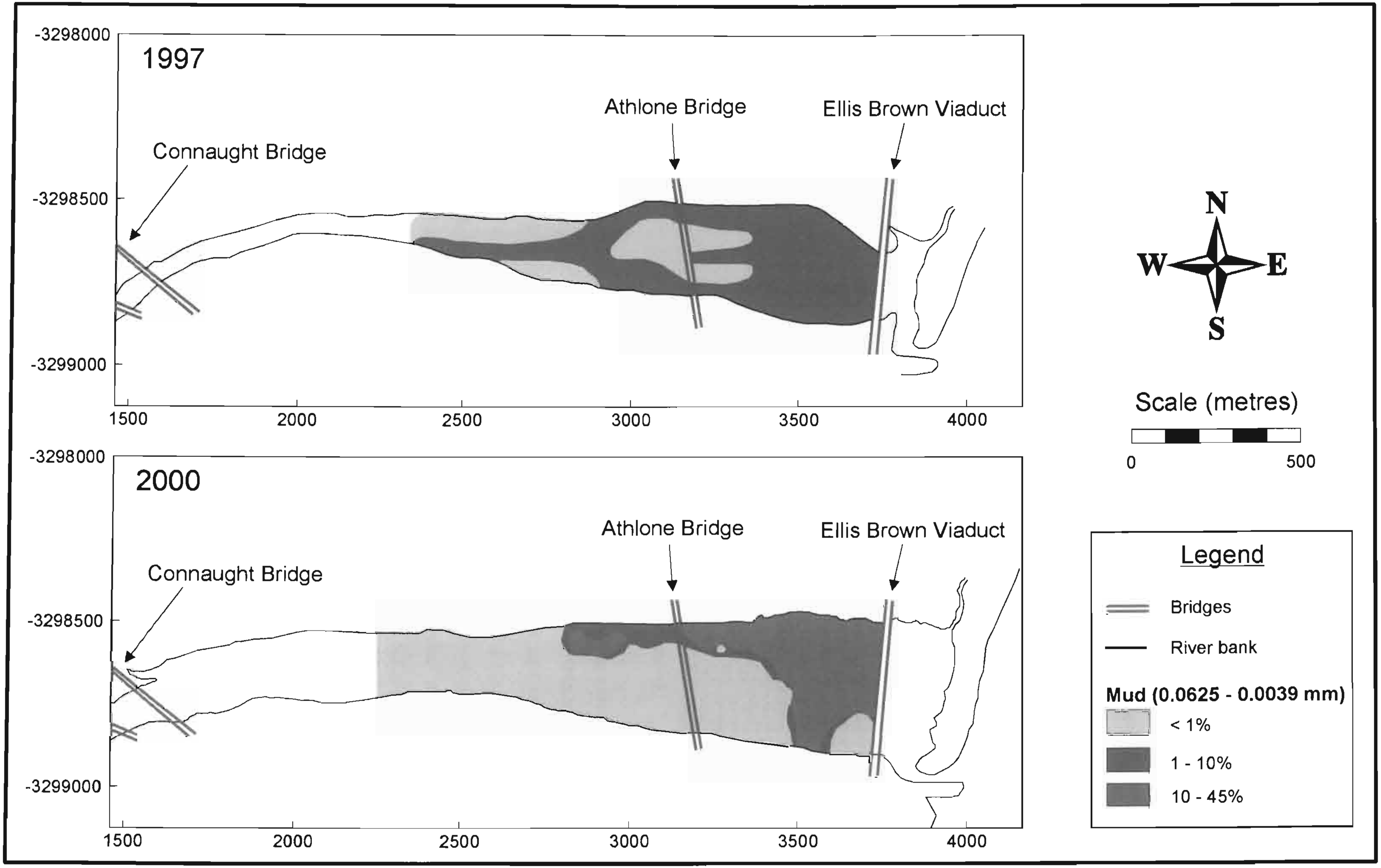


Figure 6.3(c): Mud re-distribution and dynamics in the Mgeni estuary, 1997-2000 (Data source: Moleko 1997 and 2000 sampling results).

Mud (Figure 6.3c) has lost the northern reaches beyond Athlone Bridge to sand except for a small patch to the north bank. The lower reaches, has witnessed an increase in mud fraction from 1-10% in 1997 to between 10-45% in 2000.

Textual characterisation of sediments in the estuary is presented in Table 6.1. Located no further than 10 to 30 m from the 1997 positions, they compare Moleko's 1997 sample positions with those in 2000 highlighting changes in sediment calibre in each sample over the study period.

Table 6.2: Comparison of 1997/2000 sediment textual characteristics

1997 Sample Results					2000 Sample Results				
Sample No	Mud (%)	Sand (%)	Gravel (%)	Median (mm)	Sample No	Mud (%)	Sand (%)	Gravel (%)	Median (mm)
S21	0.22	99.72	0.06	0.3	D6	0.3	99.7	0	0.29
S22	1.88	98.06	0.06	0.34	D4	0.4	99.2	0.4	0.35
S23	0.12	98.36	1.52	0.37	D3	1.1	98.8	0.1	0.34
S31	1.06	98.94	0.00	0.28	C2	0.8	89.5	9.7	0.37
S32	3.00	97.00	0.00	0.35	C4	1.5	98.4	0.1	0.32
S33	0.31	99.69	0.00	0.24	C6	0.8	97.5	1.7	0.35
S34	0.61	99.39	0.00	0.31	C7	39.8	60.2	0	0.15
S35	4.00	96.00	0.00	0.3	C8	1.3	98.6	0.1	0.31
S41	4.15	95.85	0.00	0.22	B9	0.1	99.3	0.6	0.37
S42	2.95	96.97	0.08	0.18	B8	0.5	91.4	8.1	0.42
S43	0.98	98.70	0.32	0.33	B7	3.1	96.8	0.1	0.24
S44	1.30	91.64	7.06	0.39	B4	3.2	96.6	0.2	0.25
S45	0.64	99.33	0.03	0.24	B3	16.2	83.5	0.3	0.19
S46	2.35	97.65	0.00	0.23	B1	30.2	69.8	0	0.17
S51	2.45	97.55	0.00	0.22	A1	1	98.1	0.9	0.35
S52	5.79	94.21	0.00	0.18	A3	16.2	83.5	0.3	0.18
S53	8.88	91.12	0.00	0.15	A5	44.7	55.3	0	0.17

(Data source: Moleko, 1997 and 2000 sample results)

This data was input into ArcView GIS and has been used to produce the spatial distribution of sediment in the estuary in comparison to Moleko's 1997 sediment distribution (Figure 6.3 a to c). A comparison of Moleko's 1997 median fraction with the 2000 median give evidence of gradual fining of sediments in the estuary as Moleko predicted but not statistically significant. This was confirmed by a chi-square test, which result led to the acceptance of the null hypothesis at a 95-degree of confidence, that the two sets of median are not significantly different. The 1997/2000 medians are graphically compared in Figure 6.3.

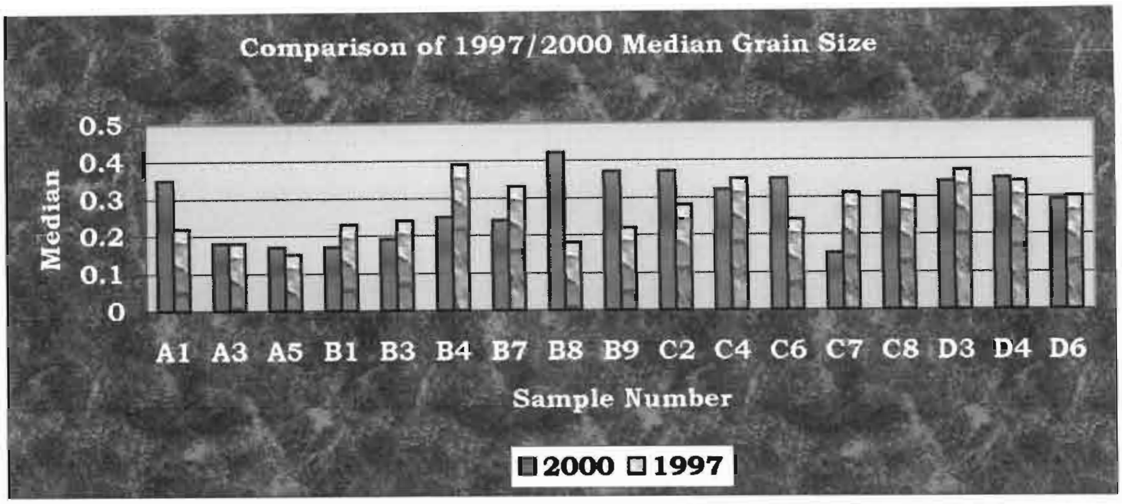


Figure 6.4: Comparison of 1997 and 2000 Median grain sizes
(Data source: Moleko, 1997 and 2000 sample results)

A careful observation of the changes both on the above graph and on table 6.2 further confirms the null hypothesis that there has been no significant change between the two medians as increases in some samples are offset by decreases in others. Moreover, except for sample B8 with a median of 0.42 in the 2000 survey results, all other medians for both study periods trail below 0.40 with averages of 0.27 and 0.28 for 1997 and 2000 again confirming the predominance of medium to fine sediments in the estuary as was the case in 1997.

6.5 Summary

Comparing the 1997 and 2000 results has identified the changes experienced in the Mgeni estuary between the two periods of study. These changes are the basis for interpretation as discussed in Chapter Seven. The changes include, a 33.5% decline of the downstream Mgeni monthly maximum average daily flow since 1997, site-specific bed scour, a slight net sediment accretion estimated at 59.7m^2 and a 35% decrease of coarse bedload with a corresponding increase in mud.

CHAPTER SEVEN

A GEOMOPHOLOGICAL INTERPRETATION OF THE 1997 TO 2000 CHANGES

7.1 Introduction

At the beginning of this study, some of the stated objectives (section 1.5) were to establish current cross-sectional profiles of the Mgeni estuarine channel between Connaught Bridge and Ellis Brown Viaduct, analyse and map the present texture and distribution of sediments in the Mgeni estuary between Connaught Bridge and Ellis Brown Viaduct and to explain any changes according to current theories of fluvial and estuarine geomorphology. Having achieved the first two objectives it is now critical to explain the resulting changes discussed in chapter six. These changes are to a greater extent explained in terms of geomorphological impact induced by an upstream impoundment. Though sediment and water retention by a dam initiates a kaleidoscope of downstream changes, this will only happen in combination with a number of favourable factors that influence the dynamism of downstream channel and sediment characteristics. These include among others, catchment gradient, bank geological composition, the effect of tides and anthropological activities like boating, sand winning and head-ward erosion along drain pipes emptying into the channel.

7.2 Topographical Change

In contrast to the rugged and dissected hinterland with a hydraulic gradient of between 1:120 and 1:132 (Cooper, 1987 and Cooper, 1993), the lower Mgeni draining into the Indian Ocean has a hydraulic gradient of 1:550, characteristic of a reduced slope and is thus a transport/depositional environment. This explains sedimentation in the Mgeni estuary and the influx of tides, which contributes fine sand to the open estuarine neck pushing mud to the closed end of the estuary.

7.3 Possible Effect of Climate

Though average annual rainfall is estimated between 900-1000mm for the Mgeni catchment, with 80% of the rainfall in summer (Cooper, 1993 and Tyson, 1987), occasional extremes sometimes result in seasonal flood events especially during summer months (Mervin, pers. Comm, 2000)-section 1.4. These occasional minor flood events have probably contributed in flushing out some of the gravel and sand from the estuary.

7.4 Bank Material Composition

The contrasting material composition on both sides of the Mgeni estuarine bank is another probable factor in the geometrical changes on its south bank. Both from geological (Figure 1.5) and theoretical evidence (CSIR, 1992; Cooper, 1987), the south bank of the estuary is made up of less resistant alluvial formations than the more resistant Dwyka Tillite-north bank, hence the former's susceptibility to erosion. This explains the existing geomorphological processes of vertical erosion at some reaches and the predominant, bank undercut, failure and erosion remarkable on the south bank of the Mgeni estuary. Reduction of flow in the channel from bank full to half bank by the upstream dam has and is aiding bank knick-point erosion and collapse as illustrated in Figure 5.11a and b; and Figure 5.12.

In areas where banks are protected or are of more resistant material, sediments tend to accrete. This hypothesis was confirmed through field observation along stabilized sections at the upper reach along the south bank and along a considerable portion of the more resistant north bank, which have experienced sediment deposition and subsequent colonization by vegetation.

7.5 Anthropogenic Causes

It is believed that the banks of any channel supporting any navigable activities if not stabilized are subject to attack by waves generated by passing boats in a process known as boat wash scour (Hemphill and Bramley, 1989). As a recreational node to the north of Durban, the Mgeni estuary supports daily recreational boating or canoeing. In September 2001, a visit to the estuary during one afternoon by the researcher encountered 3 boats in succession. Though not directly linked to impacts of the Inanda Dam, the reduction of flow in the channel resulting from the upstream dam has exposed the estuarine bank, enhancing the process of boat wash scour directly against the exposed banks. This is compounded by other phenomenon like bank retreat around drains from residences and the golf facilities emptying into the channel.

Further more, though no investigation was made about sand winning activities north of the estuary, it is quite possible that assuming the continued removal of 210,000 tonnes as noted by Moleko (1997), then the decrease in the release policy (section 6.2) of the dam could be solely blamed for sand reduction in the estuary over the study period. On the other hand it could be that sand extractors have stepped up the volume removed resulting to the reduction of sand fraction in the estuary.

7.6 Effect of the Inanda Dam

River competence to transport sediment is strongly related to volume of discharge. This relationship is evident in Manning's equation (Cooke at al, 1977; Gordon, 1992; Maidment 1992; Mitsch and Gosselink, 1993; Morgan, 1995) – see section 2.2. As these authors confirm, when flow volumes reduces, its capacity to erode and transport load reduces, paving the way to bedload deposition. A comparison of dam discharge below the Inanda dam from 1989-1997 and from 1998-2000 revealed that there has been a drastic fall in competent flows below the dam, (Table 6.1) allowing deposition of finer sediments. This reduction in downstream dam release, in addition to the retention of coarse sediments behind the dam wall probably explains the decrease in sand fraction in the Mgeni estuary from 1997- 2000. Together with the effect of incoming tides, which transport sediments and push back fluvial discharge, they probably account for the net sediment accretion noted in estuary (Section 6.4), mostly mud at the estuary mouth.

The strong association between these sediment grain sizes and their accompanying minerals explain the distribution of heavy and light minerals in the estuary. Lights minerals in the estuary predominate in sand largely due to the similarity in size between lights and sand. The presence of heavy minerals in mud is related to their fineness and cohesiveness, which make their erosion difficult. They are easily sorted away from the lights in a process of selective erosion and stick into mud downstream.

7.7 The Effects of Waves and Tides

With much of the water now being held back behind the Inanda dam, there is greater probability of increase tidal influence at the Mgeni estuary, with minimal fluvial contribution. This has encouraged not only the gradual formation of tidal deltas, intertidal sandbars and mudflats as the estuary evolves towards a new equilibrium or post-flood and post-dam recovery (Cooper, 1993) but also the frequent channel migration characteristic of the post-dam Mgeni estuary.

7.7.1 Waves and tides

The coast of KwaZulu-Natal is wave-dominated, the direction of wave approach being ESE to SE. Recorded wave heights over a 2 year period ranged from 0.3 m to 7.6 m with a median of 1.4m and a maximum wave period of >17 seconds (Cooper, 1993). Waves at the estuarine mouth play an important role in transporting sediments into the estuary following the reduction of river input by the Inanda dam. Their effect is enhanced by tides, which are semi-diurnal on the KwaZulu-Natal coast and carry sediments generated by waves and saline water further into the estuary as far as 2.5km (CSIR, 1992). Though the barrier at the estuarine mouth is said to dissipate wave energy (Cooper, 1993), flood tides occasionally washes sediments over the barrier and through the constricted channel inlet into the estuary altering the distribution of sediment patterns in the estuary. Coarser material is deposited further north from the mouth by both fluvial and flood tidal discharge and at the mouth by strong ebb currents and ocean waves, while fine sediments are deposited in the lagoon-a low energy environment just behind the barrier at the mouth. That tidal effect has increased in the estuary was confirmed by communication with the Windsor Golf Course management (Eric, pers. comm., 2001) adjacent the estuary, who testified to the estuary suffering from more frequent flood tide than was pre-dam. Moreover, observations and photographs (Figure 2.2) at the estuary reveal the development of intertidal mudflats, sand bars and colonization by salt marsh vegetation, confirming the effects of reduced flow and the dominant influence of tides. Dam construction on a river catchment thus reduces river flow leading to the dominance of such tidal effects as described above.

7.7.2 Flood tidal deltas, intertidal sand bars and mudflats

Suspended and bedload material is transported into the Mgeni estuary by breaking waves and tidal advance (Archibald et al, 1990). These sediments settle down at the tip of the flood tide when flood tidal velocity wanes and around the mouth during ebb tide. As the incoming normal waves constantly push back fluvial discharge, this causes fine sediments to settle in the blue lagoon extending behind the sand barrier at the mouth to just above the Ellis Brown Viaduct. Continuous sediment accretion in areas of low velocity has led to emerging bars on which intertidal mud transported into the estuary by flood tide has been deposited. These mud deposits form intertidal mudflats which develop into salt marshes supporting various salt tolerant vegetation This is especially the case at the margin of the north bank and further inland of the south bank between the Connaught and Athlone Bridges where most of water reeds and plants are either stout, robust or gigantic. In addition to these, the gradual growth of an intertidal mudflat from the above processes is building a central island that was also identified by Cooper (1993) and Moleko (1997). The lower reaches of the south bank are mostly occupied by water with depth variation of about 2-3 m.

In addition to the above mentioned processes, evidence observed from 1999 and 2000 aerial photos reveal the existence of flood tidal delta behind the sand barrier at the mouth. This deposit is the possible consequence of tidal flood washing over the barrier together with sediment driven through the "throat" of the inlet into the blue lagoon by waves and flood tides.

During ebb tides, currents washing back on the barrier at the estuarine mouth and down the beach have led to the deposition of ebb tidal delta just immediately offshore into the Indian Ocean. The progradation of this ebb tidal delta is prevented by the steep near-shore slope, rapid sediment dispersal by waves and shelf currents (Cooper, 1993).

Looking at these geomorphological processes and their effects on the Mgeni estuary, it is reasonable to conclude that sediments in the Mgeni estuary emanate from lower catchment rocks, downstream channel, estuarine banks and from the sea, flushed in by flood tides. This conception is illustrated in Figure 7.1.

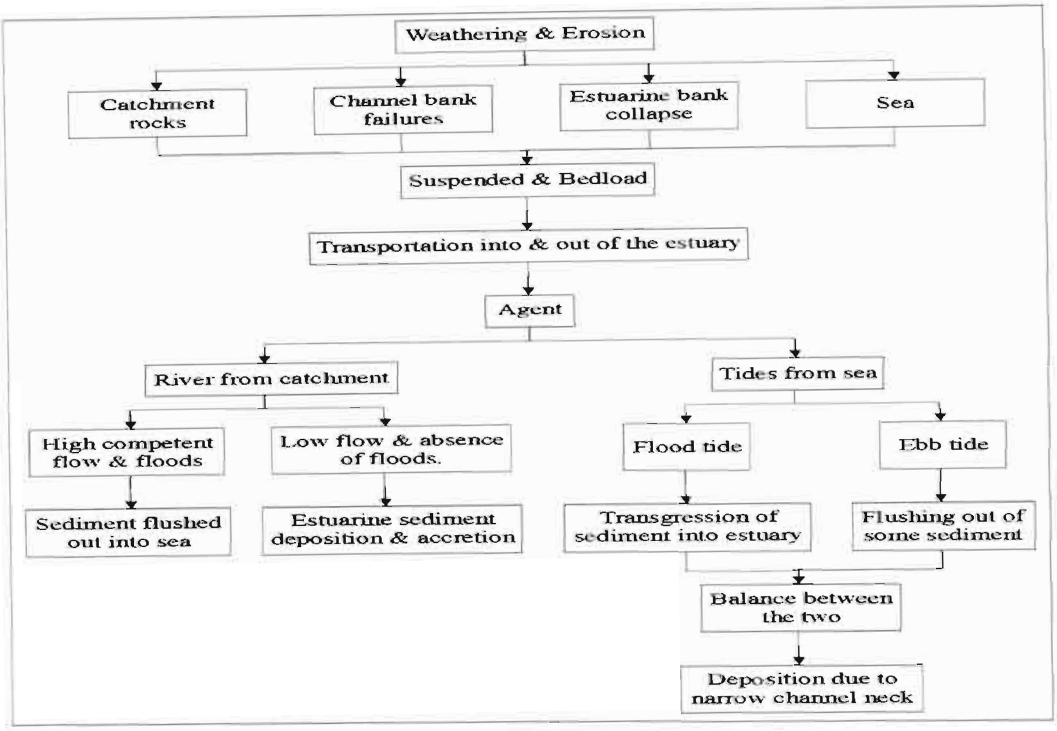


Figure 7.1: Estuarine sediment sources and budget
(Source: Researcher, 2001)

This figure identifies weathering, catchment land uses and erosion as major processes that release sediments from catchment rocks, the downstream channel, estuarine banks and the sea. They are transported into the estuary as suspended and bedload by the river or tides and may either be flushed out of the estuary or deposited depending on the competence and velocity of flow or ebb tide. In relation to the Mgeni estuary, the steps beginning with low flow and absence of floods on the one hand and tides from the sea on the other hand seem to be the determining processes leading to sediment deposition, the development of deltas, sand banks, mud flats and the evolution of the central island.

7.8 Channel Migration

Flood and ebb tidal currents occasionally affect the stability of estuarine mouths. Bruun (1978) claims that ebb currents may not always follow the same path as the flood tide, a process referred to as "mutual evasion" of flood and ebb channels. The Mgeni estuary now occasionally manifests this tendency. In this migratory process, material is flushed from one side of the barrier at the mouth to another by ebb currents. Since a groyne stabilizes the south bank of the estuarine mouth, ebb current gradually transport sediments from the barrier against the groyne. This situation is compounded by the progressive southward progradation of the barrier at the mouth causing periodic closure of the inlet causing ebb current to gradually nibble through the barrier for a new channel. This channel migratory process was identified in the estuary on August 2000 when the channel was found to be an open throat along the groyne situated on the south bank. In September 2001 however, a new channel had developed away from its 2000 position further to the north along the barrier at the mouth. Another reason for this migration could be the coriollis force hypothesis (Pethick, 1984) which states that a fluid or free moving force will be diverted to its right in the northern hemisphere and to its left in the southern hemisphere. This probably explains why the incoming flood tides prefer the southern bank, to its left along the groyne while the downward ebb currents prefers a new channel to its left further from the groyne. Moreover, it is also believed that most channel inlets on littoral drift coasts migrate in the direction of the prevailing littoral drift (Bruun, 1978).

The geomorphological impacts of the Inanda dam are summed in Figure 7.2. Notable on this figure are immediate post dams effects at the Mgeni estuary as identified by Moleko (Compare with Figure 3.2), the present as well as projected future changes.

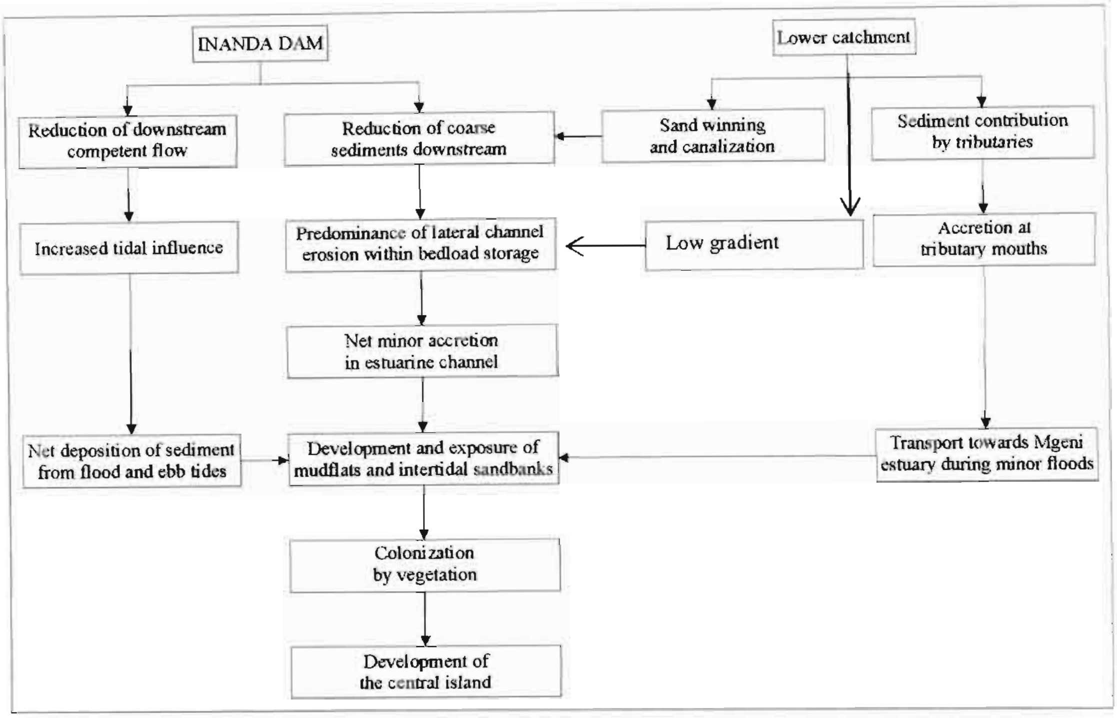


Figure 7.2: Recent geomorphological impacts of the Inanda dam and possible future trends at the Mgeni estuary
(Source: Researcher, 2001)

7.9 Summary

An examination of the various geomorphological and other processes influencing the estuary has been the best way to add reason to the changes realised since 1997. These include terrestrial, climatological, geological as well as human induced (anthropological) processes. Thus in one way or the other, the estuary is subjected to change confirming the hypothesis that rivers and estuarine systems are dynamic entities (Cooper, 1993; Knighton, 1984; Pethick, 1984). Having finished with the explanation of the perceived changes, the last chapter presents as a conclusion, an appraisal of Moleko's (1997) Model, which was the main aim of this study.

CHAPTER EIGHT

AN APPRAISAL OF MOLEKO'S (1997) MODEL

8.1 An Evaluation of Moleko's (1997) Model

The Inanda Dam conceived in 1982/3 and whose construction was completed in 1989, had prompted various studies and predictions on the possible ecological, social and geomorphological impacts (Archibald et al. 1988 and 1990; Cooper, 1987; CSIR, 1984; Diab and Scott 1989). In 1997, Moleko investigated and compared pre- and post-dam downstream channel, sediment and hydraulic characteristics to test predicted consequences of the dam. However, he propagated a conceptual model of future change for the estuary, prompting this study whose main aim has been to test Moleko's model (section 1.5). Having carried out this follow-up study the concluding appraisal of Moleko's (1997) model is as follows:

Table 8.1: An evaluation of Moleko's 1997 Model

Moleko's (1997) Predictions	Evaluation Using the 2000 Results
In the future, the channel will scour gradually due to low contribution of sediments from the tributaries and upstream trapping of catchment derived material assuming a continuous competent discharge.	Contrary to this 1997 assumption, downstream dam release has fallen and channel cross-sectional profiles show a net accretion and may likely remain in this state or further accrete unless flushed by a sudden flood event. The net accretion reveals that the rate of sedimentation (especially of mud) is above the rate of increase in channel volume.
The recovery of the central island is in process.	The central Island is still recovering as noted in 1997 by Moleko.
A massive reduction in the quantity of coarse and fine sediments in the estuary will occur.	Certainly there has been a massive reduction of coarse sediments (by about 35%) and a corresponding increase in mud.
There will be continued flushing of existing channel sediments downstream towards the estuary, without replacement from upstream sources.	There has been evidence of flushing towards the estuary mouth as gravel has shifted further downstream from its 1997 upper reach probably the effect of some minor seasonal flood event.

The will be site-specific channel bed erosion at times of peak water release.	The channel has experienced site specific bed erosion as was predicted especially along cross-sections B, C, and D with A having eroded all along its profile.
Approximate volume equilibrium at the main sediment sink-the estuary-until such a time as sediment stored in the channel has all been flushed through the system.	Though not possible to compute the actual sediment volumes, it is estimated that there has been a slight net accretion of about 59.7 m^2 of sediment in estuarine bed.
Gradual build up of sediments near the estuary mouth until an exceptionally high discharge event capable of moving material through the opening and out to the sea against tidal and coastal currents occurs.	The estuarine mouth is experiencing mud accumulation fulfilling its role as a sediment sink (Pethick, 1984). This is evident from the increase in mud fraction over the 1997 value by about 35 %
Gradual fining of bed-load channel and estuarine sediments due to the retention of coarse sediments in the system behind the Inada Dam, poor coarse sediment contribution from the main tributaries below the dam and continued extraction of this fraction by sand winning activities.	Coarse sediments have reduced by about 35 %, while fine sediments have increased by about the same percentage confirming this prediction.
If the same water release policy is maintained, then a gradual reduction in fluvial sediment volume of the estuary once channel flushing is completed, in sections near the mouth this could be balanced to some degree by incoming material transported by tidal and coastal currents.	Unlike predicted in 1997, the lease policy did change. In fact the mean monthly discharge values indicate that present peak daily water release below the dam, which ranges between 1.4 and 27.7 m^3sec^{-1} is far lower than the 1997 releases, which was of the order 4.6 to 72.2 m^3sec^{-1}. As a result, the effects of incoming tides have increased contributing fine sediments to the mouth.

(Source: Moleko, 1997 and Researcher, 2001)

In addition to these evolutional changes and although not investigated by Moleko in 1997. the 2000 survey showed that:

1) Sediment in the estuary is positively skewed indicating a predominance of fine sand over mud and gravel and is poorly sorted, which signify limited bed load transportation. The most occurring grain size or modal grain size is 0.20 m with a median of 0.28mm, indicating half of sediment in the estuary is greater than and half less than that grain size. Sediment distribution in the estuary exhibits a leptokurtic distribution a diagnosis of peak distribution.

2) The south bank, made of weaker materials is eroding faster than the north more resistant bank.

3) Lights minerals make up 98% sediment in the estuary and are predominant among sand, while heavy minerals, which accounts for 2% favours silt and mud. Heavy minerals are found mostly at the mouth of the estuary just around and below Ellis Brown Viaduct while light minerals are distributed further north inland.

5) The Mgeni estuary is presently at Cooper's (1993) stage D and E of post-flood/post-dam transition towards recovery. These stages are symbolized by braiding, colonization by vegetation and a tendency towards coalescence as shown on Figure 8.1, digitised from the 1999 area photo.

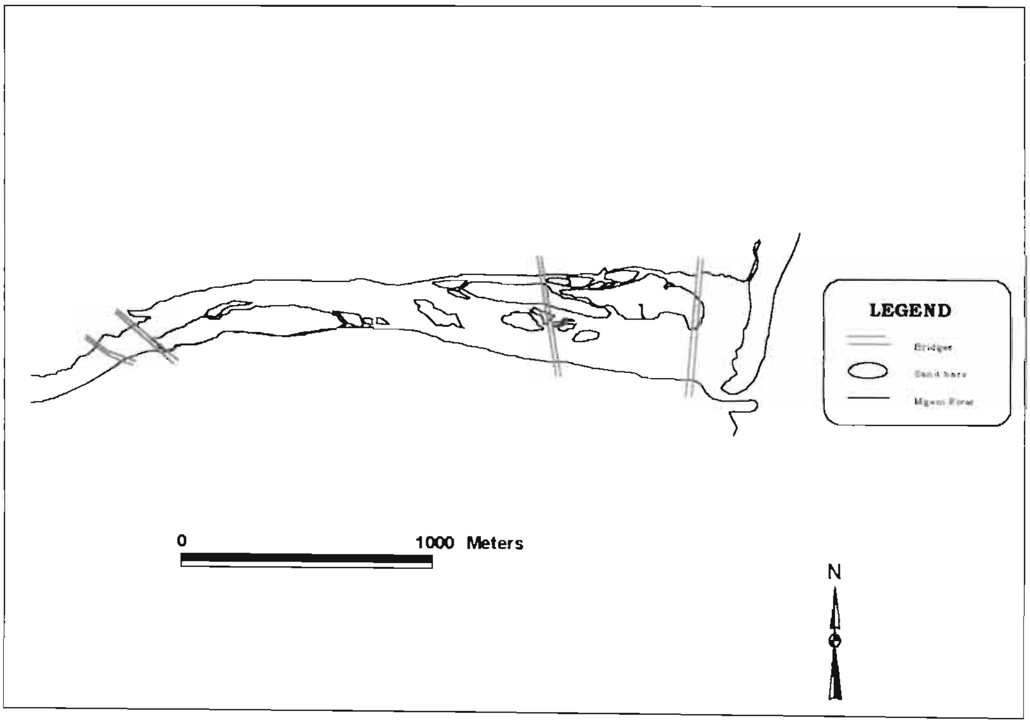


Figure 8.1: Present Mgeni estuarine channel At the D &E of Copper's Post-Dam recovery Stage

(Source: Digitised from 1999 rectified aerial photo, City Engineers)

Moleko in 1997, attributed most of the post-dam changes to the closure of the dam than to downstream engineering modifications and extreme events. This seem to remain the predominant cause of current changes and are compounded by other factors like bank material composition, boat-wash and tidal influx. Overall, hydrology seems to be the driving factor that has determined further post dam impacts on the Mgeni estuary.

8.2 Conclusion

Three years after Moleko (1997) predicted a conceptual model of change for the Mgeni estuary, its verification in 2000 confirm some of his projection but not all. Though not Moleko's entire model fulfilled as envisioned, this does not invalidate the model since the number of competent immediate downstream flows decreased and some of predictions will take time to occur. However seeing that river channels and estuaries are dynamic entities as confirmed by the current trends of geomorphological processes downstream of the Inanda Dam, it can reasonably be predicted that:

I. Sediment distribution and characteristics will continue to alter as long as dam management continues to alter their release policy accompanied by minor episodic flood events and sand wining activities.

II. There will continue to be a gradual fining of sediment in the estuary especially towards the mouth as most of the coarse sediments are still retained behind the dam and as sand winning continues to deprive the estuary of sand.

III. The southern Channel banks will continue to erode unless some major steps are taken to stabilize them.

IV. The upper end of the estuary is likely to stabilize through bed armouring (Thorne, 1998) as no further input of fluvial sediment encourages cementing of the existing bedload.

V. The channel form and central the developing central island is gradually moving towards is pre-flood and pre-dam geometry which Cooper (Cooper, 1993) theorized will culminate with the development and vegetation of the central island.

This study is by no means a complete examination of all aspects of dam impacts on the Mgeni estuary. Emerging areas of research subject to further investigation include:

a) The source or provenance of heavy minerals in the Mgeni estuary.

b) The response of aquatic organisms to post dam sediment and hydro-dynamics in the Mgeni Estuary.

c) Tidal response to diminishing fluvial influence in the Mgeni estuary.

d) Determining post-dam salinity level and tidal prism in the Mgeni estuary.

e) Post-dam vegetal colonisation on the central island at the Mgeni estuary.

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SKR Consulting (Engineers and Scientists), a consulting company based in Durban.

Umgeni water, Pietermaritzburg, water utility company

APPENDICES

Appendix 1.1

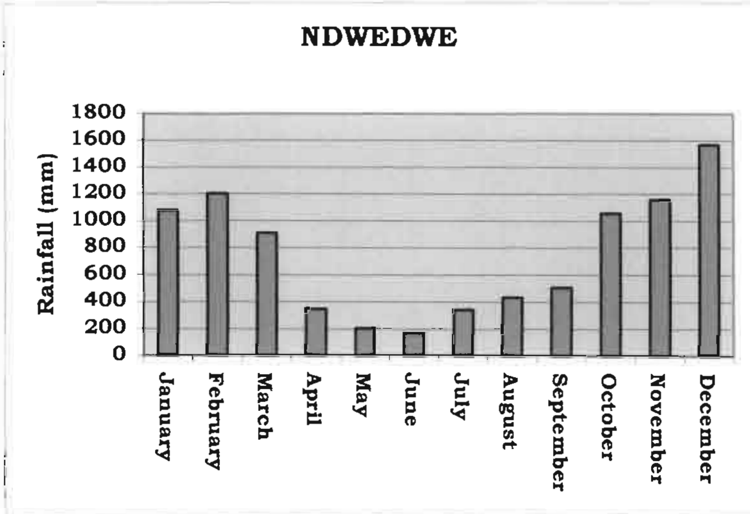
Mean Monthly Rainfall for Four Selected Stations in the Lower Mgeni Catchment.

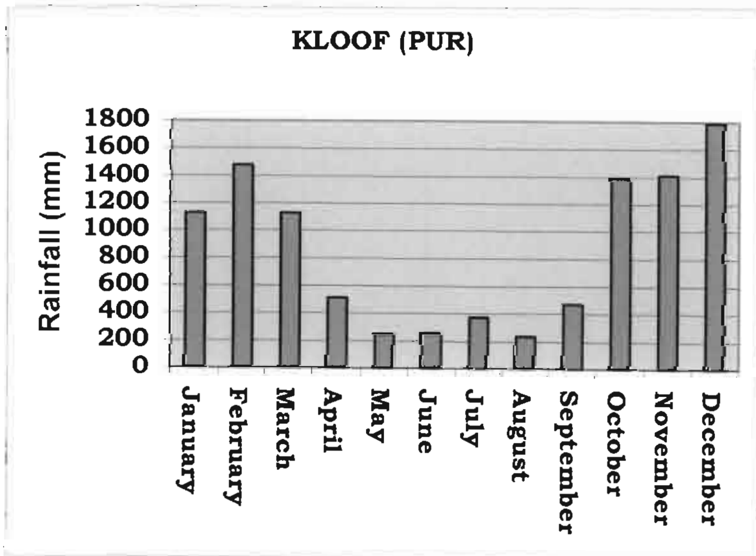
Mean Monthly Rainfall (mm) From 1989-1999

Month	Ndwedwe	Bothas Hill	Kloof (Purification)	Shongweni
January	1077.8	1366.5	1124.5	817.7
February	1203.3	1034.9	1475.9	956.9
March	909.4	760.0	1124.5	884.5
April	347.5	545.7	510.2	302.8
May	200.5	157.3	249.1	184.6
June	164.5	158.8	254.5	175.3
July	340.9	160.5	372.8	286.9
August	435.1	131.5	236.4	102.8
September	504.6	532.7	469.1	291.8
October	1055.7	1107.5	1389.5	828.4
November	1158.2	1665.3	1412.0	1077.5
December	1569.4	1764.2	1785.5	1362.4

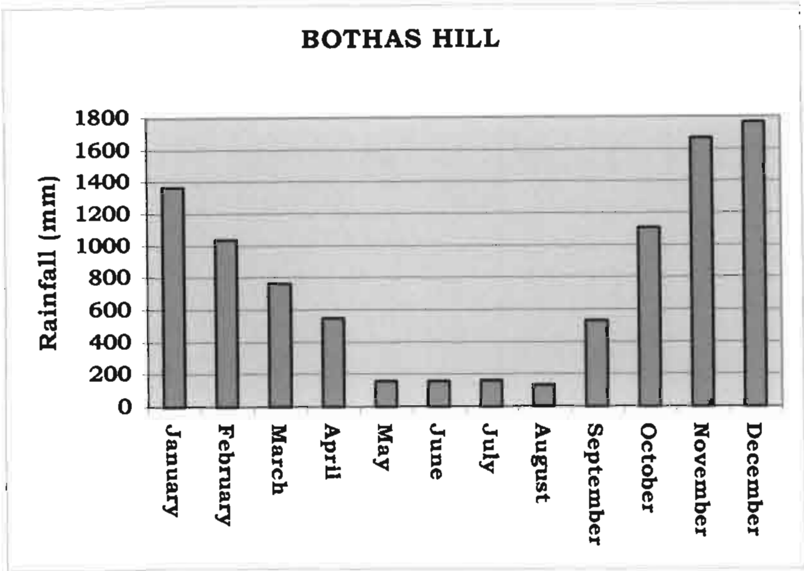
Appendix 1.2

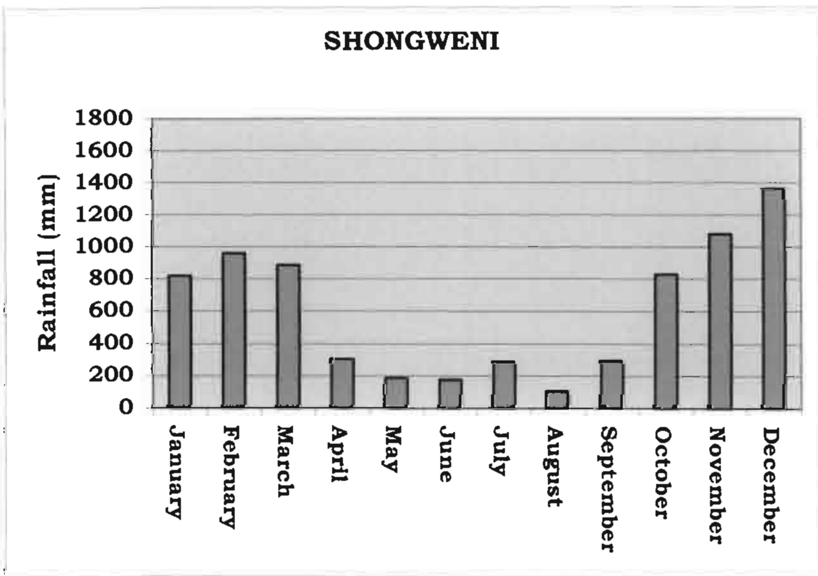
Graphical Presentation of Rainfall on the Mgeni Lower Catchment.





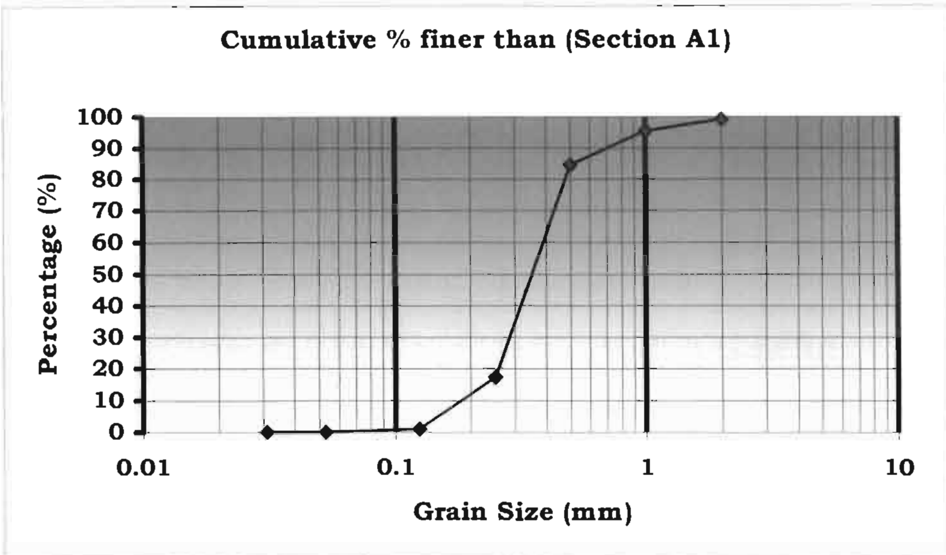
Appendix 1.2 cont'd

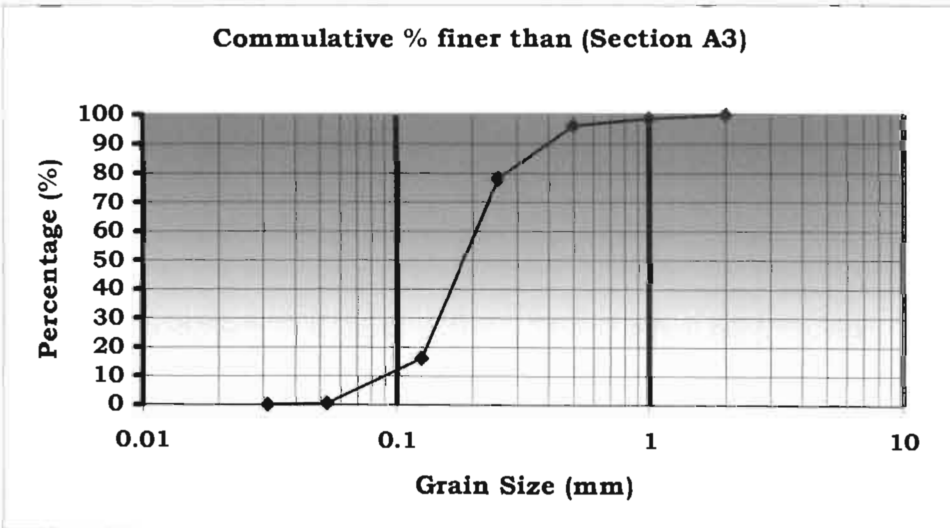


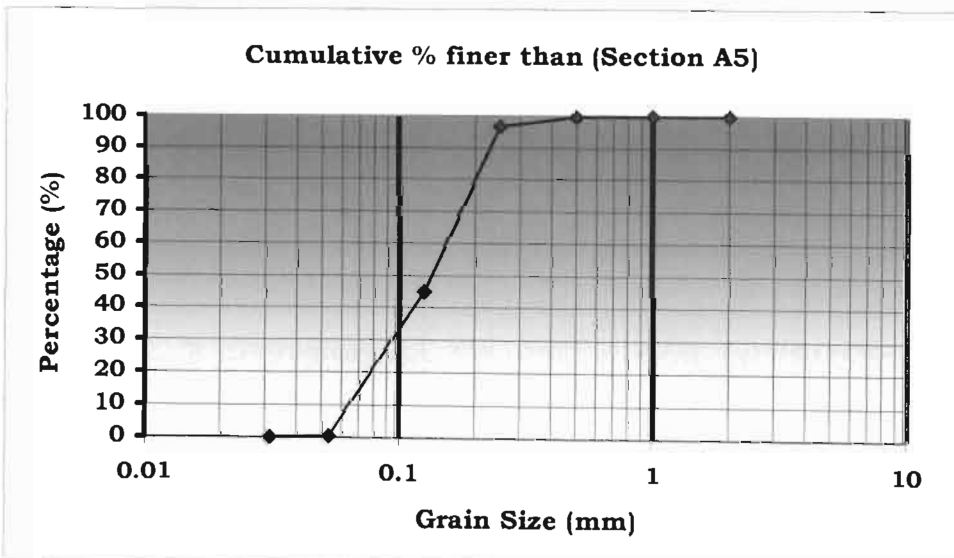


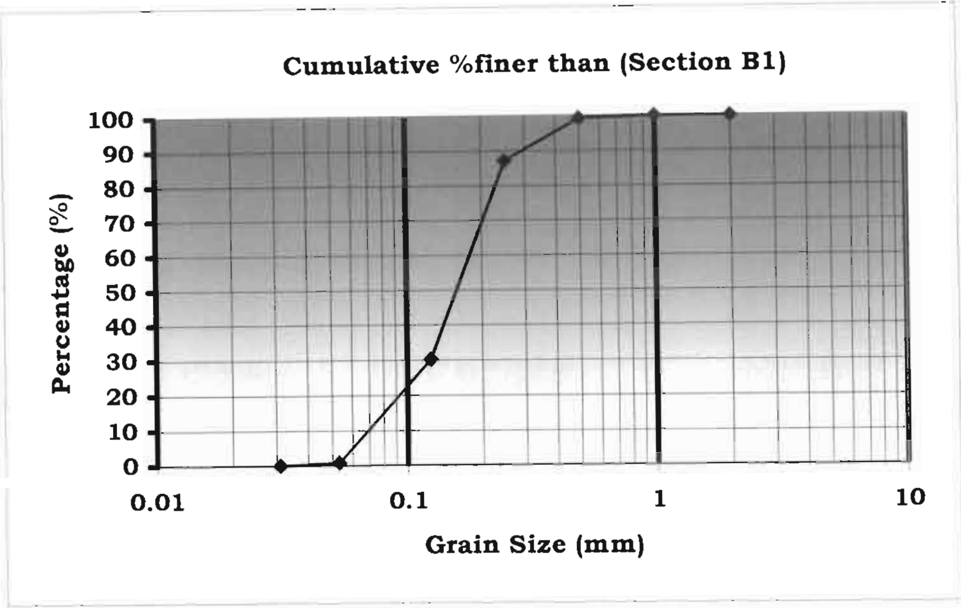
Appendix4.1

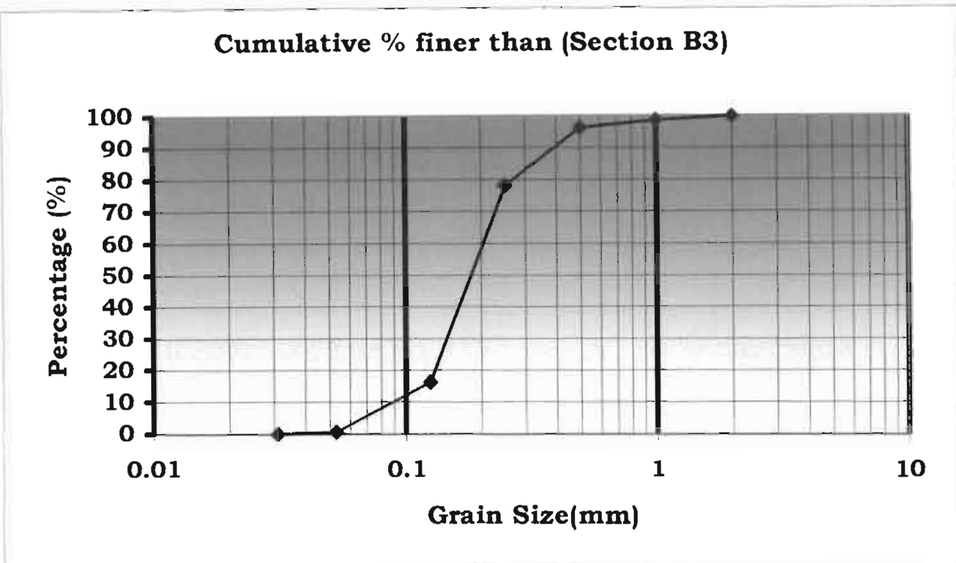
Percentage distribution of sediment grain sizes for each sample








Cumulative %finer than (Section B1)
Percentage (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Grain Size (mm)


Cumulative % finer than (Section B3)
Percentage (%)
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30
20
10
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0.01
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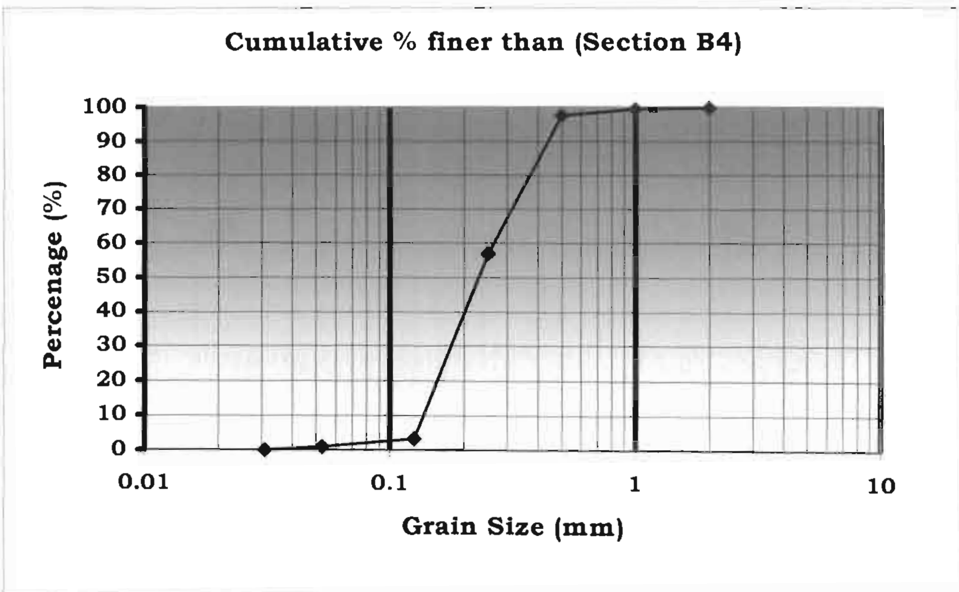
1
10
Grain Size(mm)


Cumulative % finer than (Section B4)
Percenage (%)
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70
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50
40
30
20
10
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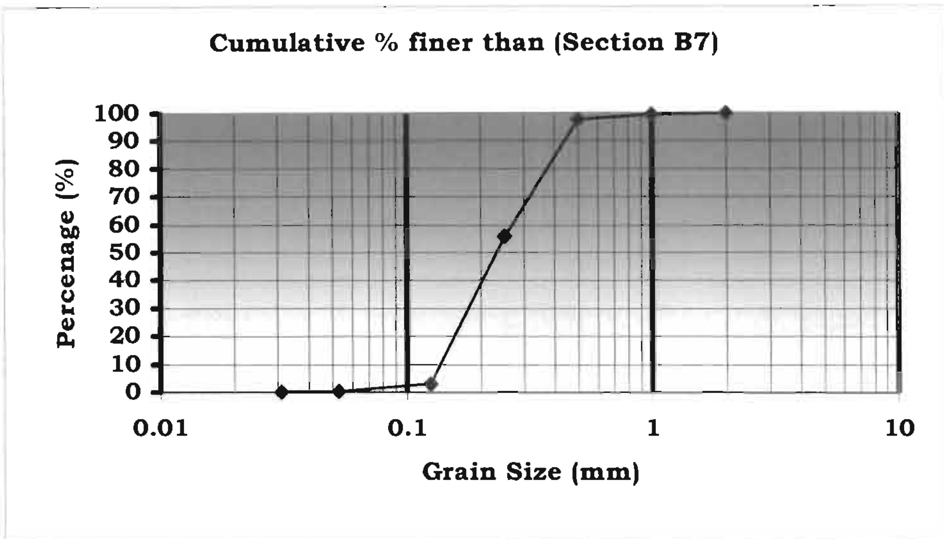
0.01
0.1
1
10
Grain Size (mm)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Percenage (%)
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50
40
30
20
10
0
0.01
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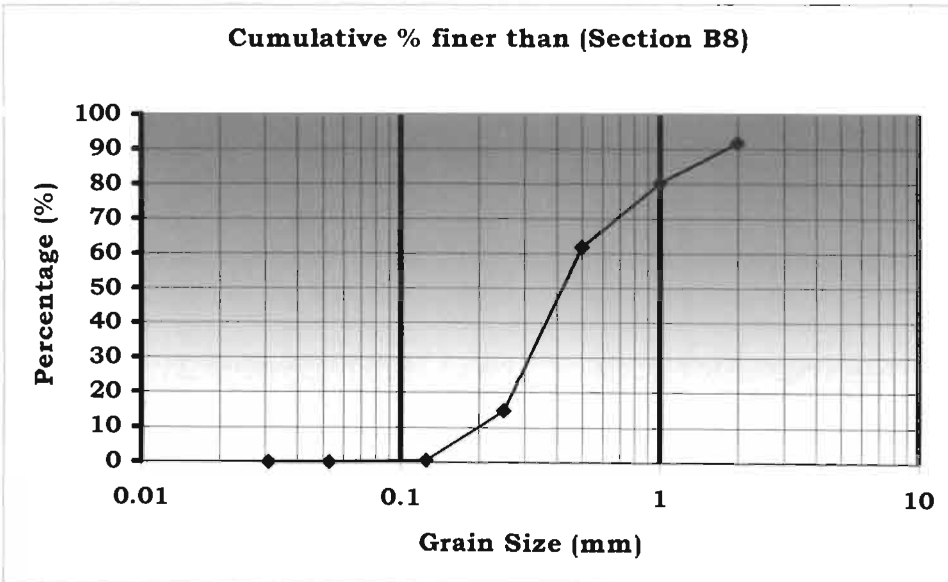
1
10
Grain Size (mm)


Cumulative % finer than (Section B8)
Percentage (%)
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60
50
40
30
20
10
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0.01
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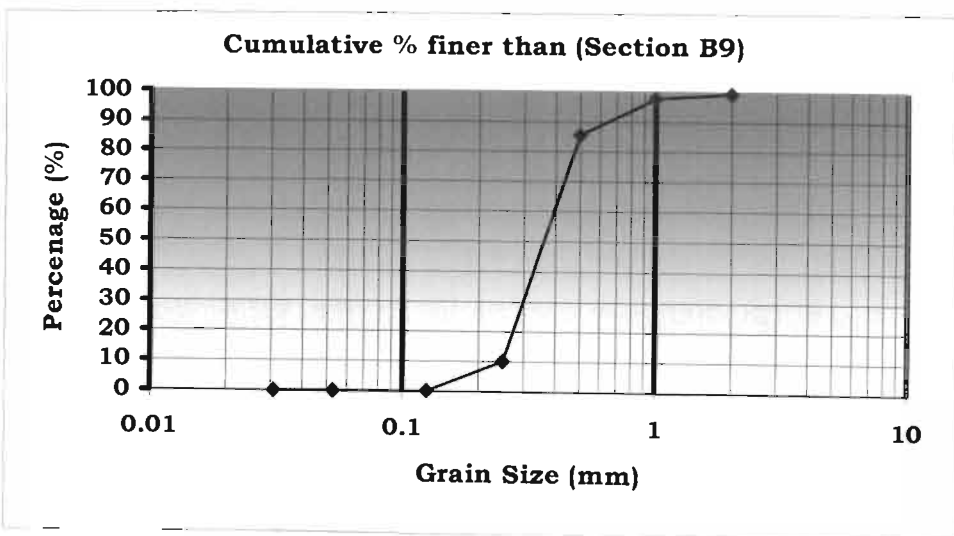
1
10
Grain Size (mm)


Cumulative % finer than (Section B9)
Percenage (%)
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60
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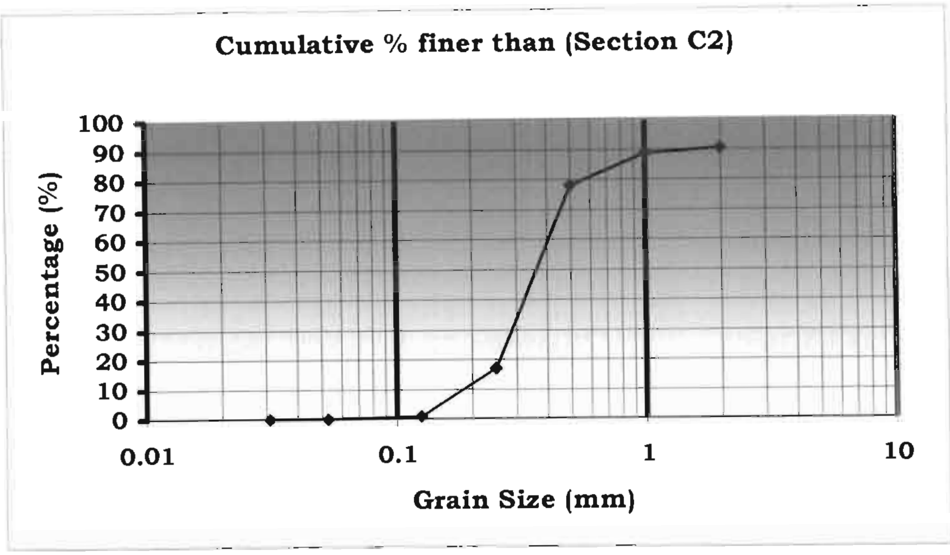
40
30
20
10
0
0.01
0.1
1
10
Grain Size (mm)


Cumulative % finer than (Section C2)
Percentage (%)
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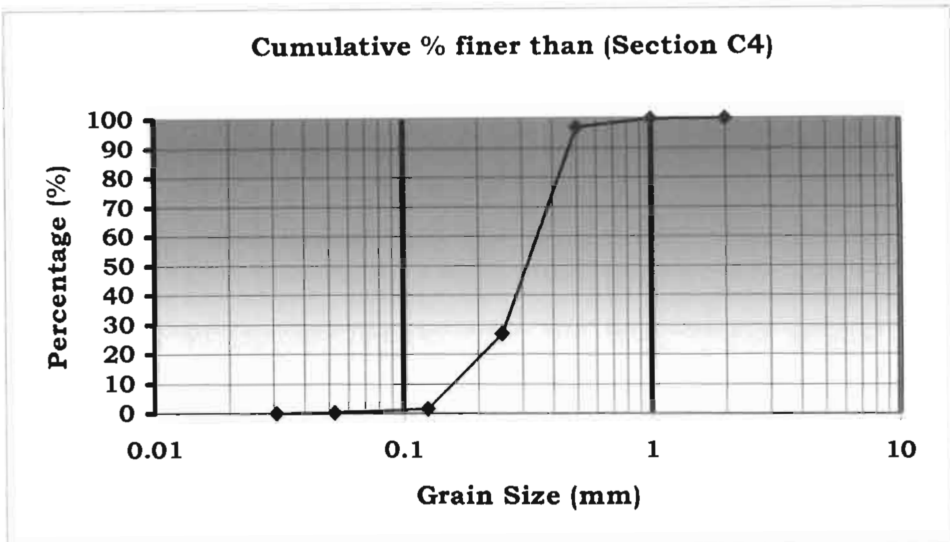
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Grain Size (mm)


Cumulative % finer than (Section C4)
Percentage (%)
100
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60
50
40
30
20
10
0
0.01
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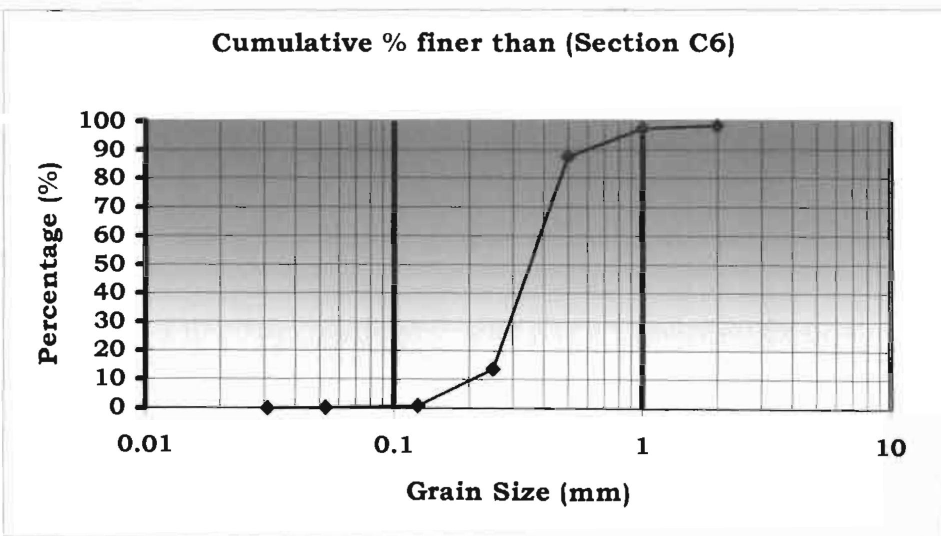
1
10
Grain Size (mm)


Cumulative % finer than (Section C6)
Percentage (%)
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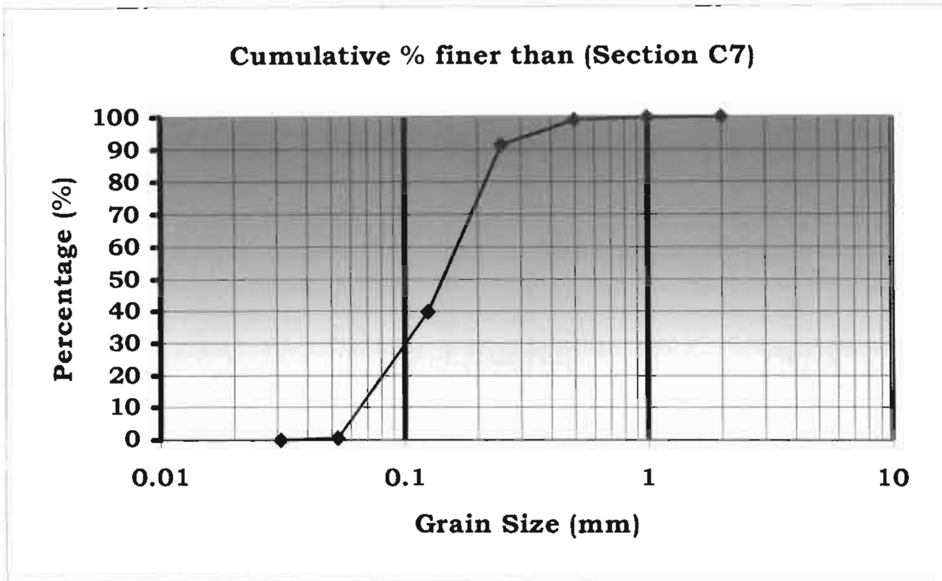
50
40
30
20
10
0
0.01
0.1
1
10
Grain Size (mm)


Cumulative % finer than (Section C7)
Percentage (%)
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60
50
40
30
20
10
0
0.01
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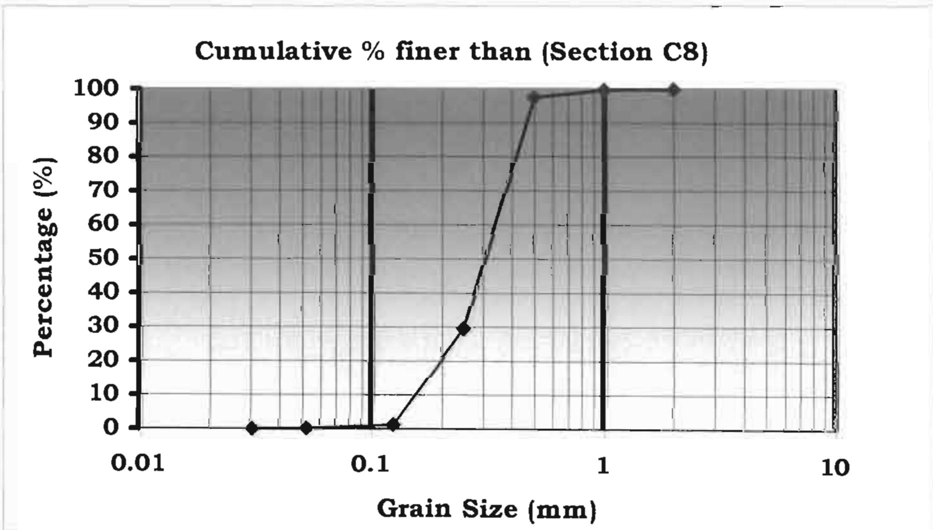
1
10
Grain Size (mm)


Cumulative % finer than (Section C8)
Percentage (%)
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30
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0.01
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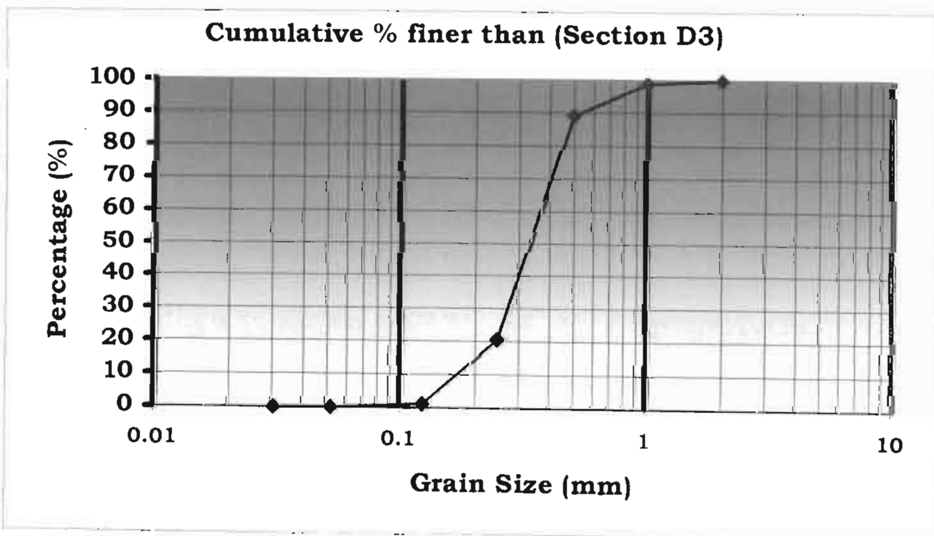
1
10
Grain Size (mm)


Cumulative % finer than (Section D3)
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40
30
20
10
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0.01
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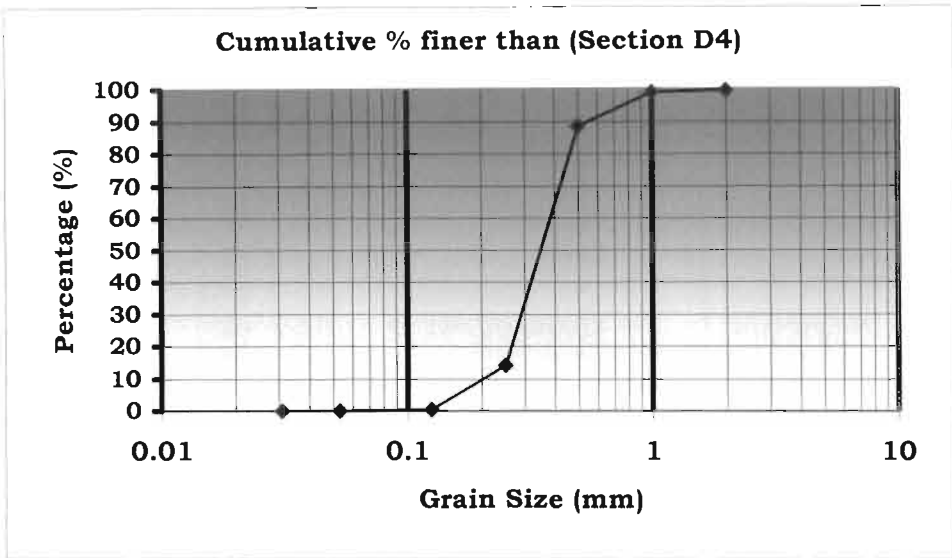
1
10
Grain Size (mm)


Cumulative % finer than (Section D4)
Percentage (%)
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70
60
50
40
30
20
10
0
0.01
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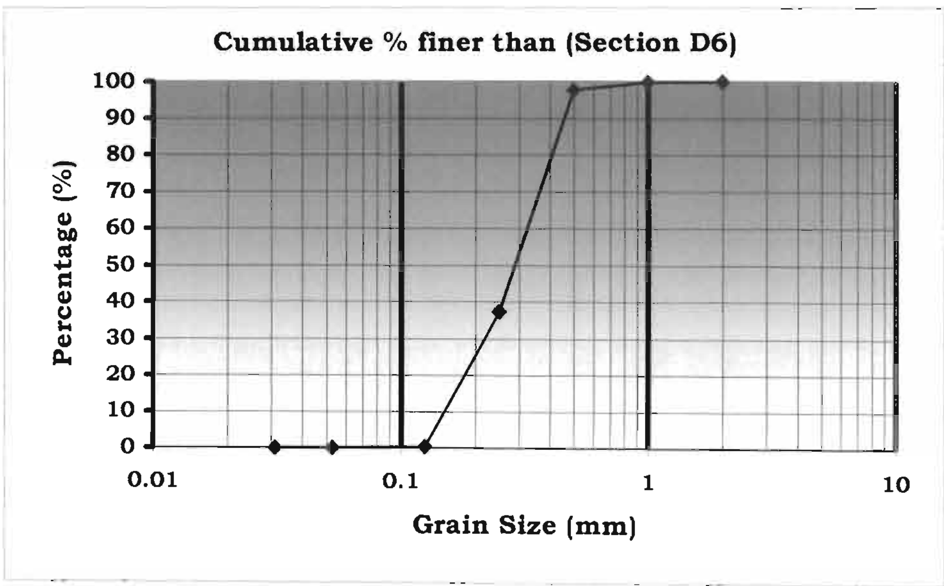
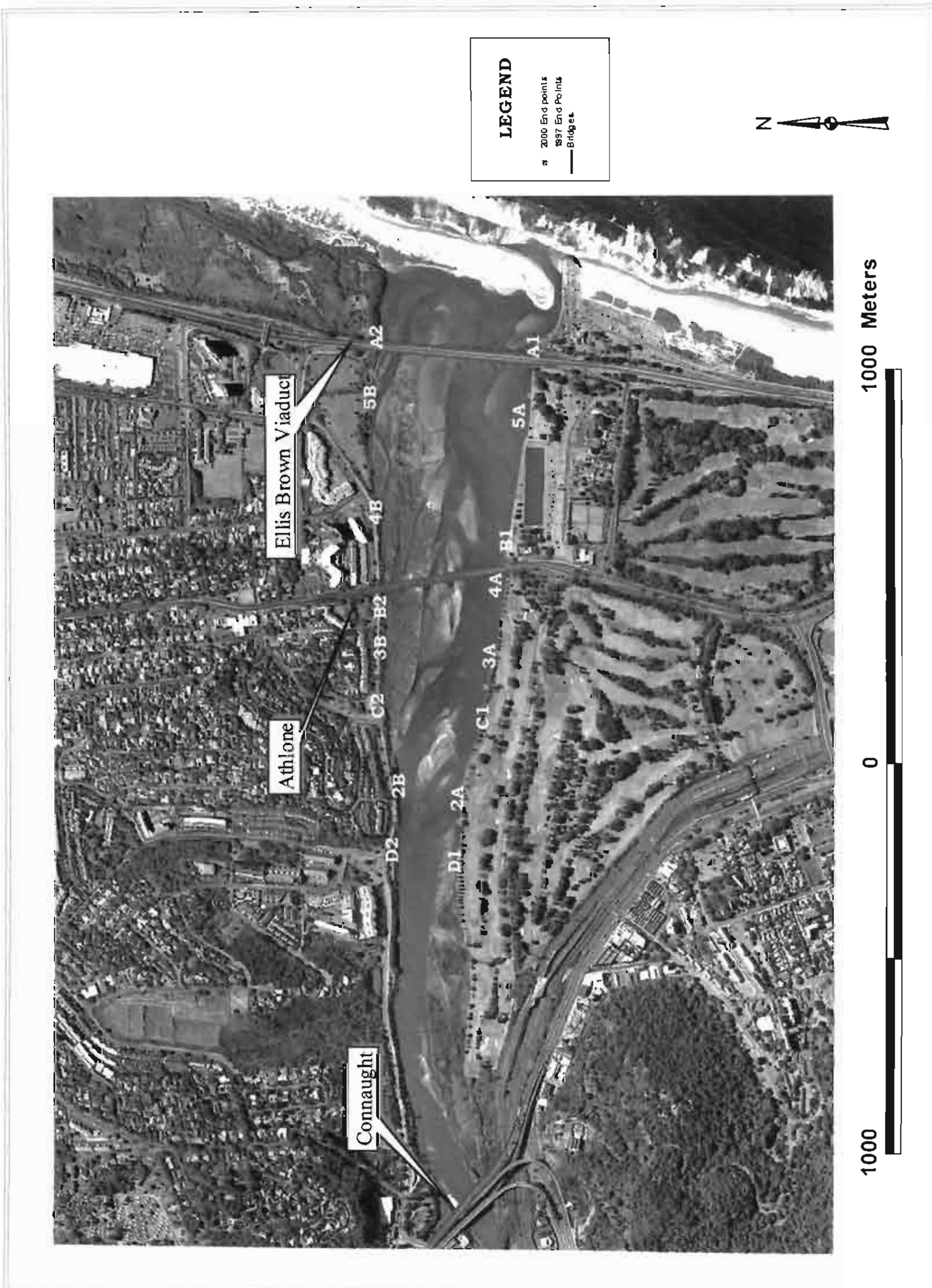
1
10
Grain Size (mm)


Cumulative % finer than (Section D6)
Percentage (%)
100
90
80
70
60
50
40
30
20
10
0
0.01
0.1
1
10
Grain Size (mm)

Appendix 4.2

The 1997 and 2000 Cross-section End Points Showing Bridges as Recognisable Land Marks



Appendix 4.3

Attributes of 1997/2000 End Points

1997 Survey end points			
Yaer	**Longitude**	**Latitude**	**Section**
1997	2576.26	-3298586	2B
1997	2550.04	-3298756	2A
1997	2923.62	-3298544	3B
1997	2893.87	-3298827	3A
1997	3270.99	-3298541	4B
1997	3209.05	-3298882	4A
1997	3695.54	-3298531	5B
1997	3638.83	-3298944	5A

2000 Survey end points				
Year	**Longitude**	**Latitude**	**Height**	**Section No**
2000	3737.96	-3298544.22	1.06	A2
2000	3704.77	-3298945.19	2.54	A1
2000	3161.20	-3298543.95	7.35	B2
2000	3217.22	-3298882.60	2.64	B1
2000	2918.37	-3298542.93	6.91	C2
2000	2907.05	-3298828.45	1.02	C1
2000	2542.84	-3298584.50	6.64	D2
2000	2528.52	-3298756.93	-0.14	D1

Appendix 4.4

Heavy and Light Mineral Composition in the Mgeni Estuary

Sample No	Dry sample wt (g)	Heavy wt (g)	Heavy %	Light wt (g)	Light %
A1	50.49	0.87	1.72	49.62	98.28
A3	50.1	1.2	2.40	48.9	97.60
A4	50.41	3.05	6.05	47.36	93.95
B1	50.36	0.82	1.63	49.54	98.37
B3	50.38	1.07	2.12	49.31	97.88
B4	50.51	1.31	2.59	49.2	97.41
B7	50.22	1.79	3.56	48.43	96.44
B8	50.23	0.69	1.37	49.54	98.63
B9	50.31	0.75	1.49	49.56	98.51
C2	50.33	0.8	1.59	49.53	98.41
C4	50.31	1.29	2.56	49.02	97.44
C6	50.46	0.95	1.88	49.51	98.12
C7	50.21	1.26	2.51	48.95	97.49
C8	50.36	1.58	3.14	48.78	96.86
D3	50.26	2.02	4.02	48.24	95.98
D4	50.3	0.9	1.79	49.4	98.21
D6	50.4	0.61	1.21	49.79	98.79

Appendix 5.1a

Graphical Statistics For Sediment in the Mgeni Estuary

Sample Number	Mean	Median	Mode	Skewness	Sorting	Kurtosis
A1	0.36	0.35	0.25	0.23	1.65	1.64
A3	0.19	0.18	0.125	0.43	0.95	1.58
A5	0.14	0.17	0.125	0.04	0.62	0.83
B1	0.17	0.17	0.125	0.00	0.74	1.10
B3	0.19	0.19	0.125	0.36	0.91	1.81
B4	0.25	0.25	0.125	0.37	1.14	0.93
B7	0.25	0.24	0.125	0.33	1.16	0.93
B8	0.51	0.42	0.25	0.72	3.71	1.66
B9	0.37	0.37	0.25	0.25	1.60	1.32
C2	0.35	0.37	0.25	0.64	3.04	8.66
C4	0.32	0.32	0.25	-0.03	1.31	1.02
C6	0.33	0.35	0.25	0.88	1.53	1.40
C7	0.15	0.15	0.125	0.04	0.67	0.89
C8	0.31	0.31	0.25	0.01	1.30	0.94
D3	0.34	0.34	0.25	0.09	1.46	1.22
D4	0.36	0.35	0.25	0.18	1.46	1.15
D6	0.38	0.29	0.25	0.33	1.52	1.27
Average	0.29	0.28	0.20	0.29	1.46	1.67

Appendix 5.1b: Mean Statistical Values Per Cross-Section

Sections	Mean	Media	Mode	Skewness	Sorting	Kurtosis
A	0.23	0.23	0.17	0.24	1.07	1.35
B	0.29	0.27	0.17	0.34	1.55	1.29
C	0.29	0.30	0.23	0.31	1.57	2.58
D	0.36	0.33	0.25	0.20	1.48	1.21