Shoreline Changes on the Natal Coast

Tugela River Mouth to Cape St Lucia

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Contents

Foreword

This volume, "*Shoreline Changes on the Natal Coast, Tugela River Mouth to Cape St. Lucia* " is the first of three to be produced for the Natal Town and Regional Planning Commission concerning possible migrations of the shore.

The coastal zone of Natal contains areas of outstanding natural beauty and considerable environmental consequence. It also contains a large and significant proportion of the population, industry and infrastructure, as well as some of the most productive agricultural land to be found in the Province.

This series of reports has been commissioned in response to possible changes in the present shoreline. Analysis is made of the separate impacts from the current geological processes of erosion and deposition and the longer term effects of a global rising in sea level caused by a general warming of the Earth's climate responding to the "*Greenhouse Effect* ".

Should either these local or global processes have some of the predicted impacts, the results for the Province could be significant and possibly disastrous.

From the data presented on current geological processes and with reference to historical shoreline movements the author has provided scenarios for future developments. With this report the critical issues concerning the location of infrastructure relating to rail, road and sea links, as well as the siting of major developments, residential dwellings and tourist facilities can be addressed well in advance.

The Natal Town and Regional Planning Commission believes that this initiative will be of use to planners, municipal authorities and developers. It also contains information of interest to seaside residents, scientists and conservationists and will, it is believed, make a useful contribution to the future of coastal zone management in the Province of Natal.

D.V. Harris
Chairman, Natal Town and Regional Planning Commission

Executive Summary

A study of historical shoreline migration was conducted along the 135 km section of the Natal coast between the Tugela River mouth and Cape St Lucia. Measurements of the position of the high water mark were made from digitised images of several sets of historical aerial photographs dating from 1937 to 1983. These were reduced to 1:10 000 scale for comparison. Future shoreline positions were estimated on the basis of a straight line projection of historical rates.

In general it was found that the entire 55 km of coastline between the Tugela River mouth and 10 km north of the Mlalazi River mouth, is accreting by means of beach ridge formation, at highly variable net rates, up to 5 m/year. Most of this sediment is derived from the Tugela and the Matigulu Rivers and is augmented by sand arriving in the area by longshore drift from the south. The Mlalazi River carries little sand to the littoral zone. Maximum accretion occurs about 5 km north of the Tugela River and in several large-scale coastal concavities where accretion has tended to straighten the coastline. North of the Mlalazi River mouth accretion rapidly diminishes. Reasons for this decrease include a decrease in carrying capacity of sand by longshore drift and even a possible drift reversal north of the Mlalazi River, which has resulted in deposition of sand in this area.

Two areas of marked coastal erosion were present. A 6 km stretch of coast backed by cliffs cut into Pleistocene sand dunes is eroding in the area around Port Durnford. Its erosion may be, in part, a response to accretion further south, as the coastline seeks to maintain equilibrium. A second eroding sector occurs on the 24 km stretch north of Richard's Bay. This area is backed by high, cliffed dunes. High standard deviations from the mean erosion rate may reflect episodic collapse of cliff faces and subsequent beach progradation.

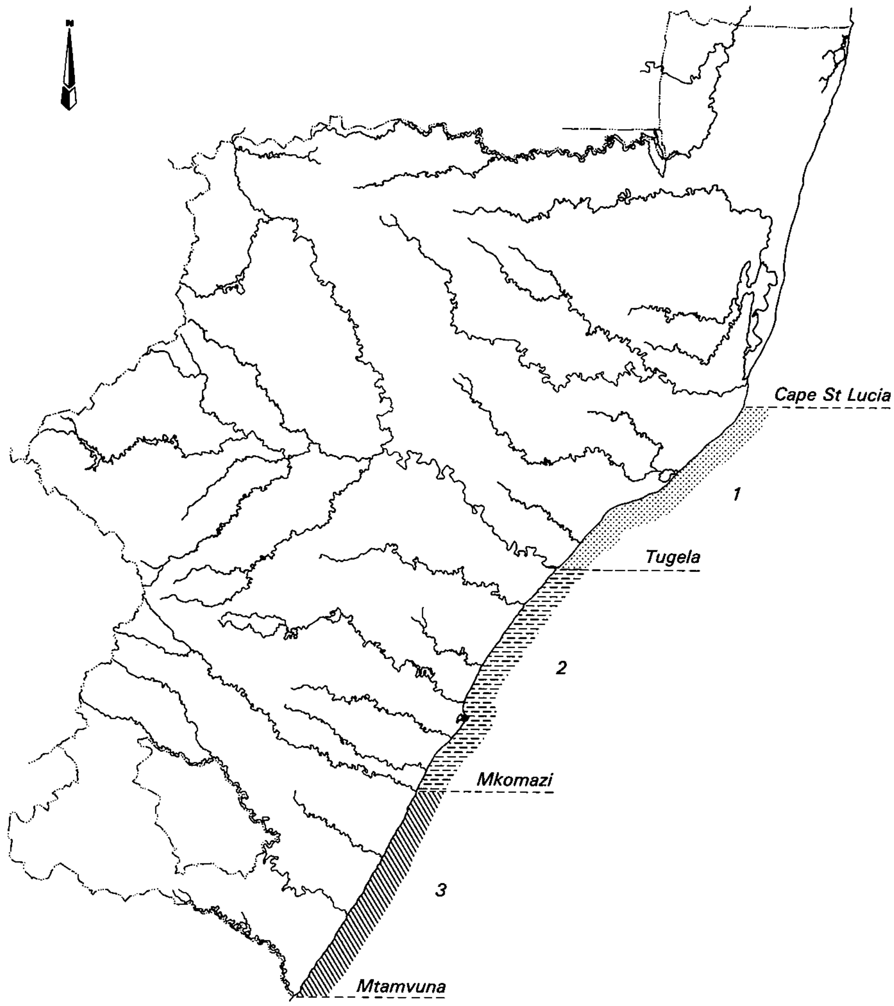
The effect of Richard's Bay harbour has been to disrupt the sedimentary cycle in that area by destroying the former sand dunefield in which a large proportion of northward-moving wind-blown sand would have accumulated. It also created a new sand accumulation against the southern breakwater.

Elsewhere, the coast shows very low rates of change, being generally accretionary with low standard deviation from the mean but the rates of shoreline migration are so low as to be insignificant. This low accretion may be a response to increased sand supply from cliff collapse in adjacent eroding areas.

The total length of eroding coastline was 44 km or about 33% of the total coastline being studied. Seventy-three kilometres or about 54% of the coastline is accreting. This includes the 6 km of coastline situated on the severely disturbed section of coast between Richard's Bay sanctuary entrance and the harbour mouth. The 9 km stretch of coastline (4%) north from this is subject to direct human influence through inputs from artificial sand pumping. This, coupled with the remaining 9 km, which may be regarded as relatively stable in the long term accounts for about 13% of the coastline.

Afforestation during the 1960s appears to have reduced the storage capacity of formerly unvegetated dunes and has altered the sediment budget. This requires further investigation. The potential impacts of future development on shoreline position are discussed.

Preface



The map of Natal shows the coastal areas covered in the first three phases of this research. Mapping of historical shoreline positions was carried out at a 1:10 000 scale and must therefore be regarded as a reconnaissance-level survey. The results from each area are covered in 3 separate Natal Town and Regional Planning Reports. The areas are as follows:

- Area 1: Tugela River Mouth to Cape St Lucia
- Area 2: Mkomazi River Mouth to Tugela River Mouth
- Area 3: Mtamvuna River Mouth to Mkomazi River Mouth

In Area 1 significant long term trends in shoreline migration were readily discernible and classification of the coastline was made according to whether an area displays long term erosion, accretion (seaward growth), or is comparatively stable.

The nature of the coastline in Areas 2 and 3 is somewhat different to Area 1. Generally no areas of long term erosion or accretion could be identified, and consequently a different type of coastal classification was required. The classification adopted is based on coastal morphology and the response of each type of morphology to projected rises in sea level.

The reports in this series are intended to act as a guide for planning future developments along the coast but more detailed, site-specific investigations may be required in certain instances.

Introduction

Recently there has been considerable worldwide interest regarding problems of coastal erosion and shoreline movement, firstly because they are becoming more obvious particularly where they pose direct threats to development, and secondly as a result of general interest in sea level rise and its effects on coastal development. A review of the erosion or accretion status of the world's coastline reveals an overwhelming dominance of erosion (Bird, 1985). A host of recently published popular and semi-scientific articles have drawn attention to the subject (see for example; *Geotimes*, December 1985 and May 1988; Charlier and De Meyer, 1985, *Sunday Star*, Jan 8th 1989).

The Natal coastal zone is experiencing changes as a result of both natural processes and man's activities. While we have little direct control over natural processes, the Provincial authorities are charged with the task of controlling development in the coastal zone. The dramatic increase in population envisaged for Natal will place increasing pressure on residential and recreational development and the need for economic development will also exert pressure for exploitation of coastal areas for mining, industrial development, effluent disposal, and so on.

In the light of such developments a thorough knowledge of coastal zone processes is essential so that minimal interference is caused with the natural ecosystem and developments are optimally sited. This study of the *effects* of coastal and catchment processes on historical and future changes in the shoreline position is an initial step toward that goal. The natural factors involved in producing such change are numerous and varied both in nature and magnitude but include sea level rise, storm frequency and intensity, wave action, sediment supply (alongshore, on/offshore and river inputs), sediment sinks, vegetation changes, lithification of coastal sands, estuary mouth position, flood frequency and intensity. Man may affect the shoreline in many ways: directly by jetty construction (interrupting longshore drift), sand removal, construction of sea walls or gabions, destruction of vegetation, planting forests on bare sand, construction of new inlets, formation of artificial water tables (causing cliff failure); and indirectly by dam construction (reducing sediment supply and flood intensity), poor agricultural practices and construction of poor roads (both increasing sediment supply), urbanisation (increasing impervious surfaces and hence runoff). These are but a few of the many ways in which human influences have the potential to alter the position of the shoreline over long and short periods.

In dealing with coastal erosion/accretion problems, the concept that "*prevention is better than cure*" holds true. If there is no development in sensitive or dangerous areas then no problem will be perceived and the coast will be free to fluctuate to regain equilibrium. This obviates the need for complex and expensive engineering solutions which often cause additional problems.

In many developed countries of the world, studies of historical shoreline retreat have been used in policy formulation for coastal development. For example, in North Carolina, U.S.A., single family dwelling units must be set back from the foredune a distance equal to thirty times the annual erosion rate and multi-family homes (apartments, hotels) must be set back a distance equal to sixty times the annual erosion rate (Pilkey *et al.*, 1989).

Purpose and scope

The research involved in this study was supported financially by the Natal Town and Regional Planning Commission through contract 67025122 with the Division of Water Technology of the CSIR. It was initiated in 1989 following increased concern over coastal erosion, particularly in the Richard's Bay area. The project is envisaged as a three year effort, ultimately covering the entire Natal coast. This report deals with the 135 km coastal sector between the Tugela River mouth and Cape St Lucia (**Figure 1**).

The aim in this report is to document the historical changes which have taken place in the sector under discussion and to assess the mean and net rates at which change has taken place. The changes are interpreted in terms of

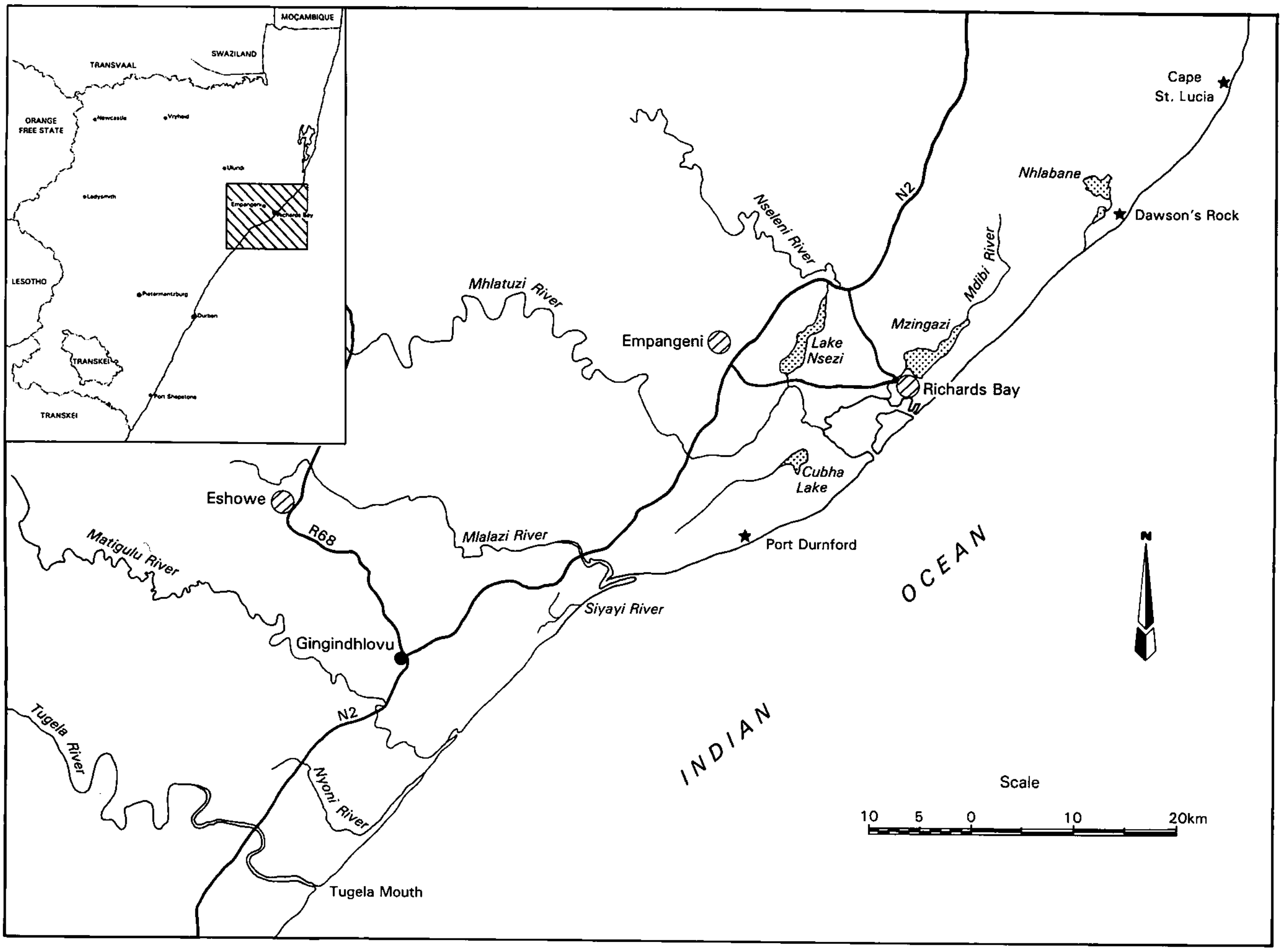


Figure 1: The key sites referred to in the text are indicated, and the location of the study area in relation to Natal is shown in the inset. For a more detailed locality definition refer to the 1:50 000 topocadastral maps in Appendix 4.

the causative processes as far as possible. Future shoreline positions are estimated in order to guide the Natal Town and Regional Planning Commission in decision-making regarding coastal zone development. Past impacts on, and potential future threats to the position of the shoreline are identified, so that they may be considered when making planning decisions regarding development.

Methods

In order to assess the positions of former shorelines, historical aerial photographs were studied. This technique of monitoring coastal change has been established in many earlier studies in other countries (Dolan *et al.*, 1978; Pilkey *et al.*, 1989) and has previously been applied in the area under discussion, principally for the purposes of mapping vegetation changes (Weisser, 1979; Weisser and Backer, 1983). Accurate historical charts, depicting early shoreline positions have been used in erosion studies in the United States (Morton, 1974) and the United Kingdom (Carter and Bartlett, 1988) for example, but are not available for much of the Natal Coast. This is unfortunate as they give a longer term perspective to the studies.

Several sets of vertical aerial photographs were obtained from the office of the South African Surveyor General, in Cape Town, for as many periods as possible, and in the area studied, these ranged between the oldest, complete coverage taken in 1937 and most recent in 1983. A full list of photographic series used is given in **Appendix 1**.

In most cases the original scale of photography was greater than 1:20 000 so the photographs were initially enlarged 2 times to place them in the scale range of 1:10 000 - 1:25 000. The second series 1:10 000 scale orthophotos, based on aerial photography of 1977/78 and field surveys of 1979, were used as a base map on which all other shoreline positions were plotted.

Correlation of scale and position between successive photographs was made by comparing the distances between fixed points which could be identified on both the orthophotos and aerial photographs. In most cases the points selected were permanent installations, buildings or road junctions. When a wide, undeveloped, coastal dune was present this was often not possible and reliance was therefore placed on physical features of the landscape which showed no change in morphology or position. These included drainage courses where it was reasonably certain that the course had not migrated. In all cases, correspondence with other features showed the selected points to have been stable for the period under review. Having established these comparative points, the aerial photographs were digitised using either a LightningScan™ image scanner or Kurta™ IS/ADB graphics tablet, linked to an Apple Macintosh II Personal Computer. The graphics tablet was most useful when the area of the photograph to be digitised was greater than the width of the LightningScan™ scanner head. The digitised images were generated on a laser printer at their original scale and then reduced or enlarged to 1:10 000 by comparing the distances between fixed points on the photographs with those on the orthophotos. The correspondence of other points was good in all cases. Once this was done the shoreline position was traced onto the orthophoto base map on a light table.

Selection of mapped shoreline position

The choice of a feature which is easily recognisable on aerial photographs and which exhibits a clear relationship to the mean high water mark poses certain problems. For example, changes in tidal state, wave set-up, barometric pressure, lunar period, beach cross-section, etc, all change the relative position of features identifiable on air photographs. Choice of a suitable mappable boundary is influenced by the fact that it is the advance or retreat of the land margin at the limit of normal tidal submergence that provides the best measure of the actual gain or loss of land (Bird, 1983). Earlier studies on this problem (Morton, 1974; Dolan *et al.*, 1978) found the most appropriate feature to be the high water mark, identified on any particular photograph by a distinct tonal change between the wet, or recently wetted, sand of the intertidal zone and the dry sand above the high water line. The relationship of this marker to the mean high water mark is most variable where beaches are relatively wide and have a low gradient but even in these cases it was generally found to be within 5-6 m of the mean high water mark (Dolan *et al.*, 1978). Fortunately, in the study area, beaches tend to be relatively steep and narrow which causes minimal horizontal displacement of this line with changing environmental conditions. Horizontal displacement is further reduced by a low tidal range (Pilkey *et al.*, 1989), as occurs on the Natal coast.

In a few instances, precise identification of this wet beach/dry beach boundary was not possible, due to reflectance from the water, and in these cases a degree of subjectivity was involved in assessing the position of this boundary. However, this was not a common problem in the study. A second, unavoidable disadvantage of using the wet beach/dry beach boundary as the mapping feature is the probable underestimation of the rate of cliff retreat on beaches backed by cliffs (Pilkey *et al.*, 1989).

Errors

Mapping historical shoreline change from aerial photographs must of necessity give rise to errors and this poses two main questions:

(a) What are the errors involved in the actual measurement?

(b) How important are these errors in methodology, in terms of the actual variation in shoreline position?

If errors can be quantified then one may be able to assess their importance and take cognisance of them in interpretations. Both questions are addressed below.

The accuracy of shoreline measurements from aerial photographs are reviewed at length in a number of publications to which the reader is referred (Hayden *et al.*, 1979, Dolan *et al.*, 1980). Many of the errors arise from factors inherent in the aerial photography itself (Leuder, 1959). Optical aberration on air photographs causes distortions at the greatest distance from the principal point (i.e. toward the edges). To minimise this error, only the central portion of each photograph was used. The best results are obtained from low altitude photography and photography generally becomes poorer with age, although in the present study the photographs of 1937 are of remarkably good quality and were often superior to later photography. Errors also occur when the camera was not perfectly vertical but this may be determined from the information supplied on the aerial photograph and allowances may be made. Further errors may be produced by relief variation on the surface photographed.

Measurements made from enlargements of photographs are also a potential source of error, as the line depicting the interface being measured is also enlarged, making the actual positioning of the trace, somewhat subjective (in general the centre of the line was chosen). The minimum distance which can be measured is about 0.25 mm which on a 1:10 000 scale map corresponds to 2.5 m. To determine rates of change, however, two positions must be measured, resulting in a combined error of up to 5 m. The process of matching the points on the ground on two photographs is another source of error which is difficult to assess. It is probably difficult to match at 1:10 000 scale to any closer than 1 mm (10 m ground distance). The maximum combined potential error in measurement is therefore 15 m (10 + 2.5 + 2.5). This is the sum of three separate errors, each with 0.5 probability, so the combined probability of such an error is 0.125. If the error is normally distributed about zero error then the standard deviation is approximately 7.5 m.

In summary therefore, the error due to measurement at this scale is potentially as much as 15 m but should usually fall within 7.5 m of the true position.

If the smallest distance mappable at 1: 10 000 scale is 2.5 m, one is faced with the question of how this relates to the average change in shoreline position between successive photographs. To assess this problem, a variation of the method of Dolan *et al.*, (1980) was followed, whereby the mean rate of shoreline change (SL) was determined according to Formula 1 (**Table 1**). The standard deviation of SL was then calculated according to Formula 2, where SL_i is the rate of shoreline change between the times of two consecutive aerial photographs and N_p is one minus the number of historical aerial photographs used (i.e. the number of intervals between successive photographs). The results are shown in **Appendix 3**.

Formula 1: $$SL = \frac{1}{N_p} \sum_{i=1}^{N_p} SL_i$$

Formula 2: $$S.D. = \sqrt{\frac{1}{N_p - 1} \sum_{i=1}^{N_p} (SL_i - SL)^2}$$

Table 1: Formulae used in the determination of mean rates of shoreline change and standard deviation from the mean.

A slight deviation from the method of Dolan *et al.*, (1980) was considered necessary as those authors did not take into account the variation in interval between consecutive photographs. In the present study this varied between 3 and 41 years. Clearly the apparent mean rate of change for a three year period cannot be compared directly to the mean rate shown over a 20 or 30 year timespan. The latter is probably more representative of the net effects of change and may tend to mask the short term, episodic changes revealed by short time intervals between photographs. For this reason, before applying the formulae of Dolan *et al.*, (1980), a weighting factor was incorporated into each of the mean rates. This was achieved by multiplying each of the mean rates by the timespan it covered and dividing by the total timespan covered by all the photographs. This value was then substituted for SL_i.

The standard deviations of the shoreline migration rates were multiplied by the average number of years between consecutive photographs (∂T) to provide an estimate of the average total shoreline change between images (D). For the 85 estimates of D which were calculated, the average distance is 16.11 m. This is approximately 6 times the minimum ground resolution (2.5 m) and indicates that the error due to ground measurement is not significant.

Important points for interpretation

An often overlooked factor in historical shoreline erosion studies is the fact that non-sequential photography is used and the time intervals between successive photographs are not constant. This poses problems when the rate and direction of shoreline change is not uniform with time, and tends to overestimate the rate of change over short periods when compared to the long term average. This must be borne in mind when interpreting the results. For example, if aerial photographs taken 20 years apart showed erosion of 20 m the calculated rate of erosion would be 1 m/year. If, however, the shoreline had accreted 20 m during the first 10 years and retreated 40 m during the ensuing 10 then the actual rates of change would be +2 m/year and -4 m/year respectively. Furthermore, if the sign were ignored in this example the actual shoreline moved 60 m and the average rate of change would be 3 m/year. Similar errors occur when the photography fails to indicate the precise time at which changes in the direction of shoreline migration occur. This problem is particularly important in the Natal context where rare or episodic events such as major river floods can, almost instantaneously, introduce large quantities of sand into the nearshore zone, causing rapid accretion of beaches which then take months or years to erode back to an equilibrium situation. To counteract this factor the weighting factor referred to in the previous section was introduced to calculate the mean shoreline migration rate (SL). The standard deviation from the mean gives an indication of the importance of episodic events. An alternative approach was also used for comparative purposes, whereby the net shoreline movement over the entire period (1937 to 1978 or 1983) was considered. This was divided by the total timespan in years to give the net averaged shoreline migration rate (NSL). This will tend to mask episodic events and will underestimate the actual rates of change when accretion or erosion has been continuously sustained. The reasons for the differences between these approaches are clarified in **Figure 2**.

Despite the limitations of methods for study of shoreline migration, extrapolated long term averaged rates have been used with confidence to predict shoreline retreat in North America and compared reasonably favourably with theoretically derived erosion rates (Pilkey and Davis, 1987).

Shoreline processes and erosion

While there are many lengthy texts on coastal processes to which the reader is referred (Bird, 1969; Davis, 1985; Komar, 1983), it is, however, necessary at this stage to give a summary of the major controls on shoreline movement in order to place the results in perspective and to introduce to the layman, some of the processes referred to in the discussion.

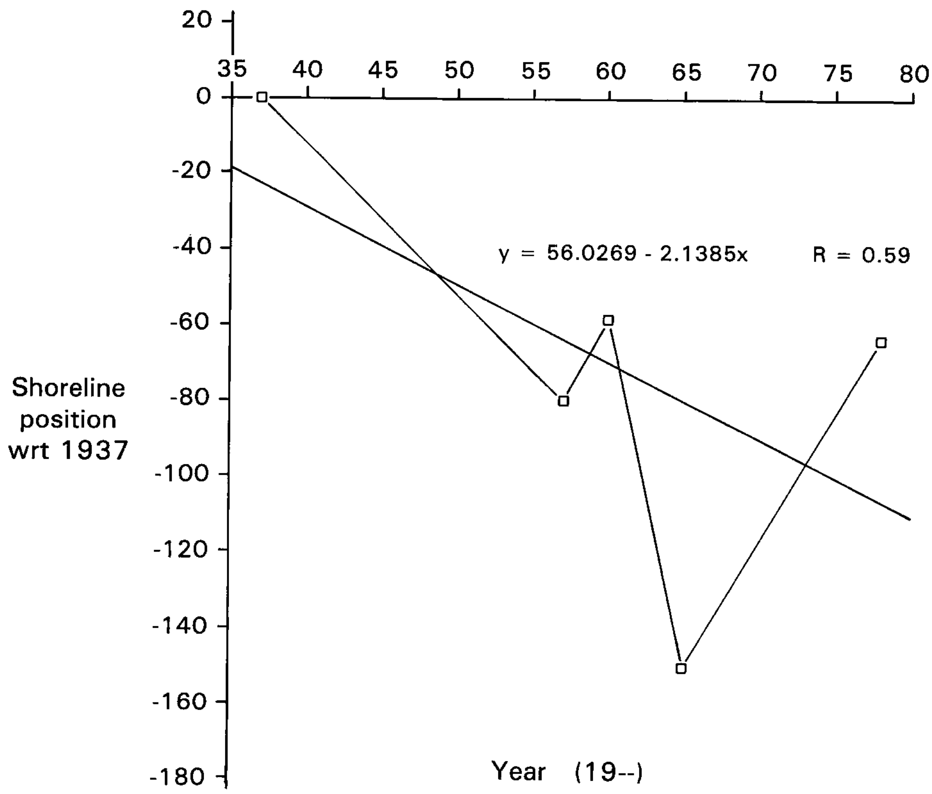


Figure 2: Illustration to demonstrate difference between mean rates of shoreline change (SL) and net averaged rates (NSL). In this example, the positions of the shoreline were firstly plotted against time and secondly a regression line was drawn through them. This illustrates the difference produced where all the points are considered and when only the first and last points are considered. Although regression analysis was not used in this study (due to the low correlation coefficients), the resulting effect is similar.

Sediment in the coastal zone is supplied to the nearshore (littoral) system from a number of sources. It is moved around in that zone by a combination of forces, and is either retained there or is ultimately lost to a number of areas (sinks) where it is deposited.

Sand and, to a lesser extent, gravel are the dominant grain sizes found on Natal's beaches. Finer-grained material (clay and silt) after a temporary residence period in estuaries, is carried offshore and deposited seaward of the littoral zone (Goodlad, 1986). Potential sources of sand and gravel, suitable for incorporation into beaches are more numerous than one might think and the relative contributions of each source are often difficult to measure. They include inputs from rivers, artificial beach nourishment, longshore drift from adjacent areas, wind action, and cliff erosion. To illustrate the input of sand from cliff erosion, consider the following example. A cliff 20 m high if it erodes by 1 m will introduce a volume of 20 m^3 of sand per metre of beach, into the littoral zone. In an area where waves break parallel to the shore the coastline is in a state of dynamic equilibrium and sand deposited on such beaches from cliff failure will therefore not move much alongshore. This may be revealed by an increase in beach width in front of apparently eroding cliffed sections. Bird (1985) actually cities an example of an area where an accretionary beach ridge has formed in front of a formerly eroding sand cliff by this process.

The forces which act on sand in the littoral zone are a combination of wind, waves, and ocean currents which may come from a variety of directions at varying intensities. In areas where cliffs are present, fluctuations in local groundwater tables, and even earthquakes may play a role in moving sediments. Where waves break obliquely to the shore, a longshore movement of sand is generated in the direction of dominant wave approach.

Sinks of sand include estuary mouths where flood- and ebb-tidal deltas accumulate sand. In the study area these are present periodically in the Matigulu, Mlalazi and Richard's Bay Sanctuary inlets. Other sand sinks include coastal sand dunes, losses to offshore areas via rip currents, mechanical removal (sand mining) and transport out of a particular area by longshore drift.

The most stable type of shoreline is considered to be a sandy beach backed by contemporary sand dunes (Bird, 1969). Such coasts respond rapidly to storms or other episodic events and may undergo large amounts of erosion, but their ability to reform sand dunes makes them stable in the long term.

A number of threats exist which threaten to change the position of any given shoreline. Ten of the most important were discussed by Bird (1983) and are listed below.

1. Variations in fluvial sediment yield.
2. Variations in sediment yield from cliffs and rocky shores.
3. Variations in aeolian (wind-blown) sand supply.
4. Variations in sand supply from the sea floor.
5. Losses of sand onshore, offshore and alongshore.
6. Interception of longshore drift.
7. Losses and gains due to human activities.
8. Effects of weathering.
9. Changes of sea level relative to land.
10. Climatic variations.

In addition, Komar and Enfield (1987) have documented short term sea level changes due to coastal currents, atmospheric pressure variation, wind action and so on, which they suggest may play an important role in short term fluctuations in coastal erosion. Daily mean sea level records are available for the South African coast (Brundrit, pers. comm.) and show variations up to 30 cm.

Sea level rise

The study area has experienced several ups and downs of sea level (transgressions and regressions, respectively) during the past million years. The most recent fluctuations affecting coastal morphology have occurred within the past 15 000 years in what is termed the Holocene Epoch. Fifteen thousand years ago sea level stood some 120 m lower than present (Dingle and Rogers, 1972). It rose rapidly during the next ten thousand years during what is termed the Flandrian Transgression and reached a level some 5 000 years ago about 1.5-2 m above its present level on the South African coast (Reddering, 1987). It subsequently dropped to its present level but is thought to be rising once again in common with other areas of the world.

Evidence is mounting that the rate of this global rise in sea level is accelerating (Clark and Primus, 1987) and, while its effects will be felt more in some areas than others, it nonetheless poses a threat to all coastal development. Current estimates put the rate of eustatic (i.e. excluding any vertical movement of land relative to the sea) sea level rise at 1.0-1.2 mm/year (Gornitz *et al.*, 1982; Gornitz and Lebedeff, 1987). Relative sea level rise is often much higher due to subsidence or compaction (Braatz and Aubrey, 1987, Davis, 1987). In the Natal situation there is little evidence regarding subsidence or uplift of the land, although King (1953) presented equivocal evidence that land in the vicinity of Durban was subsiding with respect to sea level at one quarter of an inch to one inch (6-25 mm) per year. Recent studies predict that global climate warming as a result of the greenhouse effect could lead to a sea level rise of between 0.5-1.5 m in the next century (NAS, 1987; Ramanathan, 1988). Sea level curves from Durban and Lorenço Marques (Maputo) were obtained from tide gauges at these stations (Hughes, pers.comm.) These particular records show little upward trend over the recording period but this may be due to instrument error, land movement or several other factors. The data from the oldest tide recorder in South Africa (Simonstown) does show a trend which can be statistically shown to be upward and Gornitz *et al.*, (1982) demonstrated a regional sea level rise of 32 cm/100 years or 31 cm/100 years at a 95% confidence level for southwestern Africa. This was subsequently revised to 1,9 mm/year or 1.0 mm/year at a 95% confidence level (Gornitz and Lebedeff, 1987). There is however, considerable international debate as to the magnitude of sea level rise. This is discussed further in the section dealing with projected future shoreline position.

The study area

The study area stretches from the Tugela River mouth (29°13'S 31°30'E) to Cape St Lucia (28°31'S; 32°24'E) on the Zululand coast of Natal, South Africa (**Figure 1**). It was chosen for the first year of study as a result of visible signs of erosion which posed direct threats to existing installations, and because part of the area had been identified as one of only two prograding sectors on the South Africa coastline (Tinley, 1985).

The geomorphology of the study area varies longitudinally, largely as a result of the nature of the antecedent coastal geology. From the Tugela River mouth to just north of the Mlalazi River mouth, the shoreline takes the form of a linear, sandy coastline, broken only by the mouths of the Matigulu/Nyoni, Siyayi and Mlalazi Rivers. The beach is backed by a series of low (average height 5 m) beach ridges, typically running parallel to the coastline. The vegetation structure of these has been reported on by Weisser (1980) and shows a distinctive increase in maturity landward, indicating relative stability of the older ridges and long term accretion. These ridges originate as small, isolated foredunes which coalesce to form coastwise ridges (Weisser and Backer, 1983). In some cases, oblique dune ridges may also be discerned, both on the modern shoreline and behind several lines of modern beach ridges. Along this stretch of coast, beaches average less than 80 m in width and offshore bars are often developed. Just north of the Matigulu River the coastal beach ridges are backed by an area of low-lying land, 200 m wide. This in turn is backed by a cliff line partially covered in blown sand. It is likely that the flat low-lying area represents a former extension of the Matigulu Lagoon during the period 5 000 years ago when sea level was approximately 2 m higher than present. This infers that the beach ridges on the modern coast have formed since that time, and were probably initiated as a result of the minor regression of the sea to its present level.

Between the Mlalazi River mouth and Richard's Bay much of the coast consists of a relatively narrow beach, backed by a cliff cut into dunes of the Port Durnford Formation (Hobday and Orme, 1974) in which occasional exposures of muddy lagoonal deposits occur. However, for about 4 km north from the Mlalazi River mouth, a situation similar to that north of the Matigulu Lagoon prevails, in that, a flat, low-lying area is present behind the modern coastal dune.

The age of the Port Durnford Formation is not firmly resolved, and the majority of authors still prefer the Late Pleistocene age suggested by Hobday and Orme (1974) to the Early Pleistocene age determined by Hendey and Volman (1986). It was however deposited when the sea level was between 4 and 8 m higher than present and the coastline was curiously situated some distance seaward of its present position. Muds and organic deposits of this formation outcrop in the intertidal zone and underly much of the beach at shallow depths. These ancient dunes are currently undergoing erosion, but cannot be restored as cliffs form on their seaward side. Sand eroded from these cliffs during storms falls onto the beach where it builds a wider beach which in turn protects the dunes from further attack until sand removal by longshore drift narrows the beach sufficiently for waves to attack the cliffs. Longshore drift in this coastal sector is likely to be low due to the observation that the dominant waves almost always break parallel to the shore. However, a limited amount of drift is to be expected under short term variation or even reversal in the direction of wave approach. Cliff failure in this area, however, is probably also related to onshore processes, for example, increases in pore water pressure and construction of artificially perched water tables during dune mining. Most of the area is presently vegetated but large-scale slumps are common (Tinley,1985) and expose bare, unvegetated sand which has been redistributed by the wind to form "*blowouts*" trending obliquely to the coastline. Weisser (1980) suggested that footpaths may have been responsible for destroying the vegetation, destabilising the sand, and causing "*blowouts*". It is worth noting that slumping was common even in 1937, particularly in the area around Port Durnford. Much of the slumped dune sand either remains on the beach or is transported landward once again and redeposited in the numerous blowouts.

The Richard's Bay coastal sector is the most disturbed section of the coast under discussion. In the period 1937-1960 the sandy barrier separating Richard's Bay from the Indian Ocean was covered with an extensive, largely unvegetated, sand dunefield in which sand blown off the beach, accumulated. It thus acted as a sink for sediment arriving at this position from the south. The harbour development has effectively destroyed this dune and rendered it no longer a significant sink for sand blowing alongshore. The former inlet of Richard's Bay with its extensive flood-tidal delta was destroyed during breakwater construction and maintenance of the harbour mouth and the littoral sand budget was further disrupted by construction of a second mouth to the Sanctuary area, in which a new flood-tidal delta has formed.

The area north of Richard's Bay as far as the vicinity of the Nhlabane Estuary, consists mainly of a cliffed shoreline cut into the frontal portion of a now inactive, sparsely vegetated, dunefield of probable Pleistocene age which belongs to the Port Durnford Formation. This ancient dune is up to 1 km wide. Erosion of this area was evident even in 1937 when steep, cliffed faces fronted the dunes. Extensive areas of slumping were present. A number of small areas of active aeolian sand occur as in the previous area. This effectively permits landward migration of slumped sand as newly-formed dunes transgress the Port Durnford Formation. In some cases the newly eroded sand has been blown against the cliffed faces where it has accumulated to form dunes which completely cover the formerly eroding cliff. Some of this wind-blown sand also accumulates in the mouth of the Nhlabane Estuary.

At the mouth of the Nhlabane Estuary well-developed modern dunefields occur. While these were active at least until 1937, afforestation in the 1950s has probably reduced their capability to act as sand sinks.

In the area north of the Nhlabane Estuary, a large, slightly concave embayment exists north of Dawsons's Rock and appears to have formed as a result of the presence of Dawson's Rock, an outcrop of beackrock exposed near sea level. Such development of embayments is typical of the more northern sectors of the Zululand coast and (for example Sodwana Bay) where embayments form on the downdrift (northern) side of rocky outcrops and ultimately strive to attain an equilibrium planform shape approximating a log spiral curve (Bremner, 1983). The rear of this embayment contains a partially vegetated dunefield in which much of the sand eroded from the bay was deposited by wind action. In 1937 erosion was already occurring here as the area north of Dawson's Rock was backed by steep, bare, sand cliffs.

Northward, toward Cape St Lucia, the coast is dominated by a major, historically-active dunefield, the largest section of which was artificially vegetated in the late 1950s. This dunefield both transgresses the Port Durnford Formation and runs alongshore seaward of it. This dunefield must formerly have acted as a significant sand sink. Its afforestation has probably reduced its capability to absorb transported sand. The effects on the adjacent coastline, and in particular on St Lucia Estuary mouth require further investigation. A smaller, although not insignificant, dunefield stretches along the shore at Cape St Lucia and must absorb at least some of the wind-blown sand in this vicinity.

Coastal orientation and coastal dynamics in the study area

In order to successfully interpret changes in shoreline position one requires a knowledge of the coastal conditions in the study area in relation to the various coastal sectors. It is therefore necessary to summarise available data before proceeding to the discussion.

Analysis of wind data from Cape St Lucia (HRU, 1968) indicates that dominant winds blow from the SW but a subordinate peak in frequency also occurs from the NNE. Using Voluntary Observing Ship (VOS) data (Swart and Serdyn, 1981), Mason and Wright (1989) calculated the flux of aeolian sand in the vicinity of St Lucia Estuary mouth, just north of the study area. They employed the technique of Fryberger (1979) which combines wind frequency and intensity to calculate a resultant drift potential (RDP) of 13 m^3/m of beach per year, toward the north.

Wave data from clinometer readings at Cape St Lucia (HRU, 1968) indicates dominant wave approach from the SE for both winter and summer. Subordinate wave approach from ENE was also recorded. A different situation is, however, indicated from analysis of VOS data. Van Heerden and Swart (1986) show, from analysis of VOS data, that dominant deep-sea swell approach at St Lucia Estuary mouth is from S and SW.

The interplay of wind and waves with the shoreline and their effects on the shoreline, depend to a large extent on the coastal orientation. Measurements of coastal orientation were made for linear stretches of the study area between marked points of inflexion. The results are summarised below:

Coastal Sector	Orientation (°E of N)
Tugela River mouth - Siyayi	42°
Siyayi to Mlalazi River mouth	68°
Mlalazi to Richard's Bay sanctuary	71°
Richard's Bay sanctuary - Nhlabane	42°
Nhlabane - Dawson's Rock	49°
Dawson's Rock - Cape St Lucia	45°
Cape St Lucia area	38°

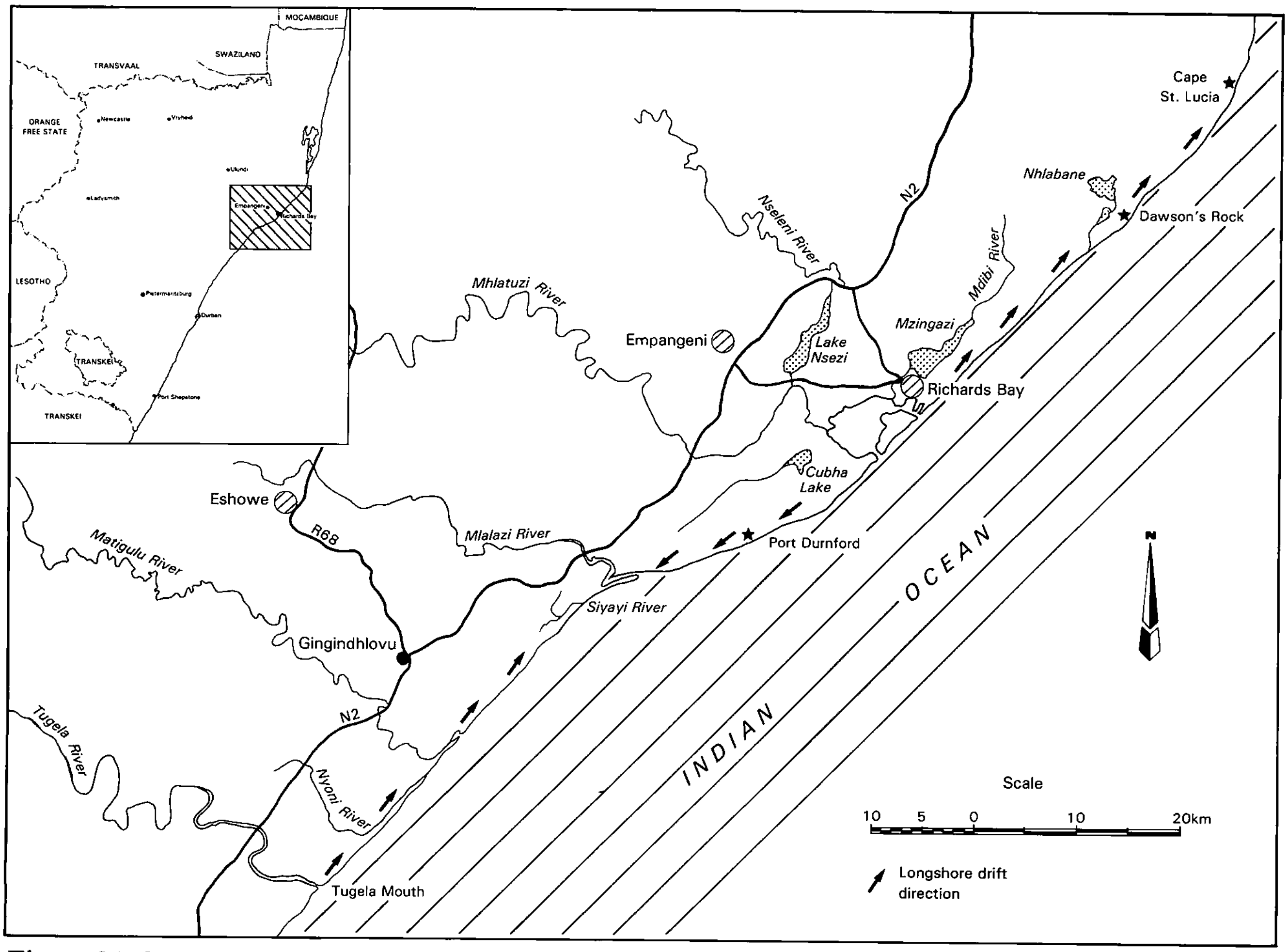


Figure 3A: Schematic representations of longshore drift direction under dominant SE wave approach. The effects of wave refraction have not been indicated. Note the longshore drift reversal in the area between Mlalazi and Richard's Bay.

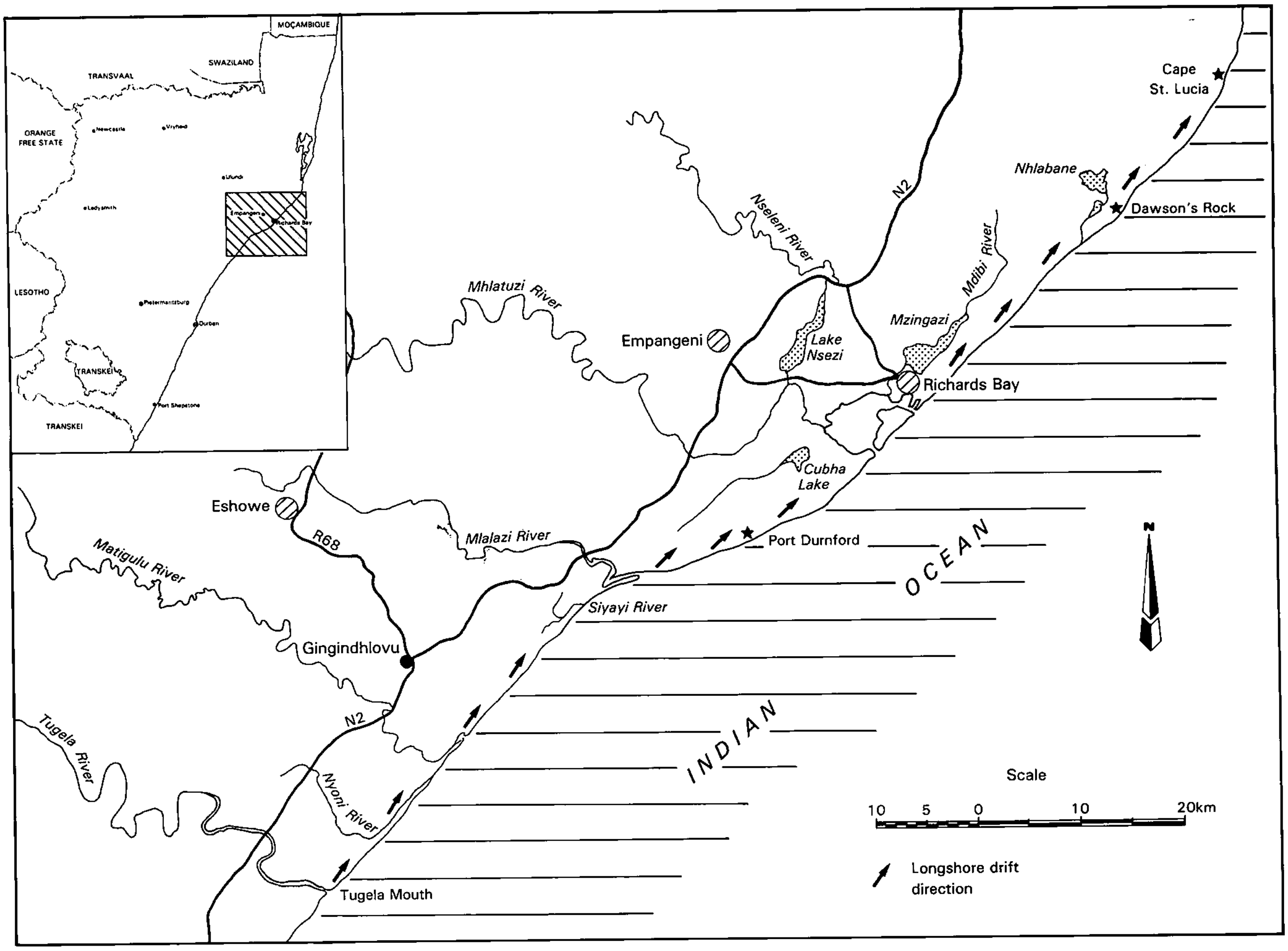


Figure 3B: Schematic representations of longshore drift direction under dominant S wave approach. Longshore drift in all areas is northward, although a reduction would be expected in the Mlalazi - Richard's Bay area due to the decrease in angle of incidence.

The coastal orientation, in relation to the dominant wave approach determines the direction of longshore drift (Bird, 1983). Examination of the orientations given, reveal that for dominant southeasterly wave approach the direction of longshore drift would be generally northward, except in the area between the Siyayi and Richard's Bay Sanctuary where it would be southerly-directed (**Figure 3A**). If, however, one accepts the VOS data used by van Heerden and Swart (1986) which indicates dominant wave approach from S to SW, this would produce a northward longshore drift in that area, albeit reduced in magnitude (**Figure 3B**). A reduction in magnitude of longshore drift in this coastal sector compared to the Tugela - Siyayi sector was indeed calculated by Nicholson (1983) who also used VOS data. Whatever data one chooses to accept, there is certainly at least a reduction in the northward flux of sand in longshore drift in this sector.

Winds blowing from the sea across the beach, pick up dry sand and deposit it as dunes. These are therefore to be expected to form

(a) where dominant winds blow onshore, either directly or obliquely and;

(b) where sand of a suitable grain size is available for transport.

The orientation of dune crests and orientation of the long axes of dunefields reflect the dominant wind direction. Dunefields, both active and stabilised, are most common on the sector north of Richard's Bay where coastal orientation is between 45° and 50°. Reasons for dunes to form preferentially in this area compared to areas where winds blow more directly onshore, must be sought in an abundant supply of dry sand of suitable grain size on the beaches. It is likely that sand is picked up preferentially where the wind has a greater fetch along the beach. Wind may even be "funnelled" along the beach as a result of the obstruction to air flow provided by back-beach cliffs in this area.

Shoreline changes since 1937

For ease of reference, and also because of distinct differences in geomorphology and sedimentary processes along the shore, the results are discussed under several geographical areas. The results were depicted initially on the 1:10 000 scale orthophoto maps. For ease of reference and for calculation of historical rates of change, 90 sites were selected in the study area, with a spacing of approximately 1 500 m at which measurements of shoreline change were made. Their locations are shown on the 1:50 000 topocadastral sheets in **Appendix 4**. The results are tabulated for each interval between photographs in **Appendix 2** and illustrated graphically in **Appendix 5**. Calculated net and mean rates of change are given in **Appendix 3**.

Tugela River Mouth to Matigulu Lagoon (Stations 1-15)

This area was recognised by Tinley (1985), as one of only two accretionary sectors on the entire South African coast, composed of a series of low shore-parallel beach ridges. Previous studies in the area, however, have dealt only with limited sections of the coast and failed to recognise differences in rates alongshore. The present study reveals that the entire coastline in the area exhibits positive migration, indicating sustained accretion since 1937. However, the net rates vary considerably and a low number of photographs make identification of the effects of episodic events (storms, floods, etc.) impossible. In most cases the standard deviation of shoreline migration rates is significant, indicating a major influence from episodic events. For instance, a small net retreat was recorded for Stations 1, 6-8 and 15, for the period 1978-1983. This, however, was against a net advance between 1937 and 1978 and most probably reflects a short term fluctuation. Stations 13 and 14 were the only areas to show a small net retreat (0.73 and 0.61 m/year) up to 1978 but a period of rapid accretion between 1978 and 1983 changed the long term trend to a net accretion rate, illustrating the dangers involved when considering net rates. The stations in question (13 and 14) are located on the sandbar of the Matigulu River and would therefore be expected to undergo rapid short term changes as a result of mouth formation in different positions, mouth migration, and rapid influxes of sediment during river floods. The fact that the sandbar is backed by the Matigulu Lagoon also permits landward movement of the bar by barrier overwash during storm conditions. Station 15, just north of the Matigulu Lagoon exhibits long term erosion trends (SL = -0.22; NSL = -0.43). This station is being eroded as it forms a slight convexity in the coast on which wave action would be focused. Examination of the 1937 aerial photographs reveals that it was being eroded even then.

Maximum net averaged rates (NSL) of accretion of over 5 m/year at Stations 4, 5 and 6 have increased the convexity of the coast in that area and have no doubt altered wave patterns. This accretion appears to have been occurring for a considerable period as evidenced by a wider accumulation of beach ridges behind Stations 4, 5 and 6 than in adjacent areas. It is likely that accretion began as early as 5 000 years ago when the Holocene sea level underwent a minor fall (Reddering, 1987), thereby causing the lower reaches of the Tugela River to be incised to a new base level. Accretion since that time reflects the fact that most of the bedload of the Tugela River now passes directly through the Tugela Estuary and is reworked northward by wave action where it forms this series of beach ridges. Short periods of apparent erosion (landward movement of the high water mark) are commonly noted during beach ridge formation, when a storm reworks accumulated beach sand landward, forming a ridge before accretion recommences in front of this ridge. The relatively high values of SL coupled with high standard deviations from the mean indicate significant influence of episodic events.

Conditions favourable to accretion are created by bedrock slope and wave refraction patterns (the latter should be elucidated by the NTRPC-sponsored EmaTek research on that phenomenon). In a few areas the standard deviation was low and reveals areas which are undergoing sustained and nearly constant long term accretion. These are Stations 9-11 where the mean weighted annual rate of accretion is in the region of 1 m/year. This probably provides the best estimate of an averaged long term accretion rate, setting aside the effects of episodic influxes of sediment which cause many of the other stations to show large standard deviations from the mean annual rate. Stations 9-11 are furthest from the influence of the Tugela River and are therefore less susceptible to short term changes associated with flooding.

Matigulu Lagoon to Mlalazi River Mouth (Stations 16-31)

This area is also located in the accretionary sector of the coast and displays both net and mean growth rates. As in the previous sector, standard deviations are high (often > 1) and mean accretion rates (SL's) average about 0.7 m/year. This compares with averaged net rates (NSL's) of 2-3 m/year. These are in close agreement with previously deduced rates of dune advance at the Mlalazi Nature Reserve of 2,4 m/year since 1937 (Weisser *et al.*, 1982) and rates of "*increase of beach width*" of 3 m/year at the Siyayi River mouth (Nicholson, 1983). At Stations 18 and 19, however, erosion has been sustained, except for a brief phase of accretion in the period 1957-1960. High standard deviations from the mean indicate that this has not been constant with time. Erosion at these stations may be attributed to long term equilibrium adjustments to wave energy, resulting from updrift accretion. Such erosion may yield additional sand to adjacent downdrift (northern) sectors which are accreting. The bulk of the sand required for accretion in this sector is probably supplied from the Tugela River via longshore drift, but the presence of an eroding sector at Stations 18 and 19 indicates a significant increment of beach-forming material from the Matigulu River. The Matigulu is a shallow, bedload-dominated river which introduces influxes of sand to the coast, particularly during floods.

Accretion rates (NSL > 3 m/year; SL > 0.7 m/year) are greatest in the area between Twin Streams and the southern end of the Mlalazi Lagoon (Stations 24-28) where the coastline achieves its greatest concavity. Low standard deviation from the mean in this area indicates sustained accretion. This suggests an overall trend toward straightening of the coastline to attain equilibrium with wave energy. In such a rapidly accreting coastal area the coastline must undergo continuous adjustments to maintain an equilibrium with the dynamic coastal forces. Such adjustments are also probably responsible for temporary short term erosion at certain stations. It is also interesting to note the temporal variation in shoreline migration rates, bearing in mind the cautions outlined above, in the interpretation of short term changes. The period 1957-1960 showed a dramatic increase in accretion rates over the previous 20 years with calculated net accretion rates for that period commonly being over 30 m/year. This trend slowed between 1960 and 1978 even becoming erosive, but when averaged over the entire period, the trend reveals net accretion (**Appendices 2** and **5**).

Mlalazi River Mouth to Richard's Bay Sanctuary (Stations 31-49)

Despite the fact that most of this coastal sector is backed by apparently erosive scarps, analysis of the high water mark position reveal, in fact, that much of the area has accreted since 1937. A major difference between this coastline and the less steep one to the south is that, once eroded, it is impossible to replace the material back into the cliff face. However, the slumped sand is of a grain size suitable for natural beach nourishment and consequently is incorporated into the beaches. This is verified by marked increases in beach width, apparent on aerial photographs, and corresponding to accretionary periods. Aeolian accumulations may occur at the rear of such beaches as sand is reworked landward, forming dunes which climb over the previously cliffed shoreline. An additional benefit of slumped sand and wider beaches is that the passage of storm waves to the cliff is reduced in frequency and erosion is also reduced. A contributory factor to beach accretion may be that when blowouts were artificially vegetated in the 1950s sand could no longer be deposited there and therefore remained on the beach. Reference to the appropriate graphs in **Appendix 5** shows an increase in the rate of accretion with time, particularly after 1960 when afforestation had been completed.

Calculated accretion rates drop steadily from the Mlalazi River mouth (NSL = 2.5 m/year; SL = 0.6 m/year) to Station 37 (NSL = 0.54 m/year, SL = 0.1 m/year). Low standard deviations indicate a lesser influence from episodic events in this area. Northward, the coastal trend switches to net erosion around Port Durnford (Stations 38-41), the rates decreasing northward. If erosion continues at the past rates a half-heart or log spiral bay will form (LeBlond, 1979, Bremner, 1983). Erosion in this area poses a direct threat to the Port Durnford lighthouse. From Station 42 to 47 the coast has been accreting at low rates (typically < 0.5 m/year), although Station 46 had a NSL of 2.8 m/year, mainly since 1957. Stations 47-49 have been eroded at averaged rates between 0.2 and

1.4 m/year but comparison of different time intervals reveals that this time has been strongly episodic (**Appendix 5**).

Richards Bay Barrier (Stations 50-57)

Development of the harbour at Richard's Bay has rendered this the most disturbed section of the coastline in the study area. Harbour construction began in the early 1970s and construction of the breakwaters commenced in 1973, being completed in 1975. A second, southern entrance to the former lagoon was also cut through the barrier. To gain an understanding of how this has affected shoreline changes one must divide the averaging interval into two periods, one pre-harbour and one post-harbour. Swart (1980) discussed in detail the effects of the harbour development on the coastline and his results are largely in agreement with the results of this study.

Pre-harbour shoreline migration

In the period 1937-1960 the sandy barrier separating Richard's Bay from the Indian Ocean was covered with an extensive, unvegetated sand dunefield in which sand blown off the beach, accumulated. It thus acted as a sink for sediment arriving at this position from the south. In addition to accumulation of sediment in the dunes, the coastline also prograded at moderate to high rates (NSL = 0.45 - 1.06 m/year; SL = 0.3 - 0.7 m/year) in this area. A short period of net erosion was also recorded between 1957 and 1960 indicating that short term variations do occur but that the overall trend was accretion. This is also reflected in the relatively high standard deviations from the mean.

Post-harbour shoreline migration

Following harbour construction dramatic changes occurred in the area. The artificial formation of a new mouth to the Sanctuary area interrupted longshore drift and an extensive flood-tidal delta rapidly accumulated. Conversely, this also permitted more direct transfer of sediment from the Mhlatuze River directly to the sea.

Development on the former dunefield prevented sand accumulation there and any sand arriving at this location had to find an alternative pathway. Construction of the harbour breakwaters interrupted longshore drift and trapped northward-bound sand, causing marked accretion on the updrift (south) side of the breakwater. This was enhanced by the deposition of 63 x $10^6 m^3$ of dredger spoil which was pumped onto the beach between October 1973 and August 1977 (Swart, 1980). The impact on shoreline migration rates may be seen in the appropriate graphs in **Appendix 5**. Mean rates of accumulation for the period 1975-1983 increased to between 8 and 43 m/year. Maximum accretion occurred directly against the southern breakwater. Examination of the aerial photography reveals an unusual bulge in the coastline in 1978 (probably due to increased pumping of sand). This was, however, eroded and a more straight coastline was restored by 1983, illustrating the rapid natural adjustment of the beach profile and planform to equilibrium conditions.

In post-harbour times, mean accretion rates increased by an order of magnitude over the natural conditions, however this was influenced largely by artificial pumping of sand from the harbour development.

Richard's Bay Harbour Mouth to Nhlabane Estuary (Stations 58-74)

Coastline migration in the area immediately north of the northern breakwater was studied in detail by Swart (1980) and, because of the potentially large and unknown influence which may be exerted by variable rates of artificial beach nourishment, it is not considered in detail here.

The sector between Stations 58 and 63 showed minimal change up to 1978 with low standard deviations. A short accretionary period at Station 58 between 1960 and 1978 may be linked to artificial pumping of sand onto the beach to reduce the effects of the north breakwater on downdrift erosion (Swart, 1980). Northward, Stations 64-74 generally displayed net erosion at relatively low rates (NSL = 0.12 to -1.34 m/year; SL = 0.03 to -0.34 m/year), a trend which appears to have been sustained throughout the entire period to 1965. High standard deviations are evident indicating large variation in rates. In the time interval between 1965 and 1978 this complete coastal sector showed net accretion. The reasons for this accretion are twofold. Firstly, Swart (1980) indicated that sand pumped onto the beach at Richard's Bay in 1977 moved alongshore, spreading out as it did so. Secondly, artificial afforestation of the area in the late 1950s caused the loss of the formerly active dunes as a sand sink. This would have occurred due to a reduction in wind velocities caused by the trees which caused deposition of sand at the base of the forested area. Thus, sand transported alongshore in a northward direction had to either remain on the beach, remain in transport, or be lost offshore. If it is not lost offshore the volume of sand being transported is increased and if the rate of transport per metre of beach width is not increased accordingly then the beach width must increase.

Nhlabane Estuary to Cape St Lucia (Stations 75-90)

The geomorphology of this area is different to that of the previous sector in that while it is backed in places by erosive cliffs containing the Port Durnford Formation, there are also extensive areas which are backed by active or recently active Holocene dunefields.

Stations 75 to 79 showed low erosion rates averaged over the entire period with a high standard deviation from the mean, explained in part by a short phase of net accretion in the period 1957-1960 and a further, more extensive accretionary phase between 1965 and 1978.

Stations 80 to 90 in general, showed low averaged net rates of accretion in spite of a tendency for erosion in Stations 79-83 in the 1965 to 1978 period. These trend changes in the 1965-1978 period may be attributed to afforestation of a large dunefield which prevented loss of sediment into that former sink. Sustained accretion in front of the now forested area has resulted and this, in turn may have caused an equilibrium readjustment in beach planform at Stations 79 to 83 which resulted in erosion over that period. This is probably related to formation of an embayment in the lee of Dawson's Rock.

The effects of loss of this sand sink on St Lucia Estuary mouth need to be investigated to ascertain whether mouth closure has become more frequent due to an increased northward flux of sand. This research will be complicated by the fact that dredging of the mouth has been in progress for some time.

Discussion

In general it may be stated that the entire 55 km of coastline between the Tugela River mouth and 10 km north of the Mlalazi River mouth, is accreting by means of beach ridge formation, at highly variable rates up to NSL of 5 m/year and SL of 1 m/year. Most of this sediment is derived from the Tugela River and the Matigulu River and is augmented by sand arriving in the area by longshore drift from areas to the south and possibly from the north. The Mlalazi River carries less sand than these two rivers as evidenced by its relatively deep channel which is largely muddy. It probably contributes little sand to the littoral zone.

Maximum accretion is evident about 5 km north of the Tugela River and in several large-scale coastal concavities where accretion has tended to straighten the coastline. North of the Mlalazi River mouth accretion rapidly diminishes. Reasons for this decrease include a decrease in carrying capacity of sand by longshore drift which has resulted in deposition of most of the sand in areas further to the south. In addition, the Mlalazi River mouth acts as a minor sink for sand transported along the coast. This is deposited in the form of a flood-tidal delta in the river mouth. The flood-tidal delta showed variations in size in different photographs. This reflects sustained growth during low river flow periods and dispersal of the accumulated delta sand during floods.

Two areas of marked erosion are present in the study area. Between Stations 38 and 44, a 6 km stretch of coast shows low but sustained erosion rates. This area is backed by eroding cliffs cut into sand dunes and its erosion may in part be a response to accretion further south as the coastline seeks to maintain equilibrium. A second eroding sector occurs on the 24 km stretch between Stations 64 and 79 where a greater standard deviation from the mean occurs, than in the other eroding sector. This area is backed by high cliffed dunes and the standard deviations may reflect episodic collapse of cliff faces which causes subsequent beach progradation, followed by a period of stability before further cliff collapse occurs. The rate of retreat of the cliff line may therefore be greater than that indicated by the high water mark but this in itself would act to reduce the angle of the cliff and increase future stability.

Elsewhere, the coast shows very low rates of change, being generally accretionary with low standard deviation from the mean but the rates are so low as to be insignificant. This low accretion may be a response to increased sand supply from cliff collapse in adjacent eroding areas. The effect of Richard's Bay harbour has been to disrupt the sedimentary cycle in that area by destroying the former sand dunefield in which a large proportion of northward-moving wind-blown sand would have accumulated. It also created a new sink for sand against the southern breakwater.

The total length of eroding coastline is about 44 km or about 33% of the total coastline being studied. Seventy-three kilometres or about 54% of the coastline is accreting. This includes the 6 km of coastline situated on the severely disturbed section of coast between Richard's Bay Sanctuary entrance and the harbour mouth. The 9 km stretch of coastline (4%) north from this is subject to direct human influence through inputs from artificial sand pumping. This, coupled with the remaining 9 km, which may be regarded as relatively stable in the long term accounts for about 13% of the coastline. These results are summarised on the 1:50 000 topocadastral maps in **Appendix 4**.

It is clear, however, that differential erosion/accretion rates along the coast, if sustained, will cause a gross change in morphology of the coastline which will cause adjustments in physical forces (wave approach, wave energy, coastal currents, etc.). Alternatively the dynamic coastal forces will prevent the coastline from undergoing dramatic shape adjustment, by maintaining a dynamic equilibrium through small changes in morphology. Sustained accretion in one area would therefore cause a readjustment in adjacent areas to the new equilibrium which may involve erosion so that wave fronts approach the shoreline parallel. These factors, combined with episodic influxes of sand during floods, ensure that migration rates are highly variable and difficult to predict.

Prediction of future shoreline position

The question of where the shoreline will be situated at some time in the future is one which is of obvious importance to planners. The legal liability of a planning authority which permits construction in an area which within a few years is eroded, is open to question but without at least an idea of shoreline trends and, if possible the rates of change, it is impossible to make accurate assessments of planning applications. It would be disastrous if an installation were built which within a few years collapsed into the sea, but equally problematic would be a jetty which due to accretion rapidly became stranded, high and dry, some distance from the shoreline. It should be borne in mind that the scenarios painted in this section are based on the situation over the timespan covered by this study (1937-1983). Rates of change and even erosion/accretion trends, may be reversed due to future development, sand removal, jetty construction, dune vegetation and so on, right up to changes in the upper catchments of the main sand supplying rivers. They may even have been changed in the timespan covered by this study, by afforestation.

In this section two scenarios are given for the position of the high water mark, an arbitrary period of 100 years into the future. 1978 was taken as the baseline as that is the date of photography of the orthophotos. To predict further into the future introduces more uncertainty and is probably beyond the scope of modern day planning where structures would probably be obsolete within a much shorter period than 100 years. The two positions are based on

(a) a straight-line rate of change, assessed by simply extrapolating the historically averaged rates of change into the future, and

(b) measurement of the net change over the total study period, i.e. the difference between the oldest and most recent photographs divided by the number of years between the two.

The latter approach takes no account of variations in rate and simply averages the net shoreline migration, multiplies this by 100 and plots the calculated position 100 years in the future (this is shown as a dotted line on the orthophoto map overlays). The former method is a mean value of the historical rates and to it can be assigned a standard deviation of the rate of change (this is shown as a dashed line on the orthophoto map overlays). To illustrate the difference in these two figures the reader is referred to **Figure 2**. It is clear from this graph that a line joining the first and last points would produce a quite different slope to that of the regression line shown. While the regression technique was not employed in this study due to the low value of *r*, it illustrates the difference between the mean rate and the net rate of shoreline change. The net rate does not take into account the possibility that the initial and/or final data points may in themselves be anomalous.

The effects of accelerated sea level rise on the future shoreline position are extremely difficult to assess. To take this factor into account, it would firstly have to be established that the magnitude of the sea level rise was greater than the annual or seasonal or daily variation in sea levels produced by local factors (atmospheric pressure, wave set-up, coastal flooding, etc). Analysis of the historical records for Durban, Richard's Bay and Maputo, (Brundrit, pers. comm.) the closest tide gauges to the study area, suggest that normal inter-annual variation is in the region of 25-30 cm.

As sea level rises, its effects on erosion are not simple, particularly on a soft (sandy) coastline punctuated by rivers. In the Natal context the larger estuaries are generally mature and have historically simply been acting as conduits of sediment rather than sinks for river-derived sediment. This sediment is passed directly to the littoral zone. River adjustment to a new base level caused by sea level rise would involve a temporary increase in estuarine sedimentation. This would, at least temporarily, reduce the supply of sediment to the coast from this source and therefore reduce sediment supply to beaches and enhance coastal erosion. Conversely, enhanced coastal erosion would cause collapse of dunes and beach ridges and thus increase the sediment supply from these sources. This amounts to a potential change in provenance of beach sediments during transgression, from river-derived to dune and beach ridge-derived.

While theoretical methods have been developed to assess the shoreline position in the future (the Bruun rule), these are not generally applicable other than to a barrier-lagoon coastline and in one of the few cases where it has been compared with projected historical rates (Pilkey and Davis, 1987), it appears to underestimate erosion rates. Everts (1985, 1987) has proposed another theoretical method of prediction of future shoreline position, based on retention of the shoreface slope but this too is generally applicable to barrier coastlines.

At its most simple level, one could simply project the future shoreline landward to a position corresponding to the 1 m contour, based on the assumption that beach cross-sectional morphology would remain unchanged. This may not be true on a cliffed coastline where additional sand supplied from cliff erosion would act as a natural beach nourishment source. Furthermore, a rising sea level would cause adjustment of the planform of log spiral bays which would have to re-equilibrate to the new shoreline position. This would certainly involve localised erosion and accretion.

Given the problems and uncertainties involved in assessing the probable effect of rising sea level for the purposes of this study, it may be assumed as a first approximation, that the high water mark would be located in the position occupied by the 1 m contour. This is, in the present study, well within one standard deviation of the mean rate of change (SL) and hence plotting it is pointless.

An alternative, though highly speculative, approach would be to firstly assume that sea level has in fact been rising at a steady rate of 19 cm/century, as deduced from the Simonstown sea level records (Gornitz and Lebedeff, 1987). Simple extrapolation of past rates into the future assumes that this increase will continue over the projected period (100 years). If, instead of rising 19 cm in the next 100 years, it did in fact rise 100 cm this would in theory involve approximately a five-fold increase in erosion rates or a five-fold decrease in accretion rates. This simple assumption, of course, neglects all of the points raised above regarding coastline adjustment, estuarine rejuvenation and so on. The effects of a five-fold increase in erosion would of course be devastating. Pirazzoli (1989) however, has cautioned that there would be a significant time lag between global warming, sea level rise, and the manifestation of the effects of sea level rise.

The effects of the Richard's Bay harbour on the adjacent coastline were discussed fully by Swart (1980) who outlined the various possibilities depending on sand pumping rates and so on. As these are unknowns and completely within human control, no projected shoreline position is shown in this study, for the harbour segment and the area up to 3 km north of the northern breakwater. The presence of the southern breakwater will in theory cause accretion until the end of the breakwater is reached, after which sand will begin to move into the harbour entrance, a phenomenon which would be dealt with by increased dredging. The spoil of this dredging would no doubt be pumped onto the northern beaches.

The projected future positions, based on both SL and NSL values, are portrayed on the overlays of 1:10 000 orthophotographs which have been handed to the Natal Town and Regional Planning Commission.

Potential threats to natural shoreline migration in the study area

In this section human factors which threaten to potentially change the rates of change of shoreline position in the study area are outlined. All of these could disrupt the coastal sediment budget and it is important to note that they have add-on effects on linked processes.

Dam construction

Reduction in input of fluvial sediment from the catchments of the Tugela and Matigulu Rivers due to dam construction pose threats to rates of shoreline accretion. This is likely to be aggravated by the fact that much of the transport of sandy sediment into the coastal zone occurs during severe floods. Dams will also act to reduce flood intensity and frequency.

In view of the fact that a proportion of sand arriving in the study area may be carried from areas to the south of the Tugela, dam construction in the catchments of rivers further to the south e.g. Mvoti, will also produce similar results but over a longer period.

Dune Mining

The subject of dune mining has received considerable attention in the press recently. Its effects on shoreline position due to slumping of sand dunes as a result of artificial construction of a perched water table on which a dredger is floated.

The effects of this on shoreline position must be viewed from the point of view that while cliff retreat does occur, this very process acts to nourish beaches which may be receiving less sand than they did historically, as a result of dam construction in river catchments.

Afforestation/deforestation

The effects of afforestation of coastal dunes requires further investigation. There is certain to be an effect as their function as sand sinks, if not lost entirely, is certainly diminished in its storage capacity. It should be determined where the excess sand goes, which would normally have been deposited in these dunefields. Likewise, the destruction of vegetation will cause instability of the underlying sand and cause disruption of existing sediment transport paths on the coast.

Sand-mining

The effects of sand mining in rivers and on beaches reduce the amount of sand in the littoral zone. The effects of sand mining in rivers, however, requires further investigation. As most sand is transported during river floods, mining during low flow periods may not be particulary detrimental as it would be replaced rapidly by new sand following the next flood as was noted in the Mgeni Estuary (Cooper, 1989).

Shore protection works

By constructing gabions or sea walls, the effect of wave action on the adjacent beach is changed. This has been demonstrated to increase erosion by downward focussing of energy, and ultimately leads to destruction of the beach as sand is transported offshore (Pilkey and Wright, 1988).

Coast-normal jetty construction

The construction of jetties causes an interruption of the longshore drift and tends to cause an increase in beach width on its updrift (in Natal = southern) side and erosion of the downdrift area due to sand starvation. The negative effects of downdrift erosion may be ameliorated by artificial sand-pumping schemes but it should be noted that updrift accretion may also have negative impacts.

Groundwater exploitation

The effect of this practice on shoreline migration requires evaluation as they exert a strong control on poorly cohesive cliff stability. However, the advantages and disadvantages must be weighed up. The loss of part of a cliff face may be negligible compared provision of an adequate supply of water. There may even be a relative advantage in cliff collapse in certain settings as it may nourish adjacent beaches.

Concluding statement

The negative effects of shoreline migration will be minimised in areas where cognisance has been taken of changes in shoreline position over time when making planning decisions. If no developments are permitted in eroding areas then it will not be necessary to employ expensive and often undesirable, engineering solutions to protect them.

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Appendices

Appendix 1

List of aerial photography used in the study

Date	Job No.	Area
1937	117/37	entire area
1957	400/57	Nyoni to Cape St Lucia
1960	442/60	Cape St Lucia
1960	451/60	Nyoni to Meerensee
1965	499/04	Richard's Bay to Cape St Lucia
1975	752/75	Mlalazi to St Lucia
1978	orthophoto	entire area
1983	873/83	Tugela to Richard's Bay

Appendix 2

Tabulated rates of change for intervals between consecutive photographs at study sites.

Locations shown on 1:50 000 topocadastral maps in Appendix 4.

Station Number	Change (m) 1937 - 1978	Annual Rate 1937 - 1978	Change (m) 1978 - 1983	Annual Rate 1978 - 1983
1	40	0.98	-40	-8.00
2	10	0.24	90	18.00
3	20	0.49	100	20.00
4	195	4.76	50	10.00
5	245	5.98	20	4.00
6	250	6.10	-10	-2.00
7	60	1.46	-25	-5.00
8	95	2.32	-50	-10.00
9	45	1.10	75	15.00
10	45	1.10	30	6.00
11	40	0.98	12	2.40
12	nr	nr	nr	nr
13	-30	-0.73	155	31.00
14	-25	-0.61	70	14.00
15	25	0.61	-45	-9.00

Station Number	Change (m) 1937-1957	Annual Rate 1937-1957	Change (m) 1957-1960	Annual Rate 1957-1960	Change (m) 1960 -1978	Annual Rate 1960 -1978	Change (m) 1978 -1983	Annual Rate 1978 -1983
16	42	2.10	40	13.33	10	0.56	-50	-10.00
17	-30	-1.50	115	38.33	-20	-1.11	-60	-12.00
18	-100	-5.00	90	30.00	-10	-0.56	-45	-9.00
19	-112	-5.60	94	31.33	-40	-2.22	-35	-7.00
20	nr	nr	100	33.33	20	1.11	0	0.00
21	75	3.75	45	15.00	0	0.00	20	4.00
22	60	3.00	70	23.33	-15	-0.83	-50	-10.00
23	-20	-1.00	100	33.33	10	0.56	-55	-11.00
24	35	1.75	75	25.00	20	1.11	10	2.00
25	75	3.75	50	16.67	20	1.11	-30	-6.00
26	115	5.75	45	15.00	15	0.83	-30	-6.00
27	75	3.75	15	5.00	35	1.94	35	7.00
28	70	3.50	50	16.67	20	1.11	5	1.00
29	nr	nr	60	20.00	25	1.39	-50	-10.00
30	20	1.00	25	8.33	40	2.22	10	2.00
31	mouth	mouth	55	18.33	mouth	mouth	40	8.00
32	40	2.00	-10	-3.33	80	4.44	5	1.00
33	10	0.50	nr	nr	75	4.17	-10	-2.00
34	nr	nr	nr	nr	nr	nr	nr	nr
35	0	0.00	10	3.33	40	2.22	20	4.00
36	0	0.00	25	8.33	0	0.00	15	3.00
37	-30	-1.50	35	11.67	0	0.00	20	4.00
38	-45	-2.25	-25	-8.33	-20	-1.11	-40	-8.00
39	22	1.10	5	1.67	-32	-1.78	-40	-8.00
40	30	1.50	-18	-6.00	0	0.00	-50	-10.00
41	10	0.50	40	13.33	-20	-1.11	-35	-7.00
42	nr	nr	nr	nr	nr	nr	nr	nr
43	-35	-1.75	115	38.33	-75	-4.17	10	2.00
44	-22	-1.10	65	21.67	-37	-2.06	37	7.40
45	-15	-0.75	57	19.00	-50	-2.78	15	3.00
46	0	0.00	64	21.33	45	2.50	20	4.00
47	100	5.00	-30	-10.00	-70	-3.89	-10	-2.00
48	0	0.00	-10	-3.33	-85	-4.72	15	3.00
49	15	0.75	-25	-8.33	-30	-1.67	10	2.00
50	27	1.35	-10	-3.33	-35	-1.94	30	6.00

Station Number	Change (m) 1937-1957	Annual Rate 1937-1957	Change (m) 1957-1960	Annual Rate 1957-1960	Change (m) 1960 -1975	Annual Rate 1960 -1975	Change (m) 1975 -1978	Annual Rate 1975 -1978	Change (m) 1978 -1983	Annual Rate 1978 -1983
51	45	2.25	-20	-6.67	110	7.33	-130	-43.33	nr	nr
52	40	2.00	-5	-1.67	155	10.33	-125	-41.67	190	38
53	15	0.75	0	0.00	75	5.00	80	26.67	85	17
54	20	1.00	0	0.00	200	13.33	305	101.67	-220	-44
55	mouth	mouth	nr	nr	40	2.67	165	55.00	180	36
56	not recorded due to variable mouth position									
57	not recorded due to variable mouth position									

Station Number	Change (m) 1937-1957	Annual Rate 1937-1957	Change (m) 1957-1960	Annual Rate 1957-1960	Change (m) 1960 -1978	Annual Rate 1960 -1978	Change (m) 1978 -1983	Annual Rate 1978 -1983
58	-8	-0.40	0	0.00	25	1.39	nr	nr
59	10	0.50	20	6.67	-15	-0.83	nr	nr
60	15	0.75	-30	-10.00	15	0.83	20	4.00
61	50	2.50	-10	-3.33	-40	-2.22	35	7.00
62	44	2.20	-15	-5.00	-30	-1.67	-5	-1.00
63	10	0.50	60	20.00	-70	-3.89	nr	nr

Station Number	Change (m) 1937-1957	Annual Rate 1937-1957	Change (m) 1957-1960	Annual Rate 1957-1960	Change (m) 1960 -1965	Annual Rate 1960 -1965	Change (m) 1965 -1978	Annual Rate 1965 -1978
64	-10	-0.50	-20	-6.67	0	0.00	25	1.92
65	-20	-1.00	-52	-17.33	0	0.00	40	3.08
66	0	0.00	-65	-21.67	0	0.00	40	3.08
67	-35	-1.75	-15	-5.00	-20	-4.00	65	5.00
68	-110	-5.50	65	21.67	-40	-8.00	50	3.85
69	-100	-5.00	50	16.67	-30	-6.00	25	1.92
70	-45	-2.25	80	26.67	-90	-18.00	10	0.77
71	0	0.00	50	16.67	-60	-12.00	20	1.54
72	20	1.00	0	0.00	-45	-9.00	10	0.77
73	-5	-0.25	-10	-3.33	-25	-5.00	18	1.38
74	-20	-1.00	0	0.00	-15	-3.00	20	1.54
75	-80	-4.00	20	6.67	-90	-18.00	85	6.54
76	-50	-2.50	35	11.67	-80	-16.00	70	5.38
77	-55	-2.75	50	16.67	-80	-16.00	75	5.77
78	-50	-2.50	70	23.33	-54	-10.80	30	2.31
79	-15	-0.75	65	21.67	-75	-15.00	-10	-0.77
80	20	1.00	50	16.67	-32	-6.40	-20	-1.54
81	15	0.75	55	18.33	-15	-3.00	-20	-1.54
82	-30	-1.50	90	30.00	10	2.00	-40	-3.08
83	-15	-0.75	40	13.33	15	3.00	-20	-1.54
84	30	1.50	0	0.00	-30	-6.00	10	0.77
85	15	0.75	-20	-6.67	-45	-9.00	50	3.85
86	-50	-2.50	110	36.67	-75	-15.00	12	0.92
87	-50	-2.50	70	23.33	-65	-13.00	10	0.77
88	-15	-0.75	20	6.67	-50	-10.00	-10	-0.77
89	-20	-1.00	28	9.33	-2	-0.40	0	0.00
90	5	0.25	-25	-8.33	0	0.00	30	2.31

Appendix 3

Mean rates of shoreline change (SL) and standard deviations compared to net rates of change (NSL) averaged over the entire timespan of available aerial photography.

Locations shown on 1:50 000 topocadastral maps in Appendix 4. Erosion is shown in bold type.

Station Number	Weighted Annual Mean Rate (SL)	Standard Deviation Weighted	Average Time between Photographs	D (S.D.*Time)	Net Annual Rate (NSL) 1937 - 1983
1	0.00	1.00	23.00	23.09	0.00
2	1.09	1.00	23.00	23.09	2.17
3	1.30	1.00	23.00	23.09	2.61
4	2.66	1.82	23.00	41.86	5.33
5	2.88	2.82	23.00	64.95	5.76
6	2.61	3.26	23.00	75.06	5.22
7	0.38	1.07	23.00	24.54	0.76
8	0.49	1.82	23.00	41.86	0.98
9	1.30	0.38	23.00	8.66	2.61
10	0.82	0.19	23.00	4.33	1.63
11	0.57	0.35	23.00	8.08	1.13
12	nr	nr	nr	nr	nr
13	1.36	2.32	23.00	53.40	2.72
14	0.49	1.19	23.00	27.42	0.98
15	**-0.22**	0.88	23.00	20.21	**-0.43**
16	0.23	0.93	11.50	10.73	0.91
17	0.03	1.69	11.50	19.43	0.11
18	**-0.35**	1.74	11.50	19.98	**-1.41**
19	**-0.51**	1.86	11.50	21.43	**-2.02**
20	0.65	1.03	8.67	8.97	nr
21	0.76	0.70	11.50	8.10	3.04
22	0.35	1.27	11.50	14.56	1.41
23	0.19	1.44	11.50	16.59	0.76
24	0.76	0.62	11.50	7.14	3.04
25	0.63	0.98	11.50	11.29	2.50
26	0.79	1.32	11.50	15.22	3.15
27	0.87	0.55	11.50	6.29	3.48
28	0.79	0.64	11.50	7.32	3.15
29	0.19	1.01	8.67	8.72	nr
30	0.52	0.27	11.50	3.13	2.07
31	0.52	0.61	11.50	7.02	nr
32	0.63	0.87	11.50	10.02	2.50
33	0.41	0.83	11.50	9.59	1.63
34	nr	nr	nr	nr	nr
35	0.38	0.37	11.50	4.27	1.52
36	0.22	0.27	11.50	3.06	0.87
37	0.14	0.61	11.50	7.02	0.54
38	**-0.71**	0.26	11.50	2.98	**-2.83**
39	**-0.24**	0.64	11.50	7.40	**-0.98**
40	**-0.21**	0.73	11.50	8.37	**-0.83**
41	**-0.03**	0.72	11.50	8.32	**-0.11**
42	nr	nr	nr	nr	nr
43	0.08	1.78	11.50	20.47	0.33
44	0.23	1.05	11.50	12.06	0.93
45	0.04	0.99	11.50	11.35	0.15
46	0.70	0.61	11.50	7.01	2.80
47	**-0.05**	1.58	11.50	18.19	**-0.22**
48	**-0.43**	0.97	11.50	11.13	**-1.74**

Station Number	Weighted Annual Mean Rate (SL)	Standard Deviation Weighted	Average Time between Photographs	D (S.D. *Time)	Net Annual Rate (NSL) 1937 - 1983
49	**-0.16**	0.51	11.50	5.82	**-0.65**
50	0.07	0.68	11.50	7.80	0.26
51	**-4.46**	12.20	10.25	125.00	0.12
52	1.11	3.08	9.20	28.33	1.59
53	1.11	0.85	9.20	7.79	4.15
54	1.33	4.88	9.20	44.88	12.80
55	5.58	3.34	7.67	25.63	
56	not recorded due to mouth position				
57	not recorded due to mouth position				

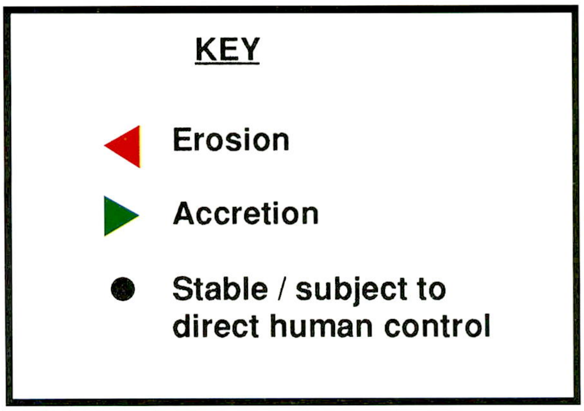
Station Number	Weighted Annual Mean Rate (SL)	Standard Deviation Weighted	Average Time between Photographs	D (S.D. *Time)	Net Annual Rate (NSL) 1937 - 1978
58	0.30	0.37	13.67	5.10	0.41
59	0.06	0.52	13.67	7.15	0.37
60	0.13	0.52	11.50	5.98	0.00
61	**-0.18**	0.51	11.50	5.91	0.00
62	0.39	0.12	11.50	1.36	**-0.02**
63	0.59	1.07	13.67	14.63	0.00
64	**-0.03**	0.47	10.25	4.83	**-0.12**
65	**-0.20**	0.94	10.25	9.63	**-0.78**
66	**-0.15**	1.06	10.25	10.87	**-0.61**
67	**-0.03**	1.10	10.25	11.24	**-0.12**
68	**-0.21**	2.00	10.25	20.47	**-0.85**
69	**-0.34**	1.62	10.25	16.63	**-1.34**
70	**-0.27**	1.79	10.25	18.33	**-1.10**
71	0.06	1.13	10.25	11.61	0.24
72	**-0.09**	0.70	10.25	7.17	**-0.37**
73	**-0.13**	0.43	10.25	4.46	**-0.54**
74	**-0.09**	0.44	10.25	4.49	**-0.37**
75	**-0.40**	2.04	10.25	20.95	**-1.59**
76	**-0.15**	1.72	10.25	17.60	**-0.61**
77	**-0.06**	1.86	10.25	19.11	**-0.24**
78	**-0.02**	1.49	10.25	15.28	**-0.10**
79	**-0.21**	1.40	10.25	14.34	**-0.85**
80	0.11	0.92	10.25	9.40	0.44
81	0.21	0.84	10.25	8.62	0.85
82	0.18	1.44	10.25	14.77	0.73
83	0.12	0.68	10.25	7.00	0.49
84	0.06	0.61	10.25	6.25	0.24
85	0.00	1.01	10.25	10.36	0.00
86	**-0.02**	2.01	10.25	20.60	**-0.07**
87	**-0.21**	1.50	10.25	15.42	**-0.85**
88	**-0.34**	0.70	10.25	7.17	**-1.34**
89	0.04	0.48	10.25	4.96	0.15
90	0.06	0.55	10.25	5.64	0.24

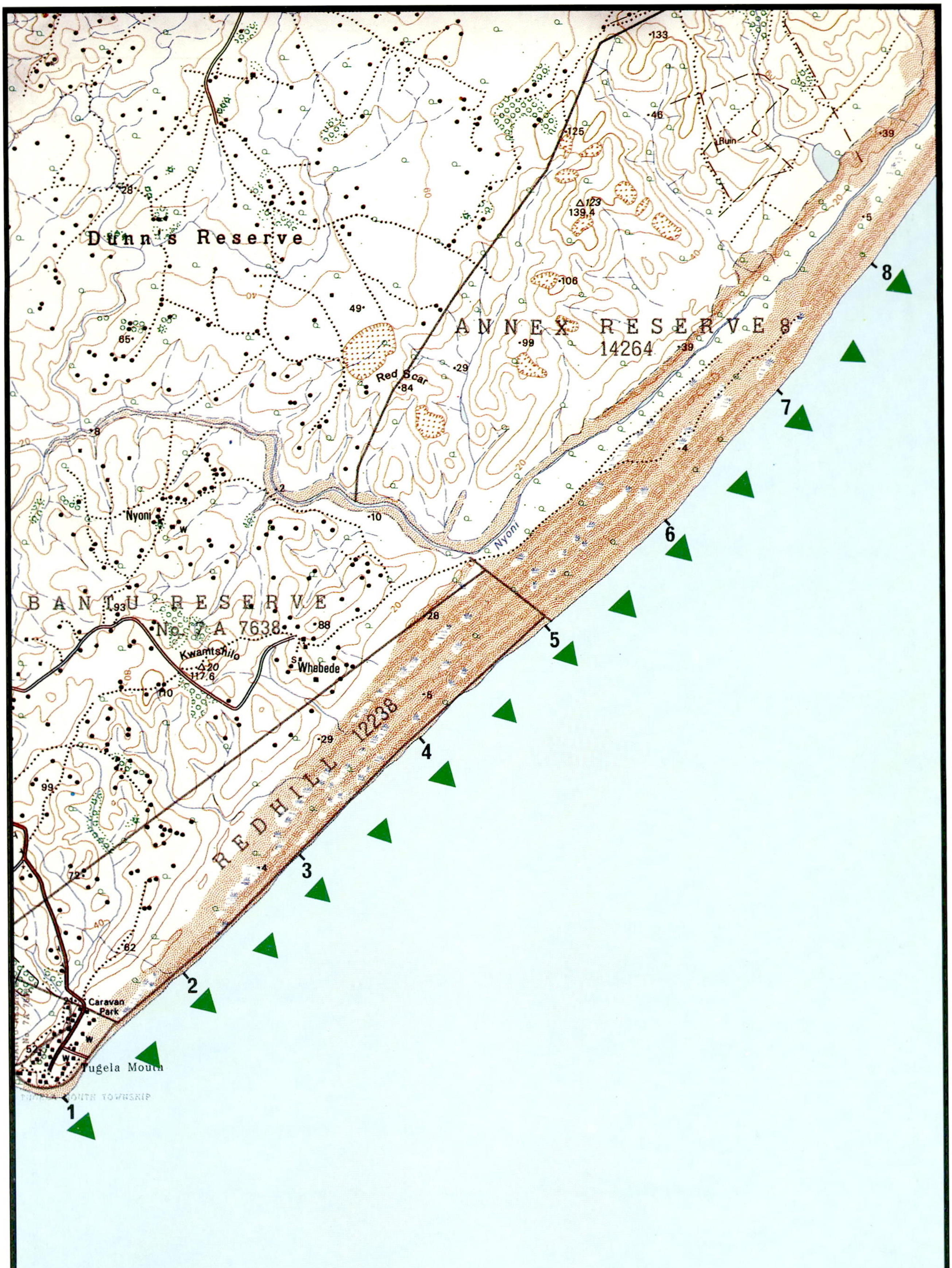
Station Number	Pre-Harbour Weighted Annual Mean Rate (SL)	Standard Deviation Weighted	Post-Harbour Weighted Annual Mean Rate (SL)	Standard Deviation Weighted
51	0.54	2.00	-0.56	6.67
52	0.76	1.38	3.19	6.13
53	0.33	0.46	3.48	0.18
54	0.43	0.61	4.13	9.86
55		5.58	2.73	
56	not recorded due to mouth position			
57	not recorded due to mouth position			

Appendix 4

1:50 000 topocadastral locality maps showing summarised erosion/accretion data schematically and location of stations at which measurements were made.

The key for the topocadastral maps is shown below.





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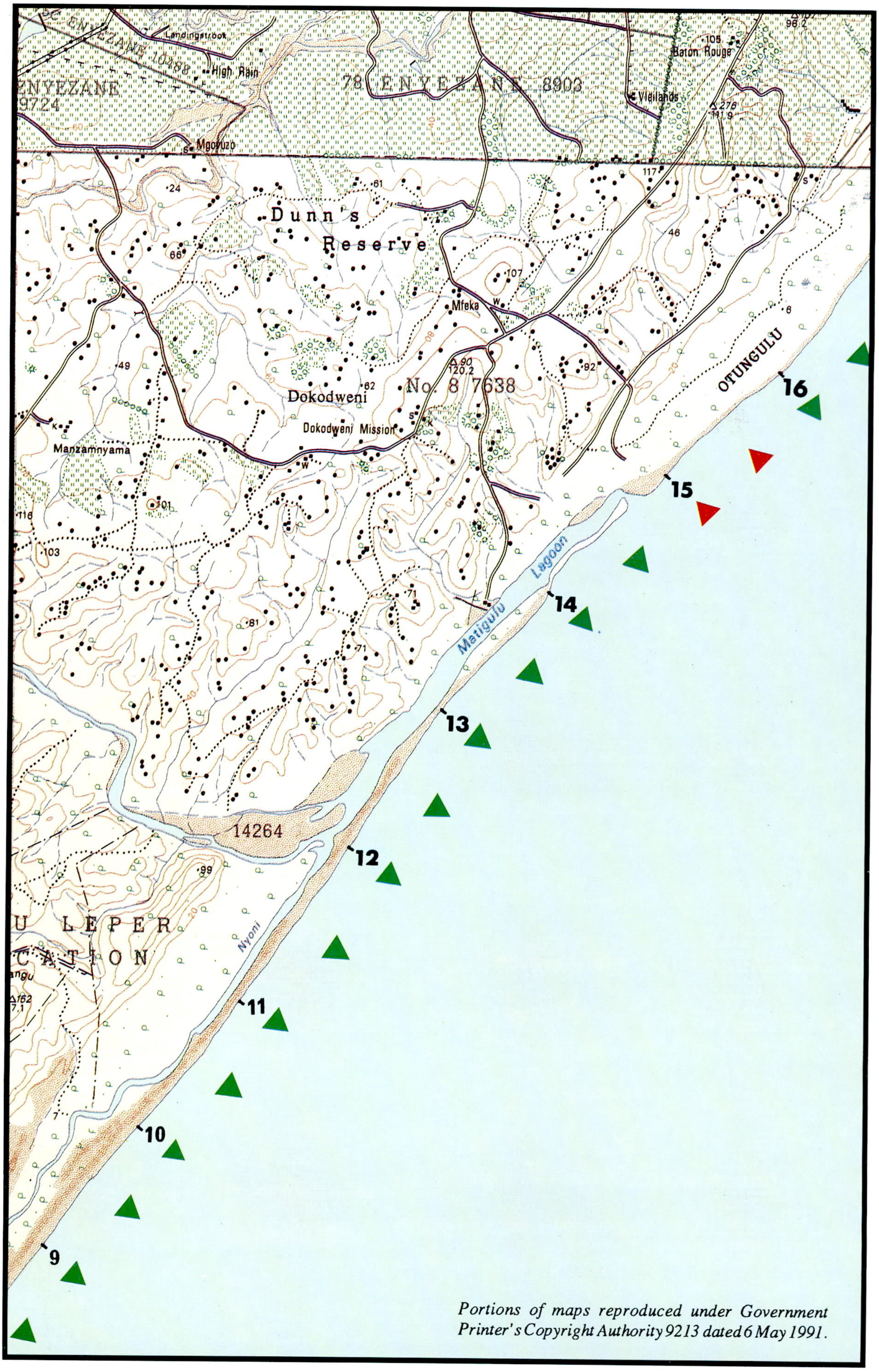

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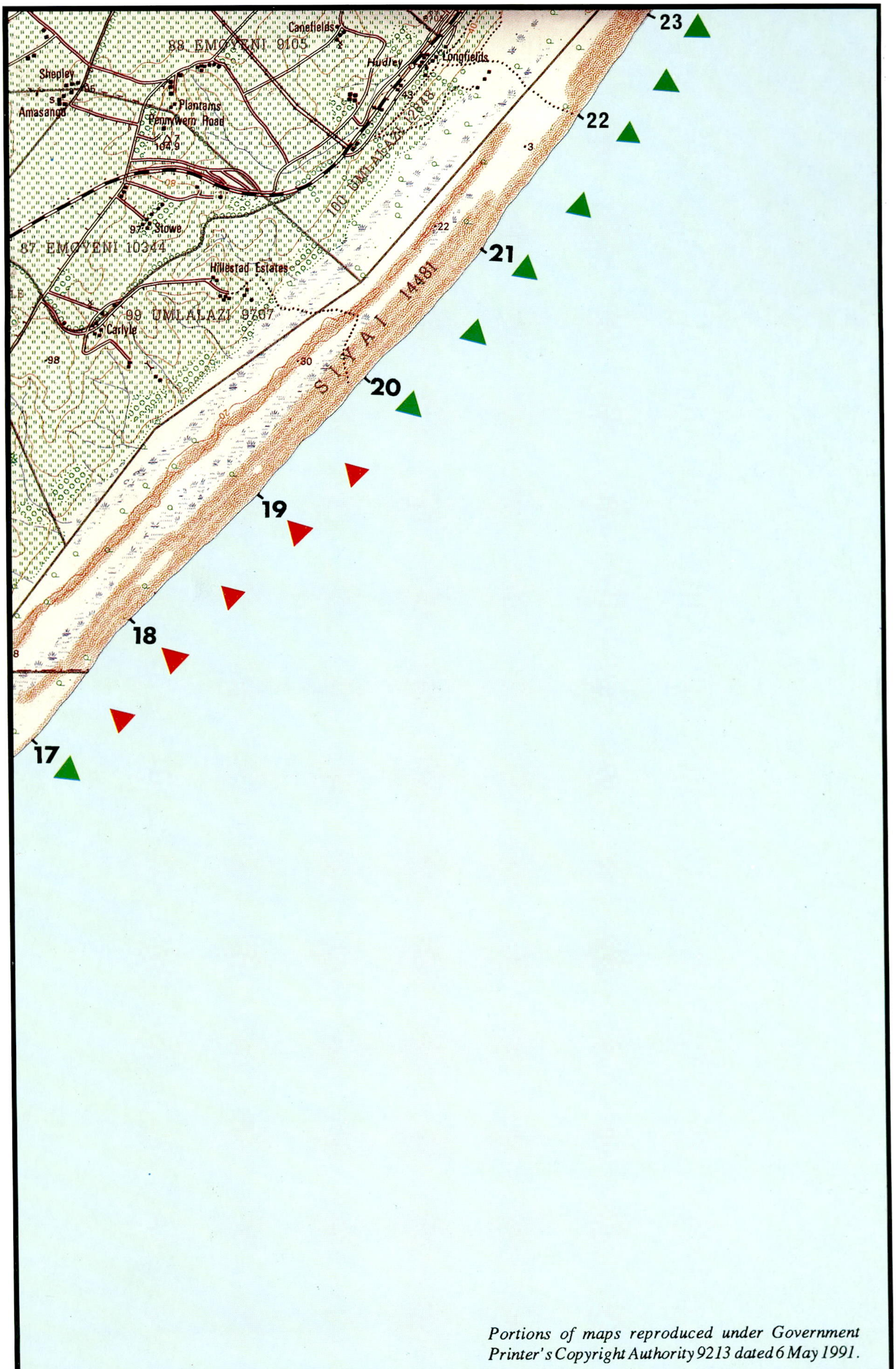
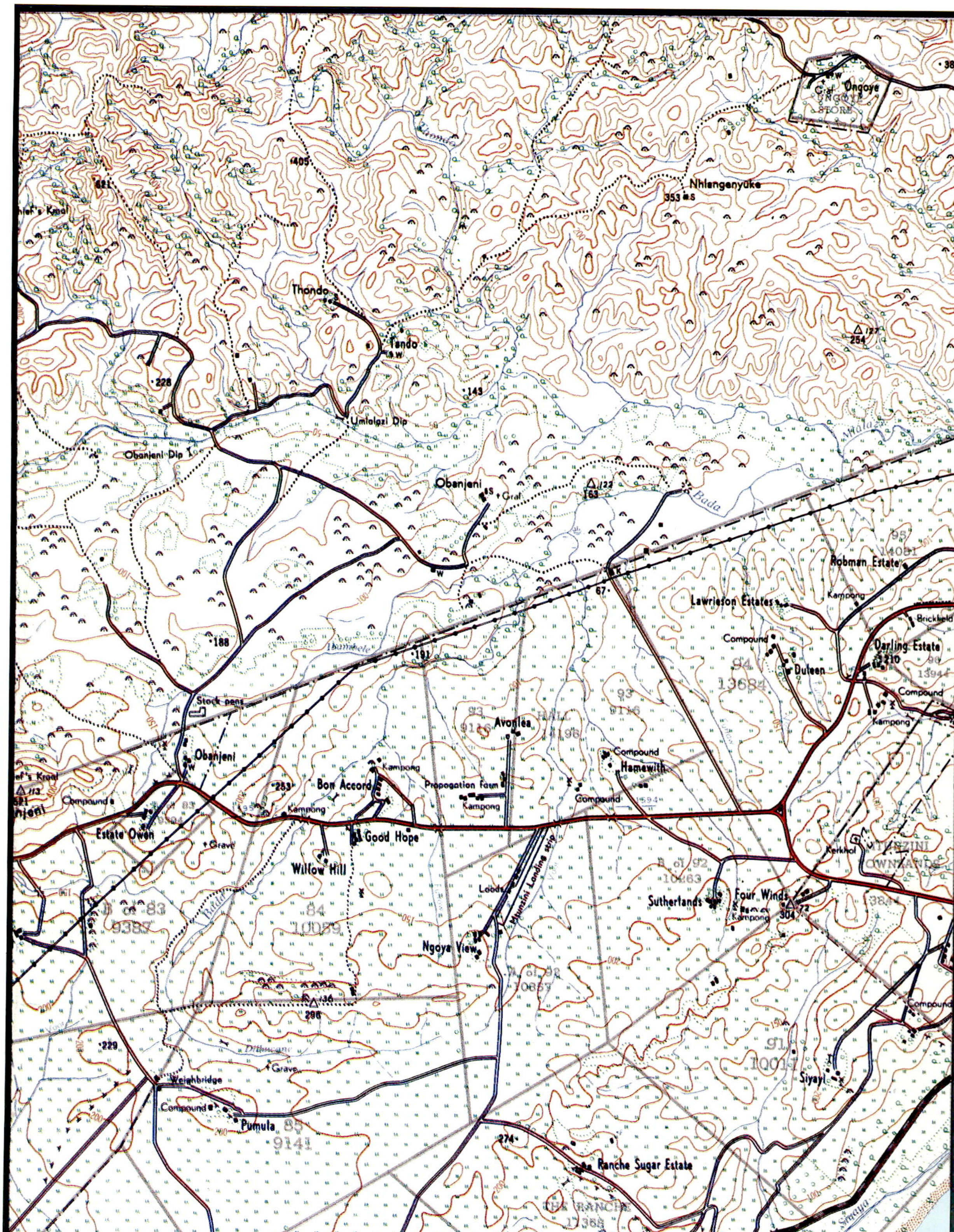

23
22
21
20
19
18
17
Canefields
Hudley
Longfields
88 EMOYENI 9105
Shepley
Amasango
Plantams
Stowe
87 EMOYENI 10344
Hillestad Estates
99 UMLALAZI 9707
Carlyle
SIYAI 14481



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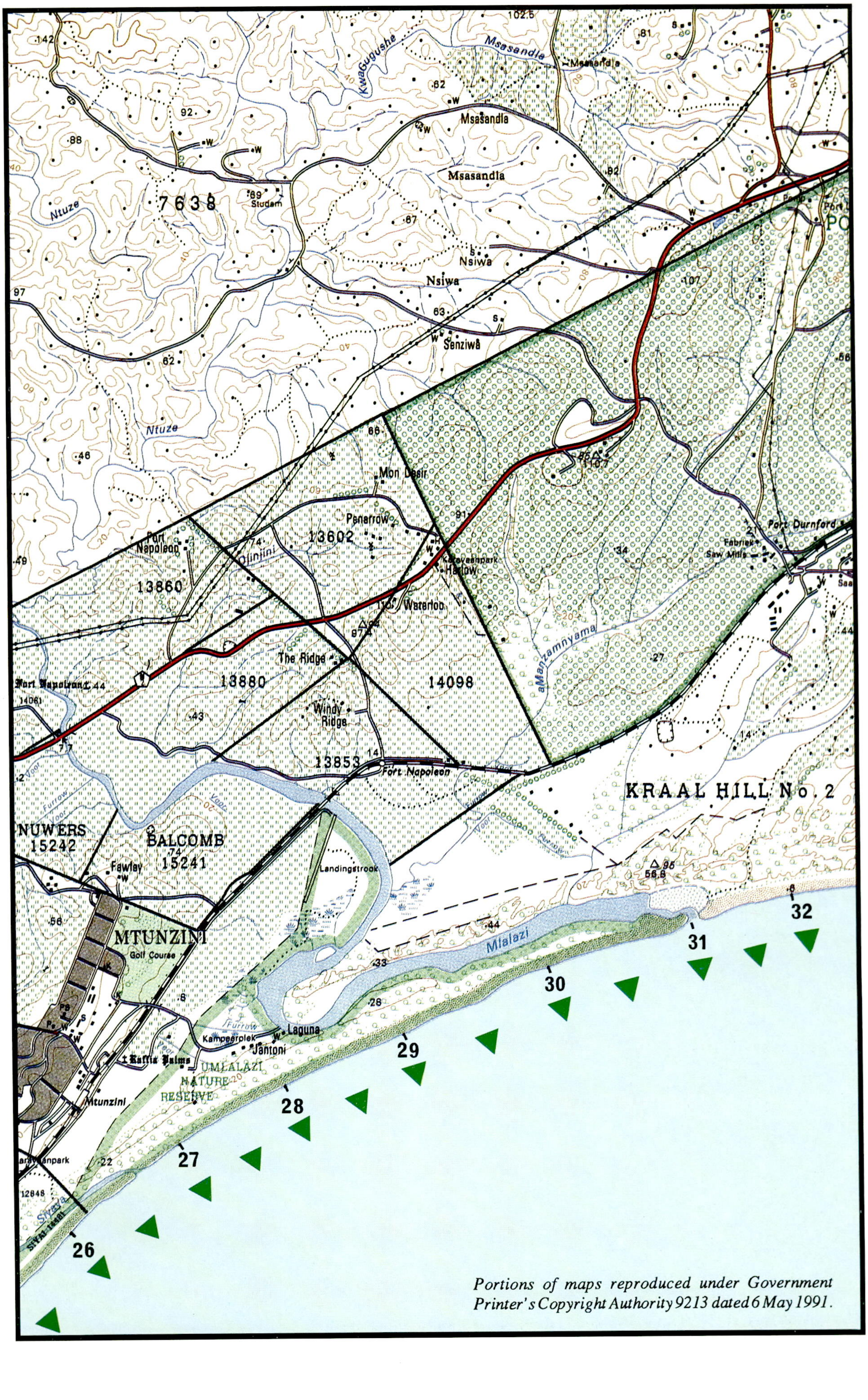

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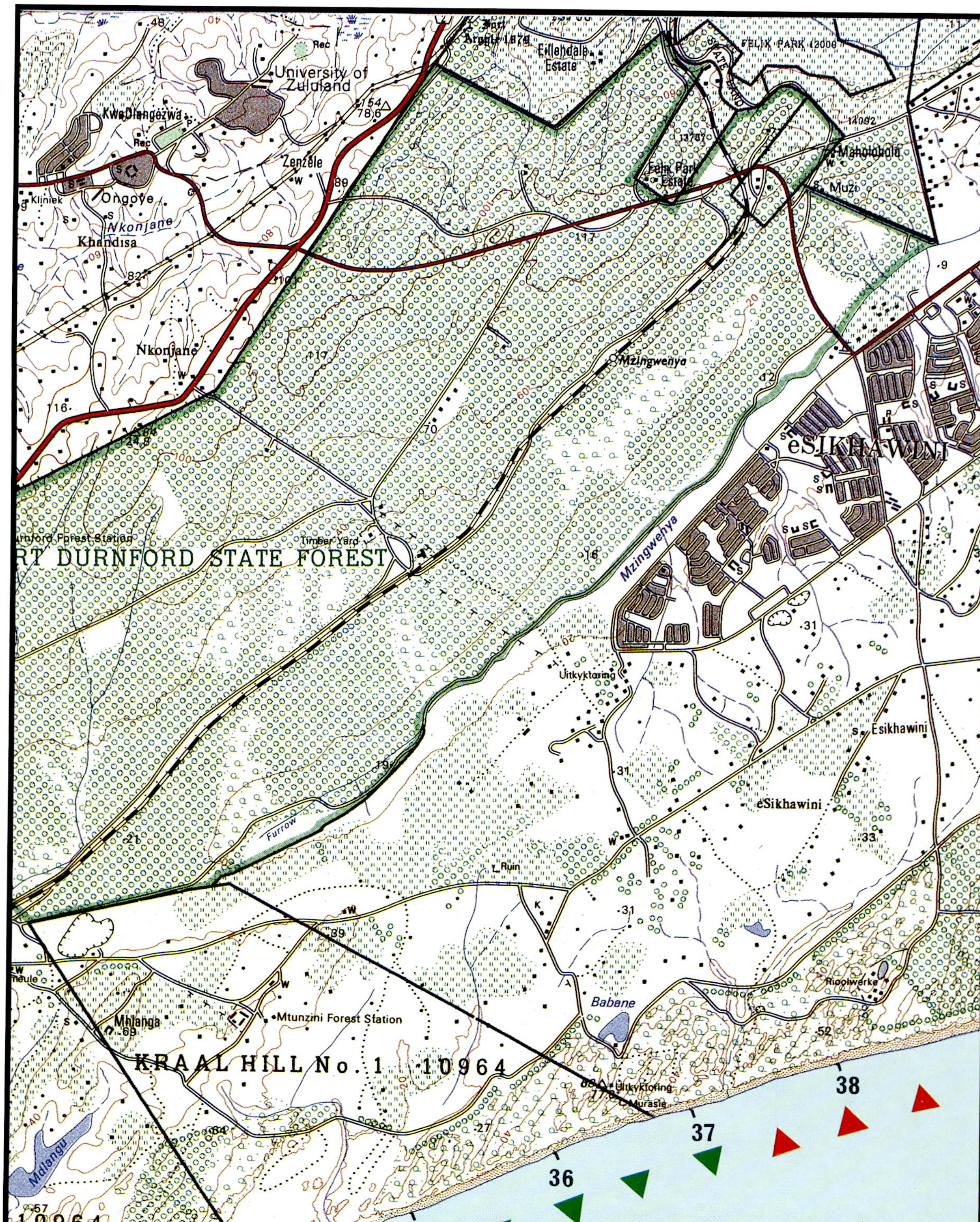
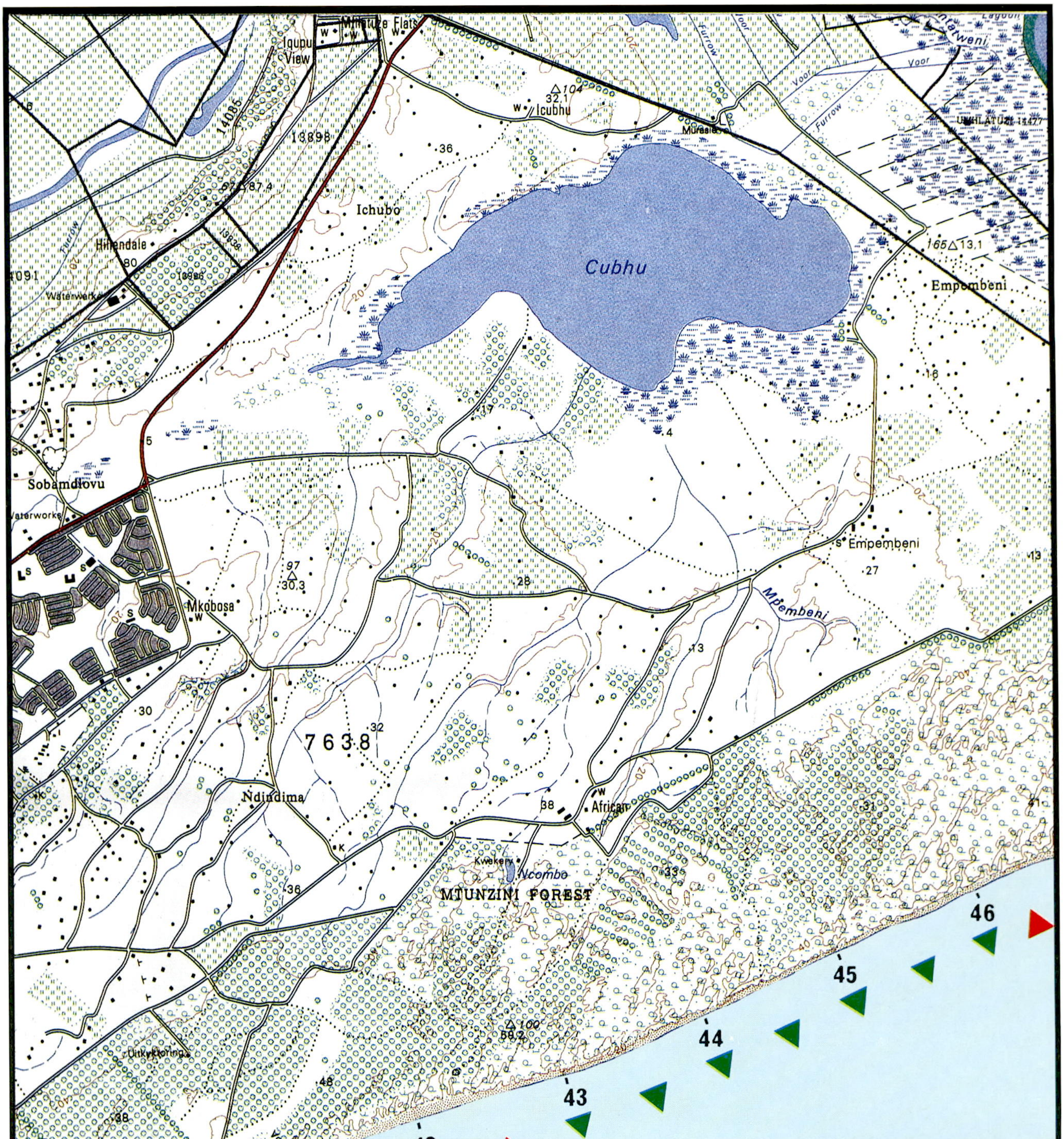
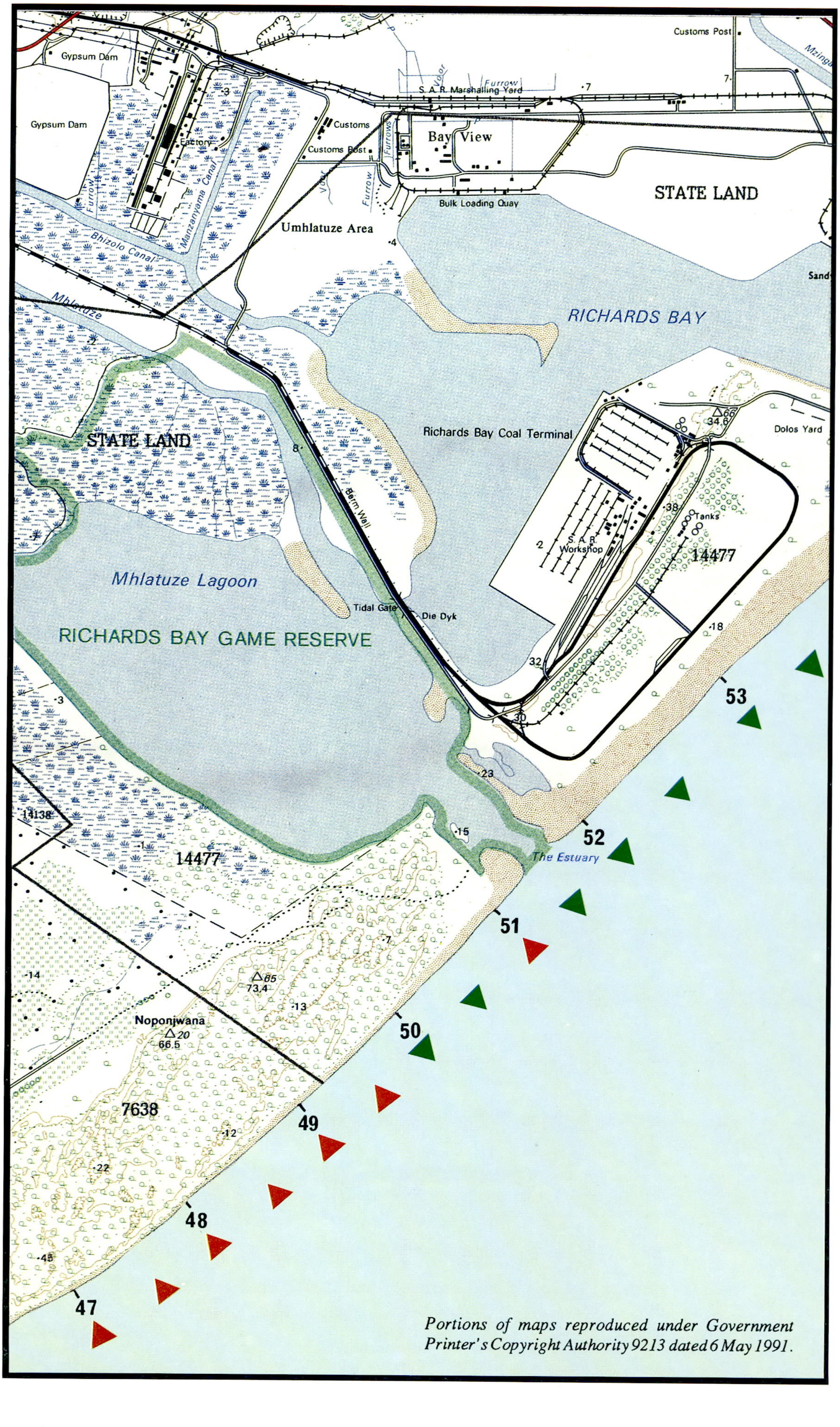

University of Zululand
KwaDlangezwa
Zenzele
Ongoye
Nkonjane
Khandisa
Nkonjane
Eillandale Estate
FELIX PARK
Felix Park Estate
Mahlobolo
Muzi
Mzingwenya
eSIKHAWINI
Mzingwenya
Timber Yard
RT DURNFORD STATE FOREST
Uitkyktoring
Esikhawini
eSikhawini
Furrow
Ruin
Babane
Rioolwerke
Mhlanga
Mtunzini Forest Station
KRAAL HILL No. 1 10964
Uitkyktoring
Mlalazi
10964
33
34
35
36
37
38

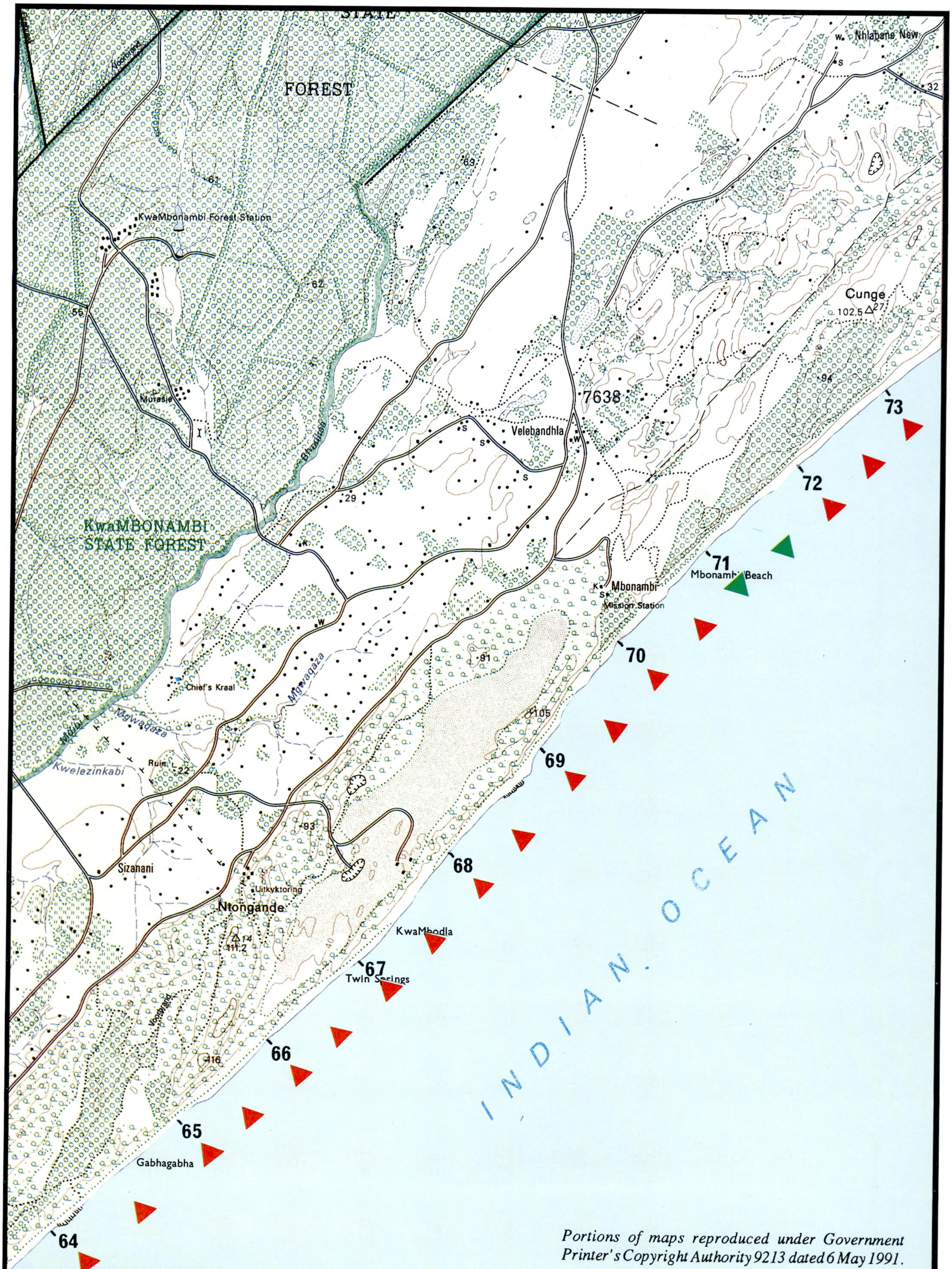


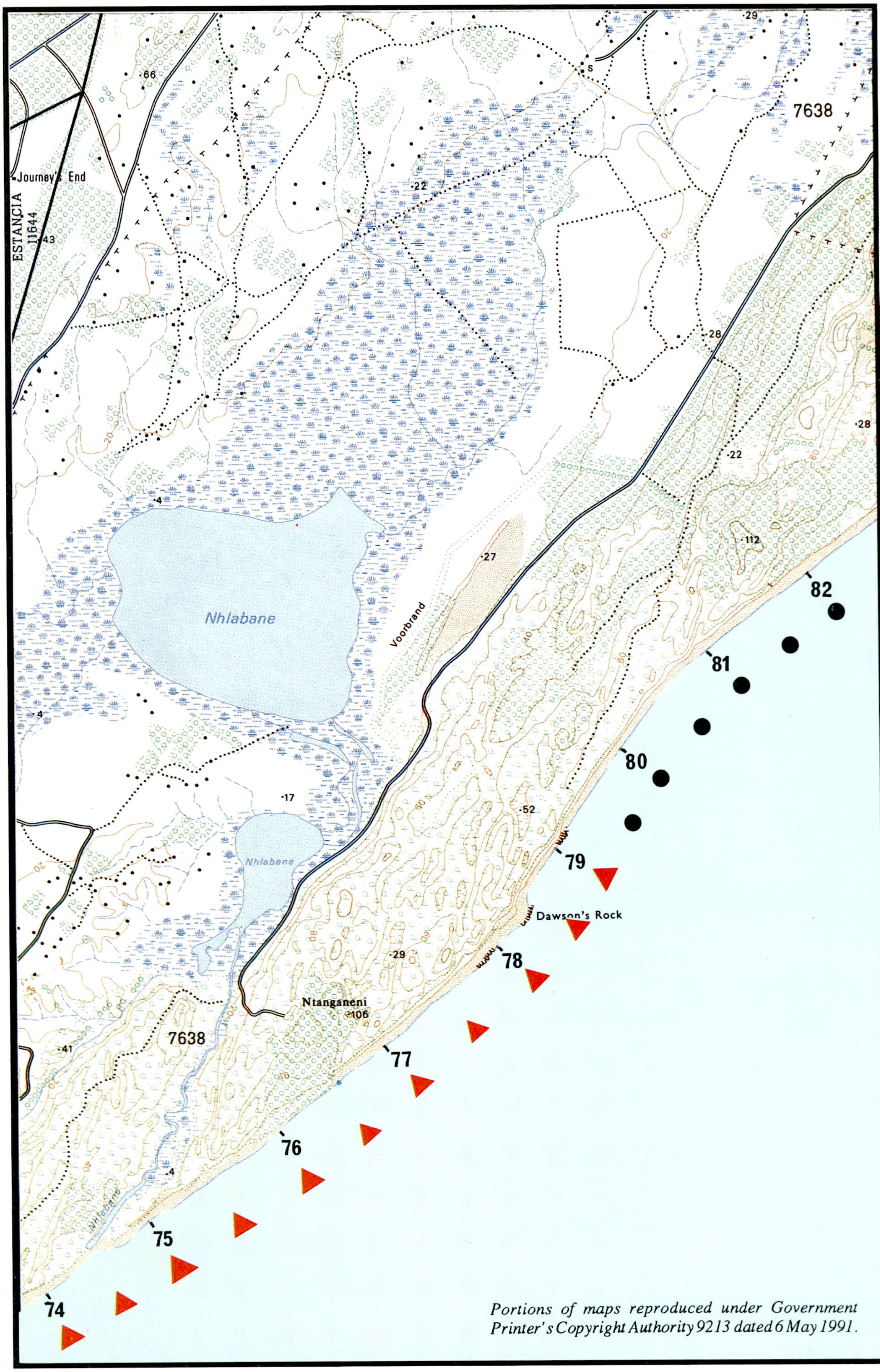
Portions of maps reproduced under Government Printer's Copyright Authority 9213 dated 6 May 1991.



Portions of maps reproduced under Government Printer's Copyright Authority 9213 dated 6 May 1991.

Portions of maps reproduced under Government Printer's Copyright Authority 9213 dated 6 May 1991.


STATE
FOREST
KwaMbonambi Forest Station
KwaMBONAMBI STATE FOREST
Velebandhla
7638
Nhlabane New
Cunge
102.5
Mbonambi Beach
Mbonambi
Mission Station
Chief's Kraal
Mgwaqaza
Kwelezinkabi
Ruin
Sizanani
Uitkyktoring
Ntongande
111.2
KwaMbodla
Twin Springs
Gabhagabha
INDIAN OCEAN
64
65
66
67
68
69
70
71
72
73



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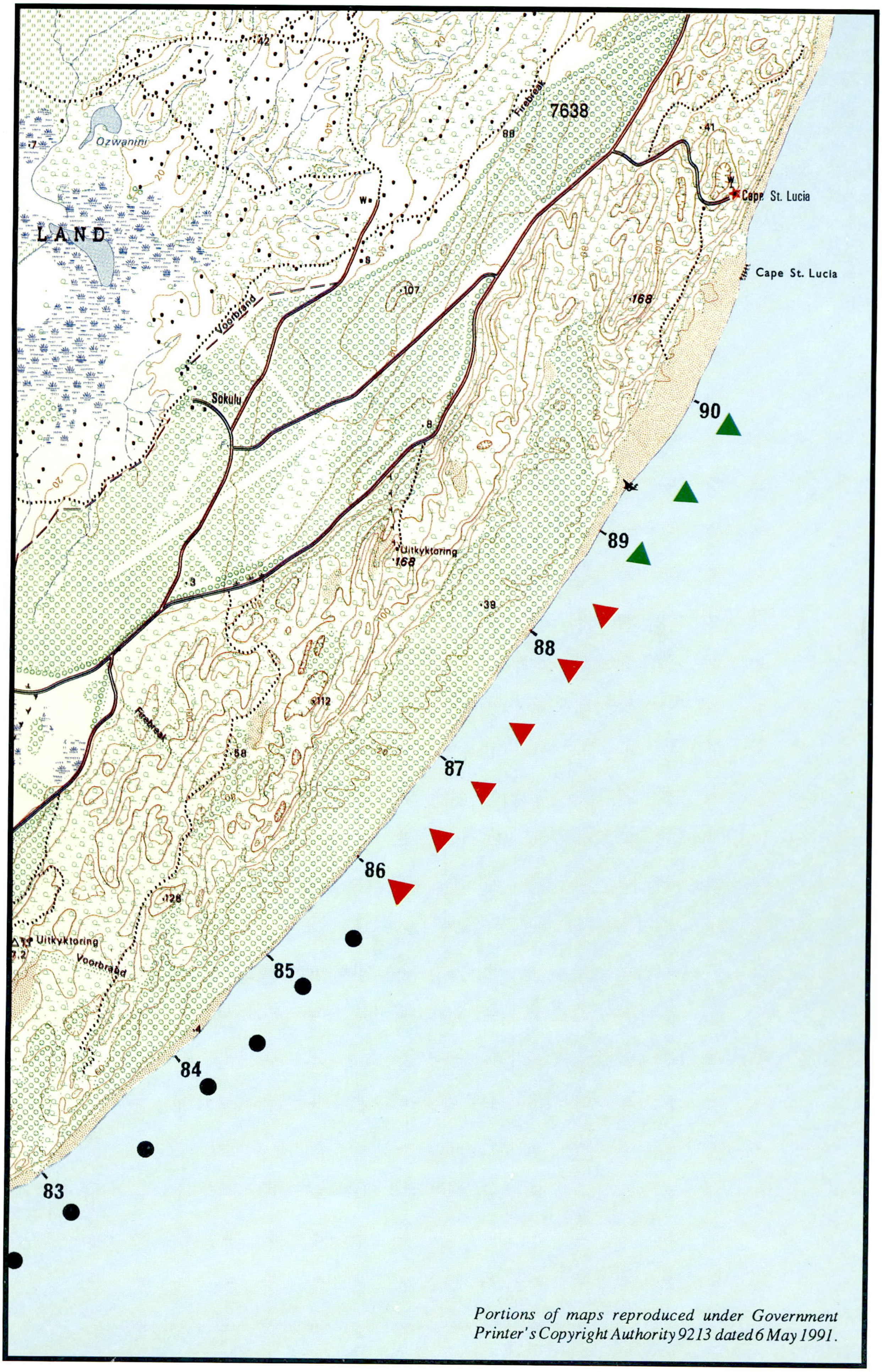

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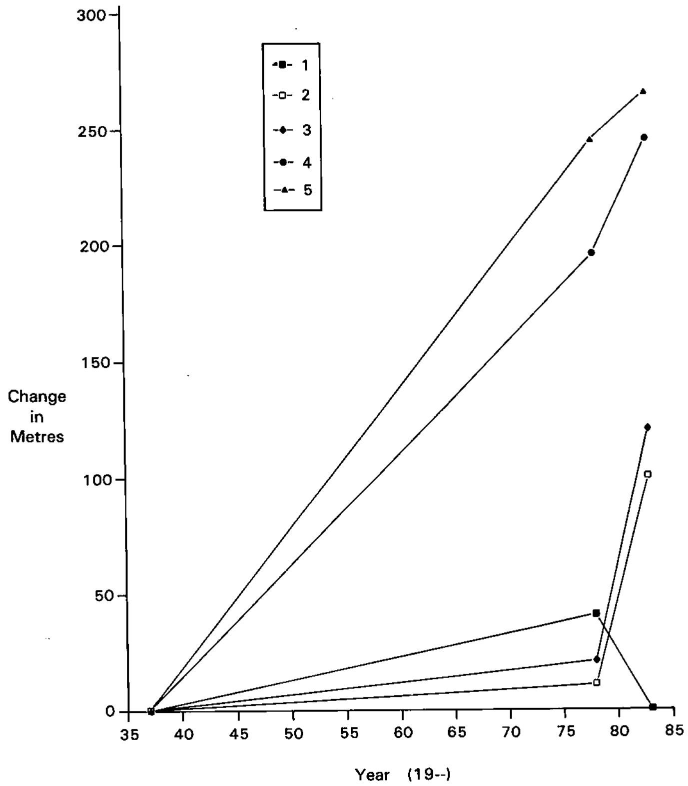
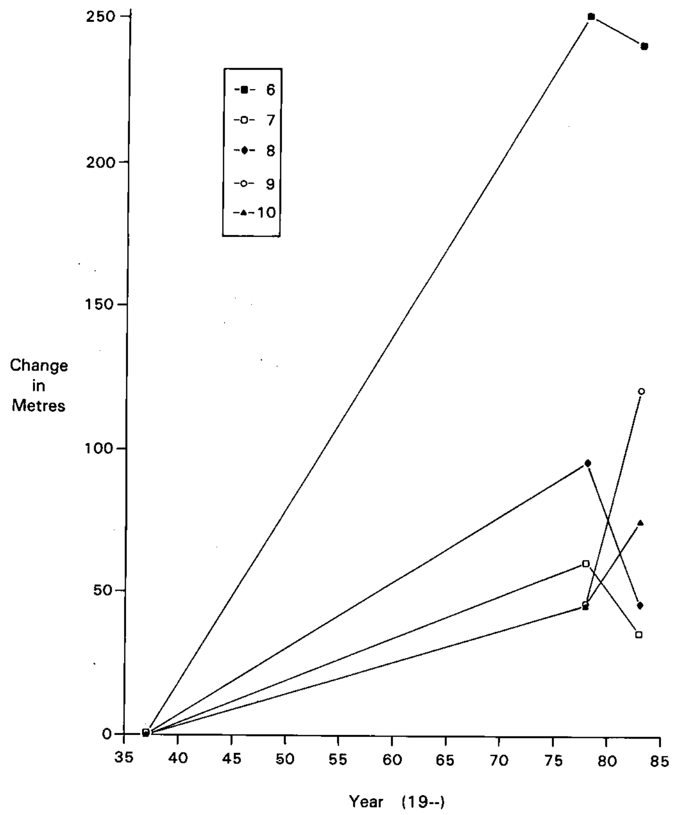
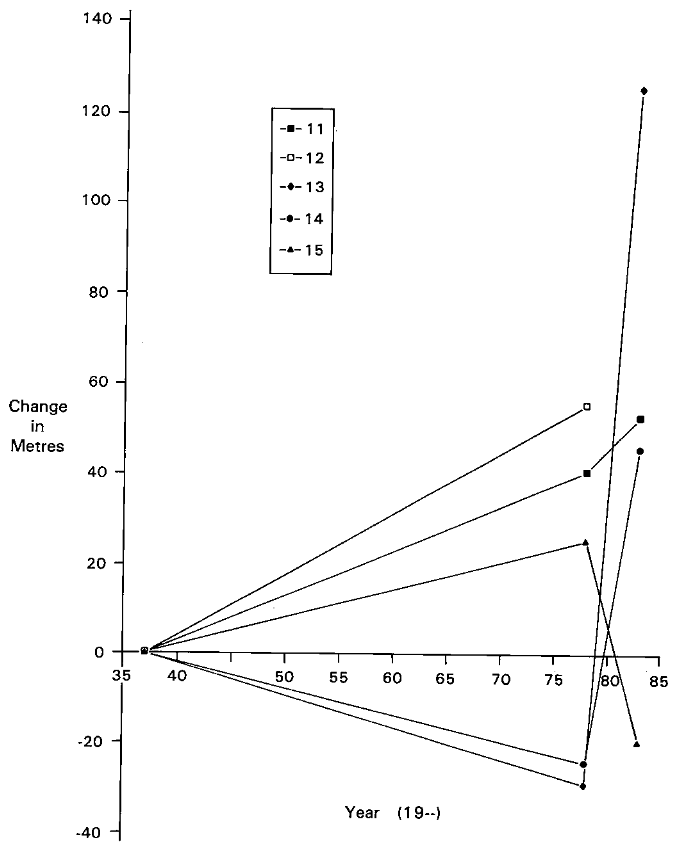
Appendix 5

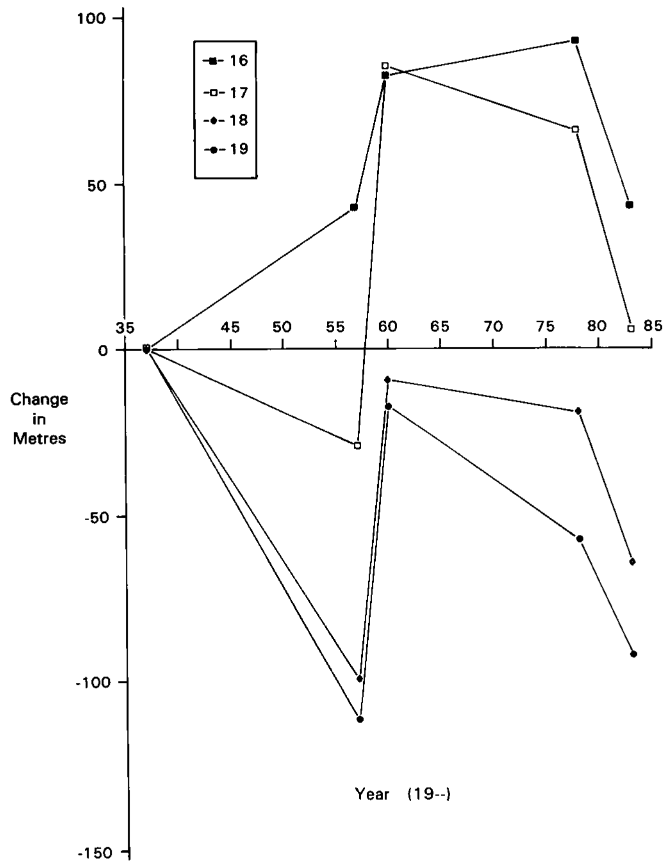
Graphical representation of temporal changes in shoreline position at sampling stations.

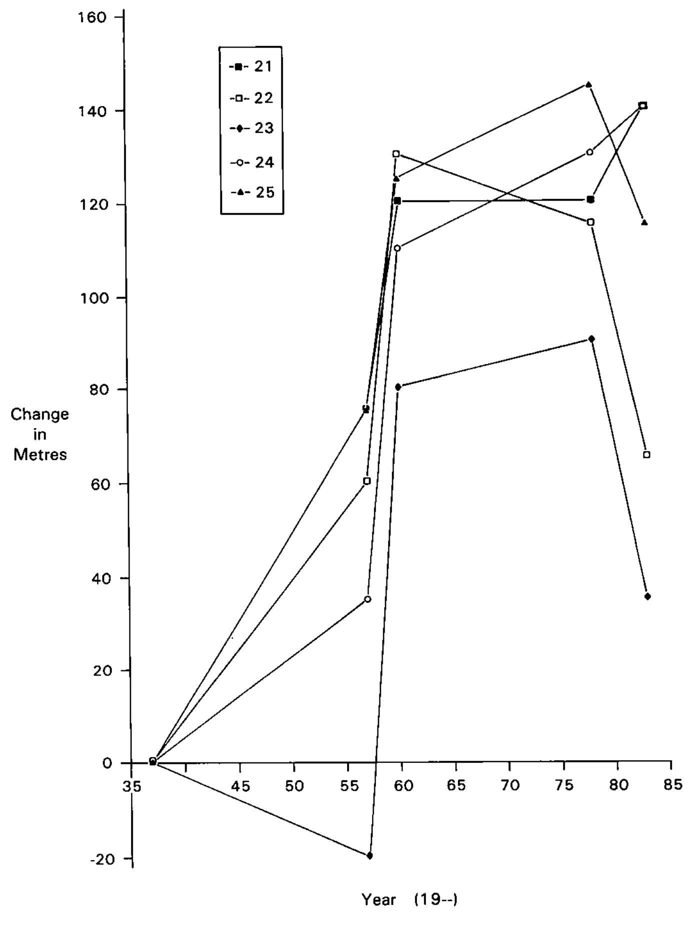
All positions are relative to 1937. The grouping of stations on particular graphs reflects sections of the study area, treated individually in the text.

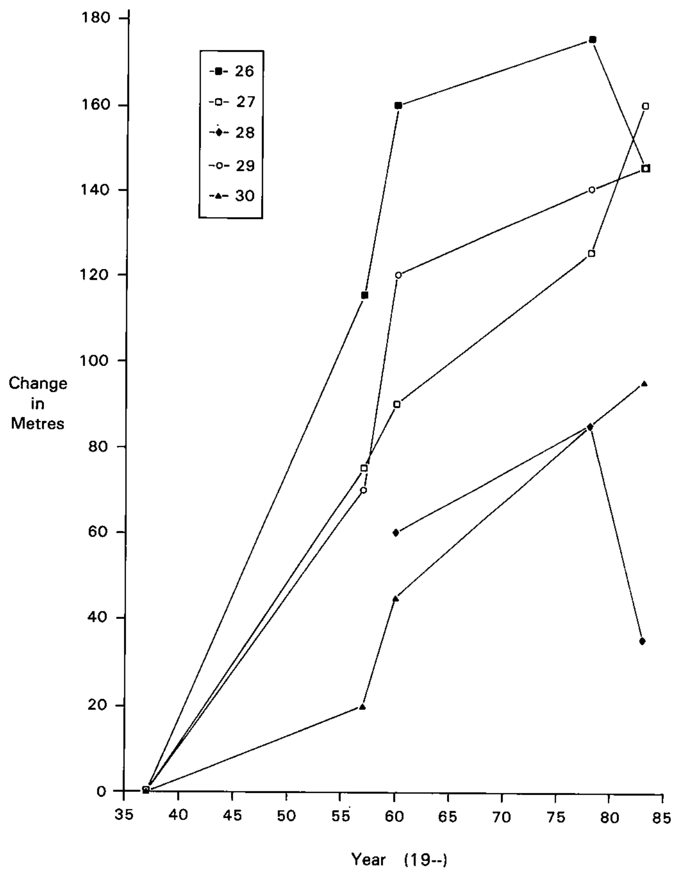



250
200
150
100
50
0
Change
in
Metres
-■- 6
-□- 7
-◆- 8
-○- 9
-▲- 10
35
40
45
50
55
60
65
70
75
80
85
Year (19--)

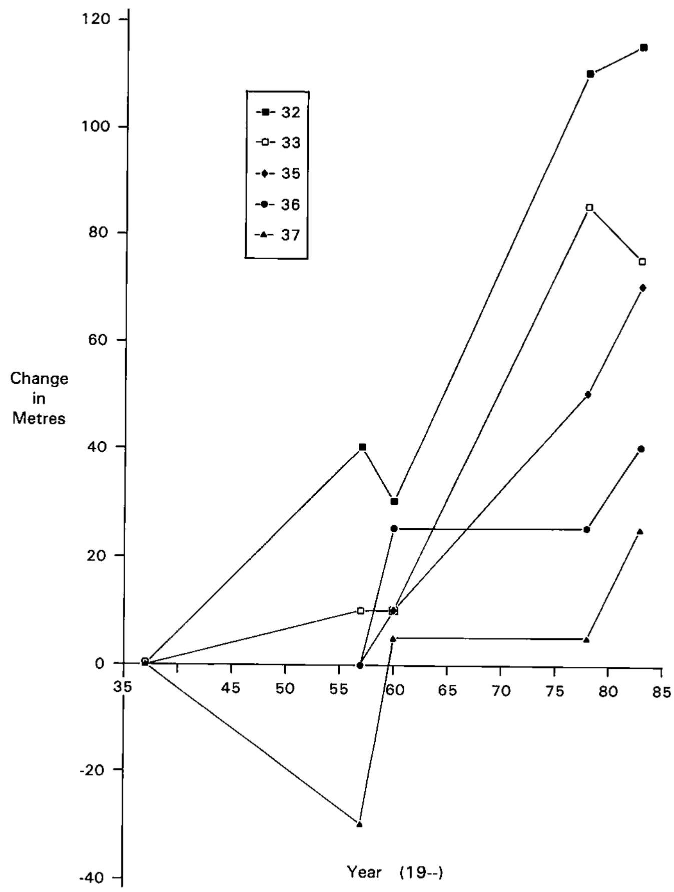

140
120
100
80
60
40
20
0
-20
-40
Change
in
Metres
-■- 11
-□- 12
-◆- 13
-●- 14
-▲- 15
35
40
50
55
60
65
70
75
80
85
Year (19--)


100
50
0
-50
-100
-150
Change
in
Metres
16
17
18
19
35
45
50
55
60
65
70
75
80
85
Year (19--)

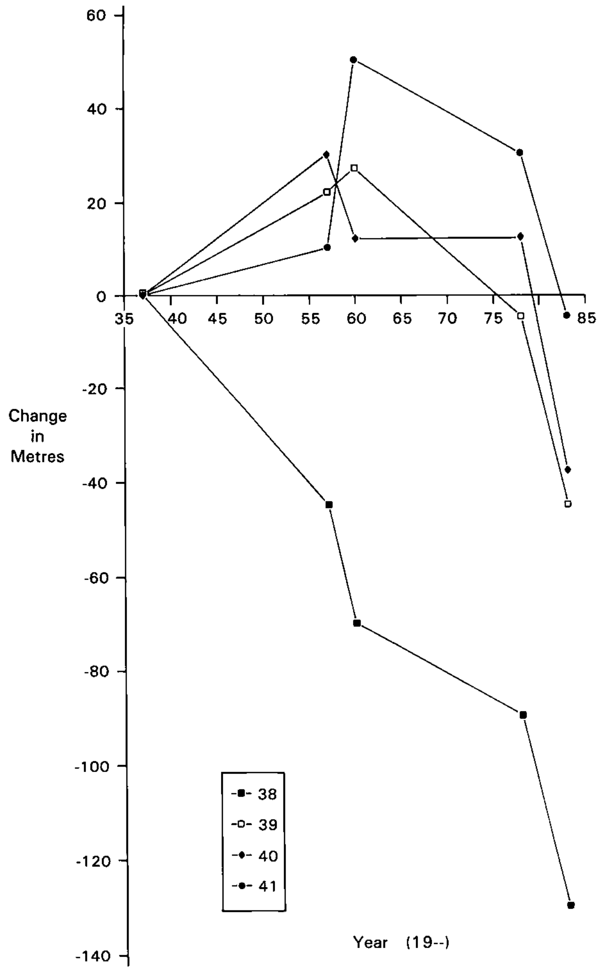

160
140
120
100
80
60
40
20
0
-20
Change
in
Metres
21
22
23
24
25
35
45
50
55
60
65
70
75
80
85
Year (19--)

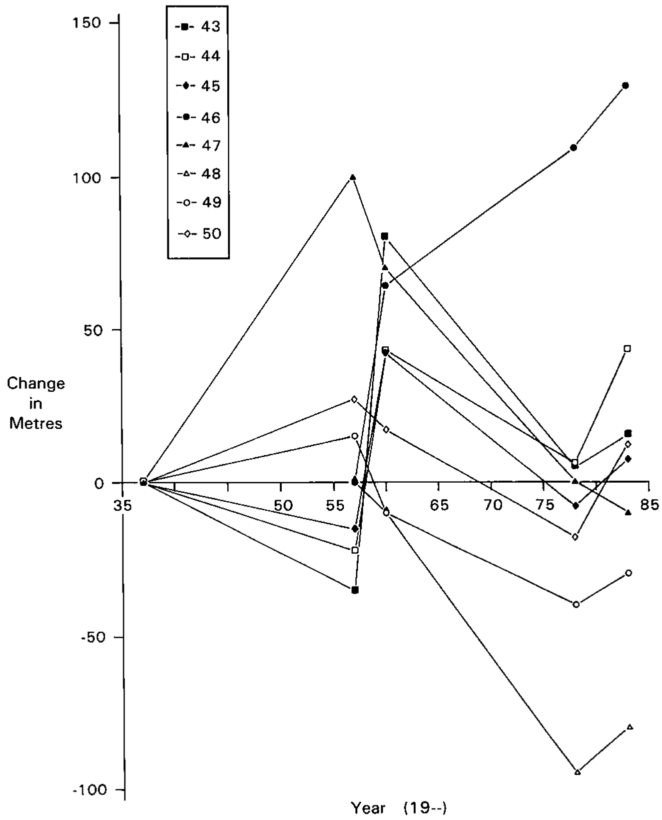


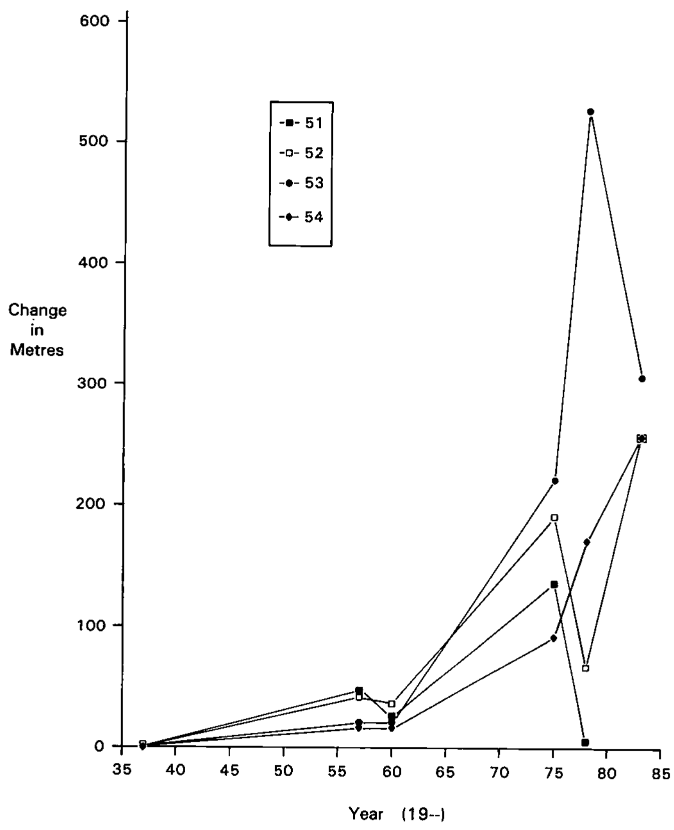
180
160
140
120
100
80
60
40
20
0
Change in Metres
-■- 26
-□- 27
-♦- 28
-○- 29
-▲- 30
35
40
45
50
55
60
65
70
75
80
85
Year (19--)



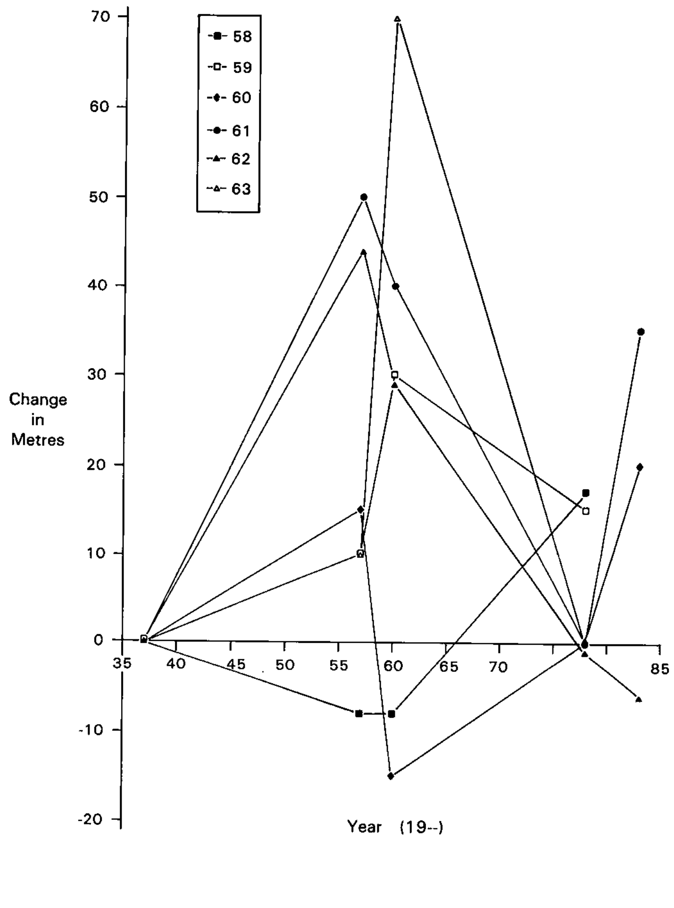
120
100
80
60
40
20
0
-20
-40
Change in Metres
-■- 32
-□- 33
-♦- 35
-●- 36
-▲- 37
35
45
50
55
60
65
70
75
80
85
Year (19--)


60
40
20
0
-20
-40
-60
-80
-100
-120
-140
35
40
45
50
55
60
65
70
75
85
Change in Metres
-■- 38
-□- 39
-♦- 40
-●- 41
Year (19--)

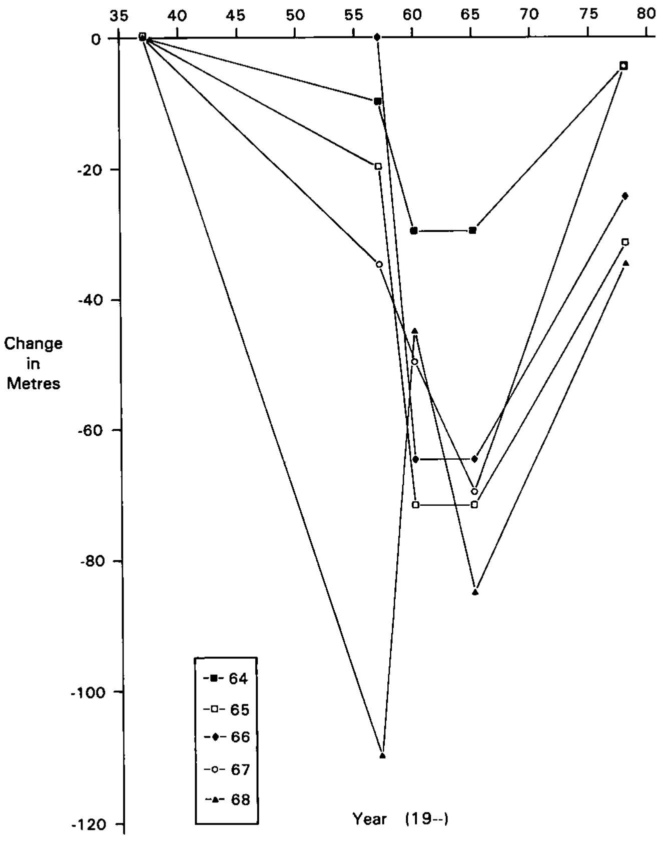

150
100
50
0
-50
-100
35
50
55
65
70
75
85
Change in Metres
-■- 43
-□- 44
-♦- 45
-●- 46
-▲- 47
-△- 48
-○- 49
-◇- 50
Year (19--)

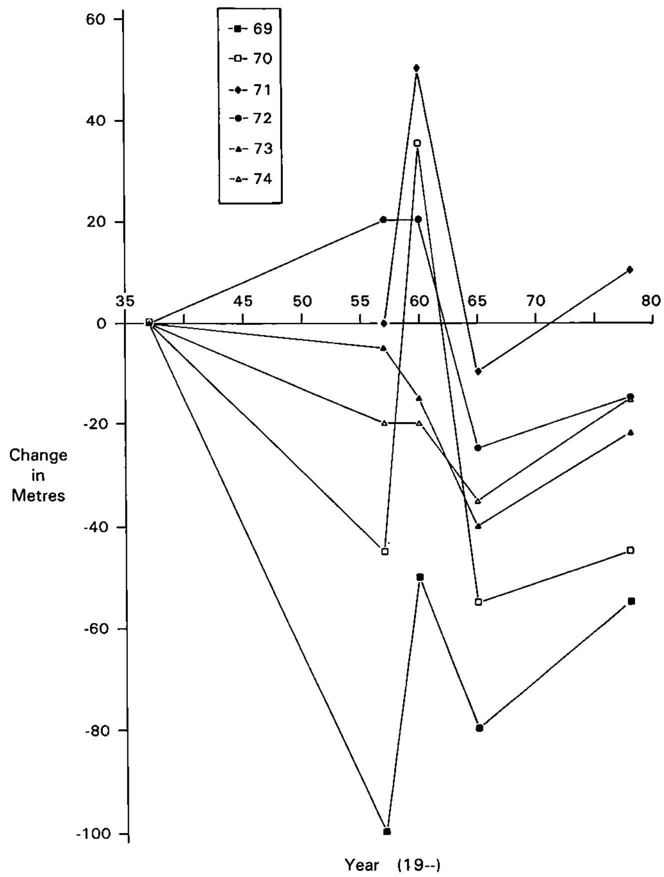


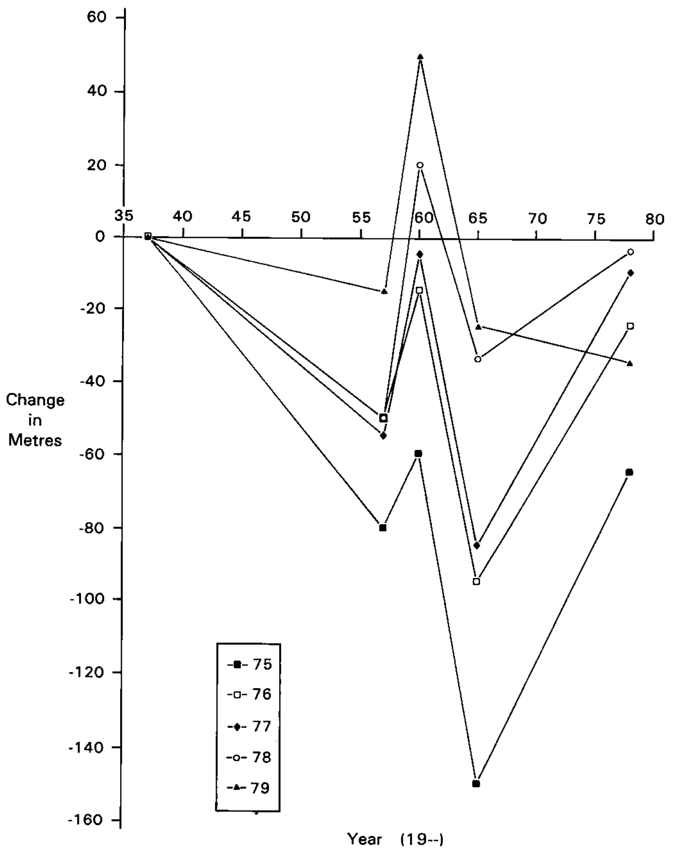
600
500
400
300
200
100
0
Change
in
Metres
-■- 51
-□- 52
-●- 53
-♦- 54
35
40
45
50
55
60
65
70
75
80
85
Year (19--)

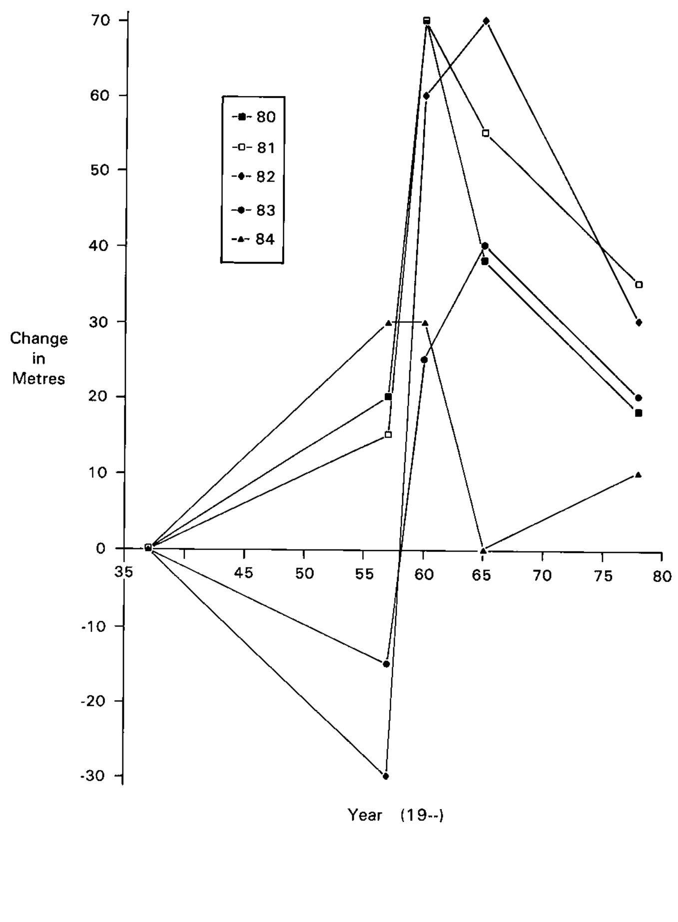


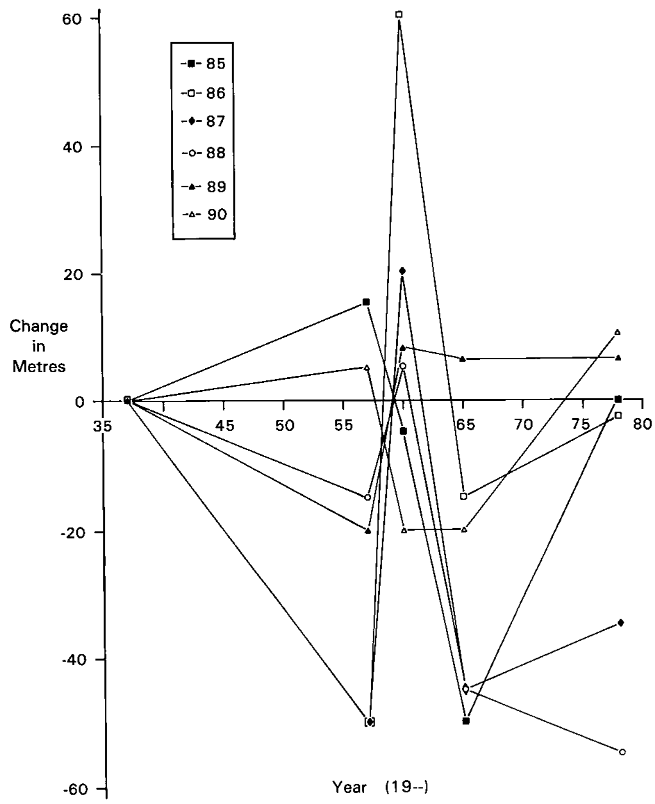
70
60
50
40
30
20
10
0
-10
-20
Change
in
Metres
-■- 58
-□- 59
-♦- 60
-●- 61
-▲- 62
-△- 63
35
40
45
50
55
60
65
70
85
Year (19--)


35
40
45
50
55
60
65
70
75
80
0
-20
-40
-60
-80
-100
-120
Change in Metres
64
65
66
67
68
Year (19--)


60
40
20
0
-20
-40
-60
-80
-100
69
70
71
72
73
74
35
45
50
55
60
65
70
80
Change in Metres
Year (19--)


60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
35
40
45
50
55
60
65
70
75
80
Change in Metres
Year (19--)
75
76
77
78
79


70
60
50
40
30
20
10
0
-10
-20
-30
35
45
50
55
60
65
70
75
80
Change in Metres
Year (19--)
80
81
82
83
84


60
40
20
0
-20
-40
-60
Change in Metres
35
45
50
55
65
70
75
80
Year (19--)
85
86
87
88
89
90