Journal of Coastal Research	11	3	887–898	Fort Lauderdale, Florida	Summer 1995

Sea Level Rise and Coastal Planning: A Call for Stricter Control in River Mouths

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ABSTRACT

HUGHES, P. and BRUNDRIT, G.B., 1995. Sea level rise and coastal planning: A call for stricter control in river mouths. *Journal of Coastal Research,* 11(3), 887–898. Fort Lauderdale (Florida), ISSN 0749-0208.

Drift-aligned type deltas are common to the South African coastline across the whole range of river sizes. They are dynamic environments and by virtue of their potential for rapid morphological change, they are inherently unsuitable for development. South Africa has a relatively short history of intense coastal development. As a result, these estuaries appear to have some margin of stability and are rapidly becoming developed.

Sea level rise will increase the occurrence of extreme flood and erosional events in these estuaries and poorly planned development contained within them will come under exaggerated risk. Two case studies of potential impacts of sea level rise are considered: the Diep river near Cape Town and the Umgeni river at Durban. Increased coastal erosion resulting from a small rise in sea level is shown to shorten the channel of the Diep, seriously affecting housing on the spit barrier and exposing previously sheltered development to direct wave attack. The combination of sea level rise with river floods and/or sea storms is shown to induce a switch in the Umgeni from a modern short channel, to a longer, abandoned channel. Durban city centre is located in the middle of this palaeochannel. The potential for flood damage is extreme. Incr*e*ased coastal erosion will also significantly reduce the available tourist beaches.

Drift-aligned deltas occur in many locations worldwide and any development contained within them is highly vulnerable to changes in mean sea level. The increased vulnerability of these environments is therefore of international significance. Their development needs to be strictly controlled with new town planning ordinances, capable of addressing the sea level rise issue.

ADDITIONAL INDEX WORDS: *Sea level rise, drift-aligned deltas, coastal planning, South Africa.*

INTRODUCTION

The combination of rivers with ephemeral flow, or periods of reduced flow, discharging onto high energy coastlines with strong longshore currents results in a distinctive delta morphology. Such wave-dominated deltas exhibit straight shorelines characterized by well-developed barriers and beach ridges with high lateral continuity of sands (WRIGHT and COLEMAN, 1973). These barriers have long linear beaches, may be capped by large aeolian dunes, and deflect the river mouth, usually in the downdrift direction of the longshore current. The growth of these barriers causes the development of shallow lagoons and wetland on their landward side. WRIGHT and COLEMAN (1973) use the Senegal river delta as their type location for wave/littoral drift dominated morphologies.

The occurrence of these delta types depends largely on the inability of the river to supply sediment faster and more consistently than can be reworked by the waves. Provided that suitable wave conditions prevail, they may therefore be expected to form in subtropical areas worldwide and other areas with arid catchments. Examples can be found in southern California, Peru, Argentina, northwestern Africa, Japan and Australia where the majority of Victoria's rivers drain into estuarine lagoons with sea entrances encumbered by inwashed sandy thresholds and flanking spits (BIRD and SCHWARTZ, 1985).

Drift-aligned deltas are dynamic sedimentary environments and these river mouths are inherently unstable. An adequate sediment supply combined with high energy angled wave attack promotes the evolution and growth of elongated spits. As the spit barrier and backing lagoon grows in length, the length of the river channel increases. Short term variability in the growth of the spits is associated with the effects of the high energy wave climate and variability in the longshore current. Under certain conditions, large waves can wash-over low or weak sections of the barrier and, if persistent, can erode a washover channel which may form a new mouth from the outside-in (Fig-

92119 received 16 October 1992; accepted in revision 15 August 1994.

ure 1). However, the striking long term changes in channel morphology are generally due to major river floods which break through the barrier and trigger the reversion of the mouth to a position closer to the river axis. These river floods typically have return periods of the order of decades. Subsequent to the flood event, wave generated longshore-drift becomes the dominant sediment transport mechanism and the new mouth usually continues its migration cycle (Figure 1).

SOUTH AFRICAN COAST AND RIVER MOUTHS

South Africa has a high energy wave climate and many of its rivers are ephemeral or, at best, are inferior to wave forcing in their effect on the coastal morphology (BEGG, 1984). The incident dominant wave fields are oblique to the shoreline and have formed the many log-spiral bays, characteristic of the western and southern South African coasts (Figure 2). Waves along the west coast are predominantly southerly and along the southwest and south coasts are mostly from the southwest. Along the east coast, wave directions are influenced by tropical cyclones and have a northeasterly component so that they are bi-modally distributed south southwest/northeast (ROUSSOUW, 1989). Geology and wave climate renders log-spiral bays less pronounced along this coast. Rainfall essentially has a dual distribution pattern with summer rainfall occurring towards the north and east of the country and winter rainfall in the south. West coast rainfall patterns are marginal. However, extremes of rainfall do occur and floods on the west and southern coasts are associated with the progression of cut-off low pressure systems—usually spring and autumn events. East coast rainfall is more tropical in character and flood events are dominated by tropical cyclones.

Both marine and atmospheric conditions in South Africa are therefore suitable for the evolution and subsequent destruction of elongated spit barriers and lagoons, characteristic of drift aligned deltas. Consequently, many fine examples exist across the whole spectrum of South African rivers, from streams to major rivers. Such examples include the delta of the Orange river on the Namibian border (which although being the longest river in South Africa still has a variable flow); the Diep river, 5 km north of Cape Town; the Keurbooms river at Plettenberg Bay; the Gamtoos near Port Elizabeth; with perhaps the finest example being the combined estuaries of the Nyoni and Matigulu rivers in Natal (Figure 2). The last section of this estuary runs parallel to the shore, forming a lagoon which reached a maximum 14 km long in 1977 (DAY, 1981). Examination of the South African 1:250,000 map series (SURVEYS and MAPPING) reveals that within the Cape nearly 80% of all rivers and streams have some form of spit and lagoon development and over 60% are backed by vleis and wetlands. The majority of the 73 river mouths along the Natal coast also exhibit spit and dune barrier formation. This is particularly true of the northern Natal coast, although the steepness of the drowned river valley sides often precludes the formation of extensive shore parallel lagoons and wetlands in the south.

Mouth mobility is documented in many of these rivers, both large and small. The Keurbooms river mouth at Plettenberg Bay (Figure 2) opens to the sea between two sandy spits, each approximately 1 km long and 300 m wide with an extensive backing lagoon. The town of Plettenberg Bay is located on the eastern shore of the lagoon and estuary mouth, and development is slowly spreading along the western spit. Two old mouths are evident at the base of each spit respectively, on opposite sides of the estuary axis (DAY, 1981) and between 1937 and 1980 the present position migrated westward at a rate of approximately 40 m per annum (DUVENAGE and MORANT, 1984). The Matigulu estuary (Figure 2) captured the Nyoni estuary during floods in 1971 and grew until in 1977 this lagoon extended for a maximum of 14 km behind the dune barrier (DAY, 1981). River floods subsequently reduced its length to 7.5 km. The 1987 floods further shortened the lagoon and the Nyoni now enters the sea along the Matigulu river axis (PERRY, 1989).

During the 1850's and 1860's the Bot river mouth, located some 110 km southeast of Cape Town, provided port facilities to the surrounding farming community (KOOP, 1982). Today the Bot river has switched exits and flows to the sea via the non-navigable Kleinmond estuary some 5 km to the northwest. KOOP (1982) provides a list of Bot river mouth closures and switches to the Kleinmond system over the last 140 years. The mouth of the Groot Berg river, 150 km to the north of Cape Town, was mobile and migrated along its approximate 3 km of spit until 1966 when it was shortened and canalised to facilitate access for

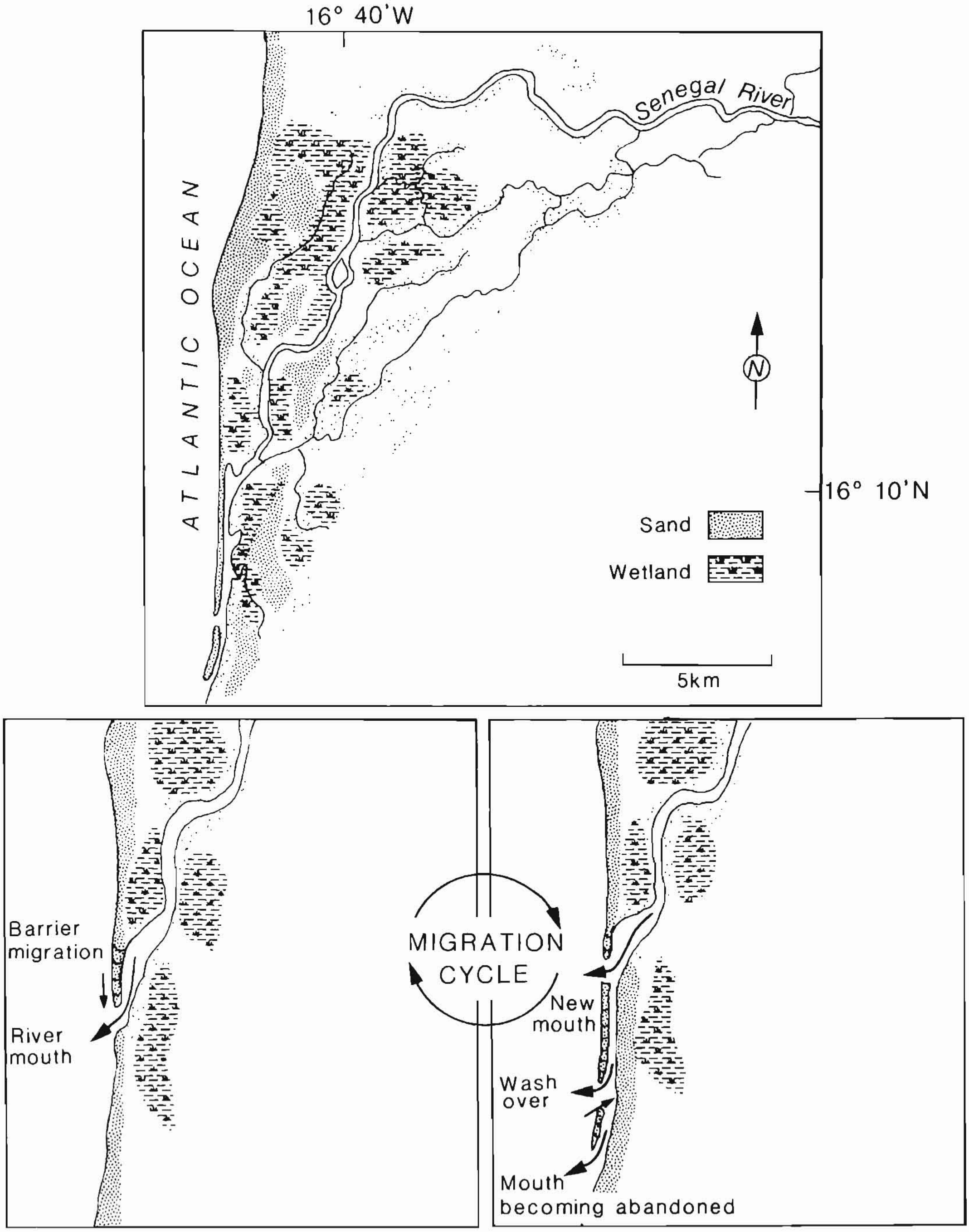

Figure 1. Drift aligned delta development and mouth migration. Senegal river delta (top) redrawn after WRIGHT and COLEMAN (1973). Spit grows in response to longshore sediment transport until river floods or barrier wash-over shorten the channel (bottom).

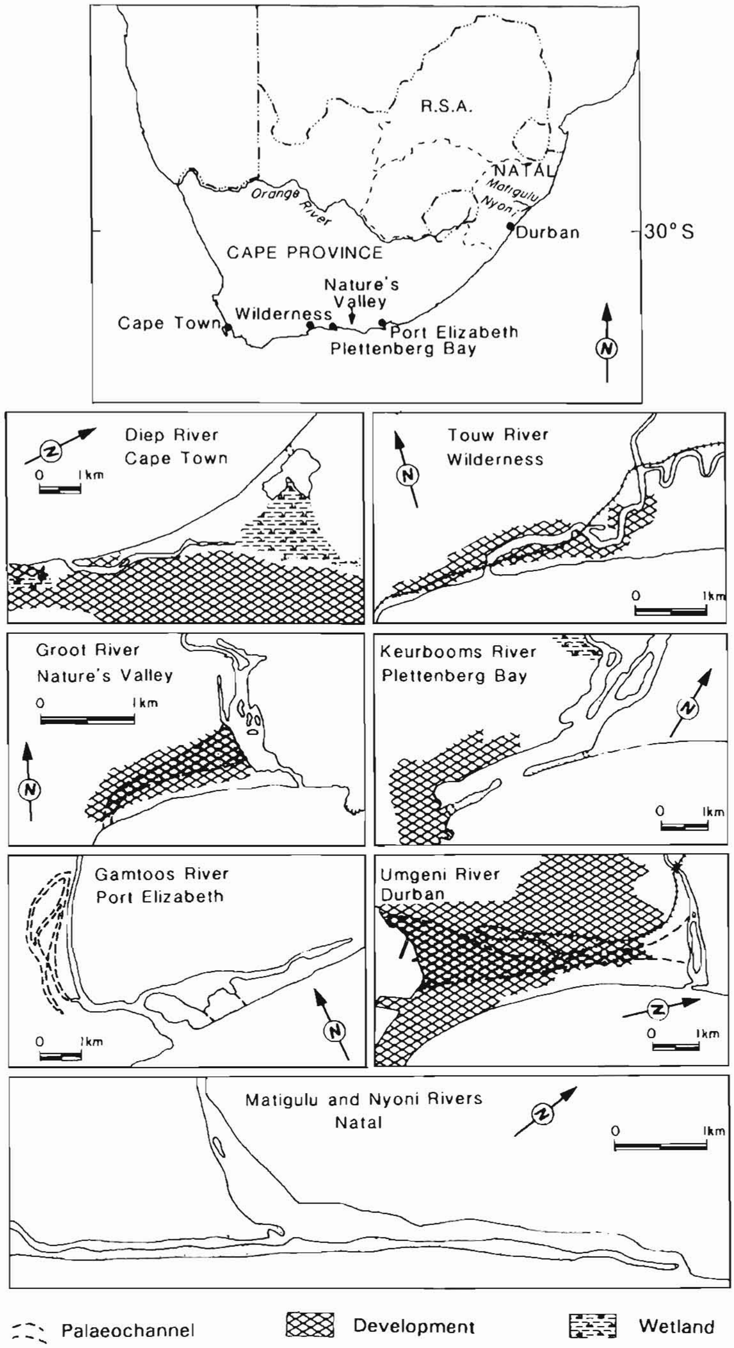

Figure 2. Location of selected drift aligned deltas around South Africa. The Nyoni and Matigulu estuaries are shown in a shortened position, prior to the 1987 floods which opened a new mouth on the axis of the Matigulu river.

local fishing boats at Laaiplek (DAY, 1981). The mouth is now in its shortest position.

DAY's (1981) summary of current knowledge of river mouths and estuaries in South Africa provides numerous examples of floods shortening channels and carrying away spits. Recent examples include the 1988 Orange river flood—although the spit was breached artificially for safety reasons (SWART *et al.*, 1990)—and the Natal floods of September 1987 which substantially altered the estuarine morphology of many rivers (PERRY, 1989).

The major coastal cities in South Africa are all associated with port facilities and international trade and are surrounded by significant industrialisation and transport infrastructure. Where the coastal plain is narrow, much of this infrastructure has been placed close to the shore or on flood plains within estuaries. For example, the Natal south coast railway, which provides the sugar industry with much of its haulage requirements, runs for some 120 km along the coast, often within metres of the high water mark.

Extensive coastal development has been carried out in recent years along the South African coast, especially in the attractive and sheltered lagoon environments provided by the drift aligned deltas. Coastal population densities are now comparable with those of western Europe and exceed those of much of the U.S.A. (HOLLIGAN, 1991). Given the ubiquity of the lagoons, development has in many cases required their stabilisation at considerable cost. For example, the majority of river crossings of the Natal south coast railway takes place along the axes of stabilised river mouth spits. Recent population migration to the coast, particularly the major conurbations, has once again focussed attention on the problems raised by town planning in the dynamic coastal environment.

There is an illusion of relative stability in these recently developed coastal regions where records and memories of coastal changes are often all too short. Development has taken place on lightly vegetated spits, on low flood plains, historically abandoned palaeochannels and even mobile spits. For example, plots of land are being sold on the actively shortening western spit of the Keurbooms river mouth, the City of Durban is built on the Umgeni river delta, Nature's Valley on the Groot, Wilderness on the Touw (Figure 2). The fact that these relatively stable sites are not safe was brought home by the 1987 river floods in Natal with their substantial insurance and damage costs. Natal was classified as a National Disaster Area. Fourteen major bridges were destroyed, 21 put out of commission, 382 roads closed and 327 lives lost. Damage to rail links, Water Board facilities and industry infrastructure were estimated at \$4.5 M, \$4 M and \$16.5 M respectively. Insurance claims ran to in excess of \$135 M and the total cost to government was estimated at \$200 M (TRIEGAARDT *et al.*, 1988).

Coastal developments can change the local downstream variability in flow and sediment supply and as a result, erosion patterns can evolve which may lead to enhanced vulnerability to storms and floods. Included in such developments are the stabilisation of river mouths, building on and vegetation of dunes, and building harbours. Sea level rise will change the expected frequency of occurrence of extreme events and increase the vulnerability of many of these developed areas to natural disasters.

Higher Mean Sea Level (MSL) will result in greater inundation of wetlands, producing larger lagoons. As a result, the increased tidal prism and associated increase in tidal currents in the mouth area, and/or the increased erosion and washover of the barrier spits will encourage mouth migration. In addition, higher coastal water levels exacerbated by sea storms and river floods may cause estuarine water levels to rise until channels break their banks and flow reverts to abandoned channels. Changes in local climatology due to Greenhouse Warming may also increase run-off and river sediment loads during floods. Estuary mouth morphology and mouth migration may be affected, although this impact is less readily quantifiable with current climate modelling capabilities. The effect of sea level rise on drift-aligned deltas, common to the South African coastline, will therefore be to accelerate the rate of mouth migration and facilitate mouth switching, increasing the risk to any development in these environments.

Two examples of such increased vulnerability of drift-aligned deltas to sea level rise are presented. The locations are considered representative of development in sensitive coastal environments around South Africa. The first case study considers the Diep river and Rietvlei system at Milnerton, 5 km north of Cape Town. Here, a combination of an increase in the tidal prism of the river mouth together with long-term and storm erosion on the outer margin of the barrier spit will be sufficient to shorten the channel length. In

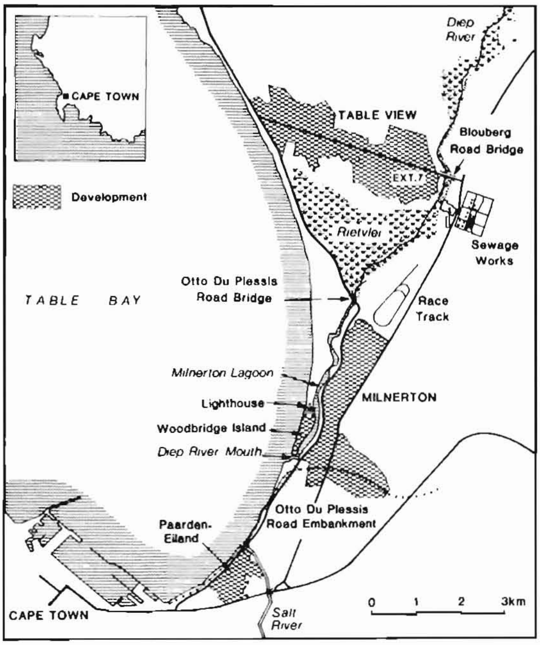

Figure 3. Location of Diep river/Rietvlei system, approximately 5 km north of Cape Town (after HUGHES *et al.*, 1992).

doing so, residential development on the barrier will be seriously affected and development and infrastructure on the sheltered banks of the lagoon will be exposed to direct wave attack. The second case study considers the Umgeni river at Durban where a rise in sea level will exacerbate flood levels in the river to such an extent that it may revert to its older, longer course. The entire Durban central business district is located in this palaeochannel and would be at risk as the river attempts to flow through the city centre to the harbour.

Demonstrating the increased vulnerability of these types of environments in the light of future global warming and sea level rise underlines the fundamental importance of town planning in reducing the potential impacts of climatic change.

DIEP RIVER/RIETVLEI SYSTEM

The study area is the coast and low lying area immediately adjacent to the mouth of the Diep river approximately 5 km north of Cape Town (Figure 3). The main features are a tidal inlet (Milnerton Lagoon) and wetland system (Rietvlei) which open onto an essentially unconsolidated coastline. The eastern and northern periphery of the system is an increasingly developed residential extension of the municipality of Milnerton. The mouth of the river is generally closed in the summer by the development of a low berm which is overtopped by high spring tides. A portion of the spit on the seaward side of the river near its mouth, known as Woodbridge Island, is a residential area with development within 2 m elevation of the current Mean High Water Springs (MHWS). To the north of Woodbridge Island, the primary dunes are moderately well vegetated with some blow-out features and are backed by a golf course at a lower elevation. The toe of these dunes and the hummocky dunes fronting Woodbridge Island are scarped—indicating erosion during winter storms. Occasionally the sea washes over onto the golf course through a low gap in the dunes approximately 100 m north of the lighthouse. This is the narrowest part of the barrier and the dune is usually repaired and the washed-over sand removed from the golf course.

The nearshore sediment is fine beach sand with occasional shelly patches and gravel lags and is in the region of 10 m–20 m thick (CSIR, 1972) increasing to more than 25 m within 1 km landward of the shore. Surface and deep water currents in Table Bay are dominated by the local wind direction and the only significant sediment transporting currents occur in the surf and nearshore zone as a result of combined wind and wave action (CSIR, 1972). Winds tend to be northwesterly in winter and southeasterly in summer. Net transport at Woodbridge Island is northwards, to which CSIR (1972) has put a value of approximately 100,000 m^3/year. This value may be an over-estimate but the south side of the river mouth is sediment starved and is actively being eroded, *i.e.*, large dune scarps, the use of dolos for protection and the recent uncovering and discovery of a number of 17th century wrecks buried just offshore. CARTER (1988) describes a scenario for updrift spit migration whereby bypassing is accelerated. During the summer months, the reduced river flow and strong southeasterly winds are probably sufficient to increase the rate of bypassing, causing an updrift migration of the spit.

Historically the Diep River has shown a high degree of mobility, with an early map from 1786 showing its mouth some 3 km to the south of its present position. This shoreline has been in a state of accretion between at least 1780 and 1900, but since 1900, the situation has reversed and approximately 80 m of erosion on Woodbridge Island has taken place (CSIR, 1983). This reversal has been attributed to wave reflections from large scale extensions to Cape Town Harbour, and a further 10 m of long term erosion is expected to take place at Woodbridge Island until the bay reaches its equilibrium log-spiral shape (CSIR, 1983). In short this section of coastline is soft and erodible, has historically shown a high degree of mobility, is currently being eroded and is exposed to westerly and northwesterly storms.

Preliminary investigations into the impacts of sea level rise on the Diep river/Rietvlei system have been carried out (HUGHES *et al.*, 1993) and the procedures followed and results obtained may be summarised. Long-term rates of erosion resulting from sea level rise were modelled by application of the Bruun Rule (BRUUN, 1962) to the sections shown in Figure 4. Longshore gradients in sediment transport rates are uncertain and the Bruun Rule was applied in its simplest form for a rise in sea level of 1 m. Inundation was modelled simply by adding the magnitude of sea level rise to the existing Mean High Water Springs (0.86 m) or Mean Sea Level (0.15 m). All land adjacent to the coast below the new elevations was assumed to be inundated. Short term storm erosion was modelled by application of the Swart Technique (SWART, 1974) to the long-term eroded profile. Derivations of storm erosion, surge and wave setup compare favourably with those observed during a major storm at the site (JURY *et al.*, 1986; HUGHES *et al.*, 1993).

After a 1 m rise in sea level the shoreline will recede between 60 m and 90 m on Woodbridge Island (Figure 4). To the north of the island, the transgression will be between 50 m and 80 m and, to the south, the shoreline will recede approximately 135 m putting the embankment of the Otto du Plessis Road and the railway within easy reach of storm wave action.

If no shore protection work is carried out, the sea will erode and wash-over the dune barrier breaking through to the river on the bend north of the lighthouse near Profile 5 (Figure 4). This second mouth will erode to a channel width of 185 m and will become the main conduit for the Rietvlei inlet. This shortened channel will reduce the resistance to water movement into and out of the inlet and hence its level of protection. As a result, the inlet will have a tidal range of about 1.3 m or 90% of the open water value. MHWS and MSL inside the lagoon are shown in Figure

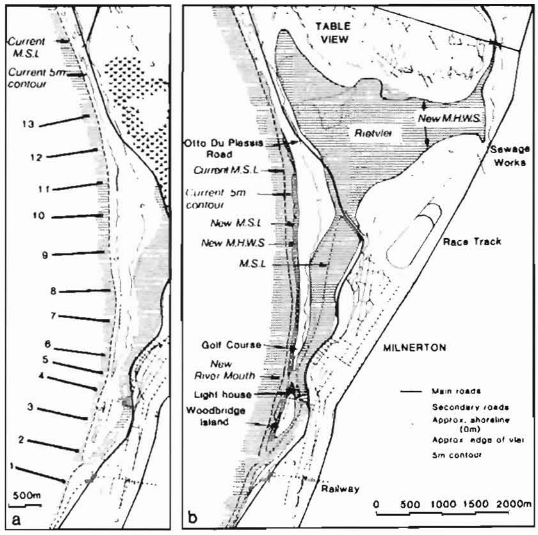

Figure 4. (a) Location of the profiles to which the Bruun Rule was applied. (b) The position of the new shoreline and new MHWS in Rietvlei after a 1 m rise in sea level (after HUGHES *et al.*, 1992).

4. The west side of Milnerton will become exposed to direct wave action through the new mouth and may experience some erosion. If shore protection work is carried out and the breakthrough prevented, the long channel will reduce the tidal range within the inlet to approximately 0.95 m or 66% of the open water value. Note that the restrictive effects of bridges along the channel have not been considered.

In the event of a 1 in 50 year sea storm, the Swart technique predicts Woodbridge Island would be eroded approximately another 25 m and the area to the south of the present river mouth could be eroded between 25 m and 30 m. This would allow direct wave action onto the Otto du Plessis Road embankment and railway. The coastline north of the Island could be eroded between 20 m and 25 m and the Island would be totally swamped by the storm surge. The Milnerton coastline up to 3 m elevation may also be flooded by the storm surge. This will cover between approximately 200 m and 500 m of Milnerton adjacent to the new and old mouths respectively and includes the railway, the main Otto du Plessis road and several residential blocks. The new river mouth will temporarily widen to around 500 m further exposing the Milnerton coast to direct wave action, erosion and flooding. Should

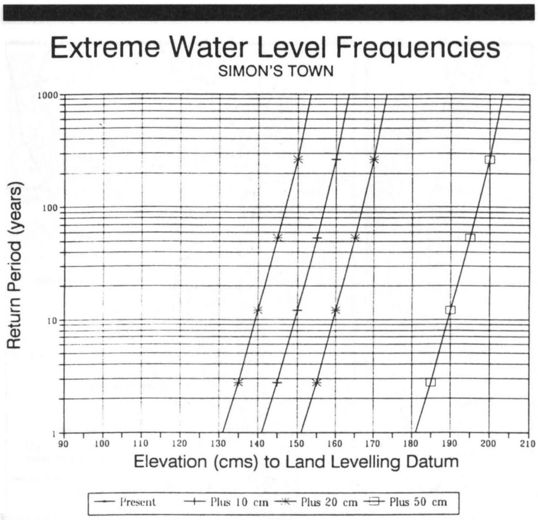

Figure 5. Extreme water level frequencies for Simon's Town, near Cape Town, sea level increments of 10 cm, 20 cm and 50 cm are shown (after SEARSON, 1993). The water level currently expected during 1 in 300 year event can be attained by an annual event after a rise of 20 cm.

an extreme sea storm and river flood be coincident, then flooding and associated damage would be exaggerated in proportion to storm's duration.

The extreme water level return periods are shown in a Port Diagram for Simon's Bay near Cape Town Harbour (Figure 5) (SEARSON, 1993). Simon's Bay is used here in preference to Cape Town Harbour because of its superior data quality. The increase in storm damage potential with sea level rise is clear. A rise of only 20 cm will be sufficient to change the water level expected by the occurrence of a 1-in-300-year event at present to that of an annual occurrence. Note that these curves do not include any wave set up component and are therefore an under-estimate of the coastal water level. Surges will clearly affect the coastline at an early stage in sea level rise, enhancing erosion and washover. They are generally of sufficient duration to penetrate inlets and consequently storm damage will become more apparent on both the open coastline and in areas previously considered sheltered.

Having identified the most serious impacts in a worst case scenario, the required rise in sea level before any serious damage potential exists can be determined. The effect of a 50 cm rise in sea level combined with 10 m of long term erosion in the location of Profile 5 would leave a gap of approximately 30 m in plan and 1.5 m in elevation between MHWS and the crest of the dune. This 50 cm is probably the maximum rise possible before a storm would break through the narrowest section of the barrier. The first breaching may not necessarily complete the opening of the second channel but would certainly lay the west side of Milnerton open to more direct wave action and facilitate subsequent breachings. At MHWS approximately 70% of the inlet would be flooded.

DURBAN

The City of Durban is centred on the delta of the Umgeni river. At present the lower reaches of the river and estuary are canalized to form a straight channel to the sea some 7 km north of Durban harbour. However, the central business district (CBD) of the City is located on a late Holocene palaeochannel and floodplain of the Umgeni (Figure 6). This palaeochannel flowed into what is now the Durban harbour, and the barrier spit separating this channel from the sea is now the site of Durban's "Golden Mile" of tourist accommodation and attractions. The Durban beachfront is essentially an unconsolidated sandy shoreline, backed in most places by significant development and infrastructure immediately landward of the beach on the barrier spit.

The timing of the switch from the long channel to the present mouth position is uncertain, but journals from shipwrecked sailors show that in about 1700, the river flowed to its harbour position (RUSSELL, 1899). Between that time and the 1840's, the switch must have taken place as a flood in 1848 broke the banks of the river and flowed through the town into Durban Bay—the area now occupied by the harbour (RUSSELL, 1899). The "Great Flood of 1856" repeated this disaster but with greater loss of life and damage to property (BARNES, 1984). Flood waters on cultivated lands, presumably the flood plains of the palaeochannel, stood 5.5 m deep; crops and a new sugar mill were destroyed to the value of £3,000. Even a new schooner, being built on-shore for the mayor, was carried off its stocks and washed away. Subsequent to the flood, two factors were recognized; first, that the townsfolk of Durban were lucky to have had the flood during neap tides, and not spring tides; and secondly, that the building of houses on the river banks and low lying areas should be discouraged (BARNES, 1984).

RUSSELL (1899) describes much of the back barrier area as swampy with ponds (although the river mouth was then in its current position) and

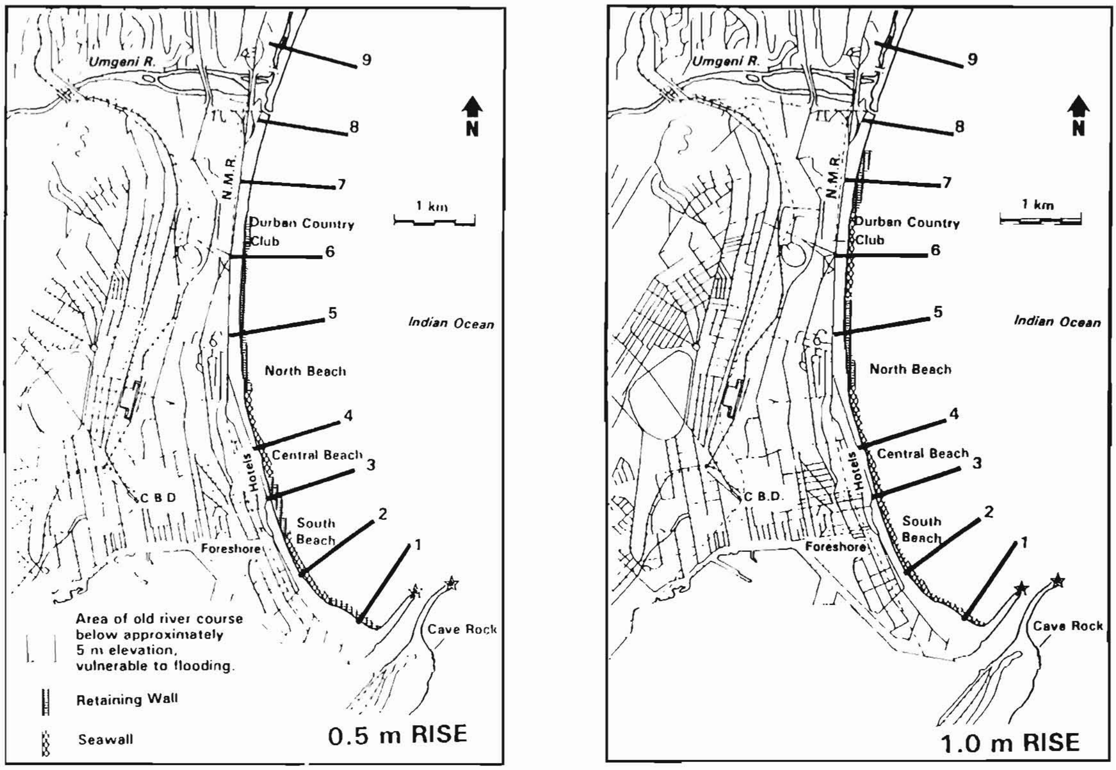

Figure 6. Durban beachfront study area, the location of the 9 profiles to which the Bruun Rule was applied and the area of old river course below approximately 5 m elevation, most of which would be affected by a mouth switch. The shore protection requirements are shown for sea level rise scenarios of 0.5 m and 1.0 m respectively (after HUGHES and BRUNDRIT, 1990).

documents the first attempts in 1856 at vegetating the southernmost end of the spit in an attempt to stabilize it and prevent washover. A member of the Admiralty, James Abernethy, wrote of the Umgeni in 1859: "it appears to have overflowed occasionally, and to have sent its waters into the harbour. I think it very possible that in ancient times the course of the Umgeni to the sea was through the harbour" (BARNES, 1984). Three years later it was noted that after the scouring flood of 1856, the river mouth was silting up, posing risk of inundation to Durban at times of severe rain. At this time, a plan was put forward by Captain Vetch to construct a canal along the course of the previous flood to serve as a safety measure for the City should the Umgeni break its banks again.

Despite this early recognition of the problem of migration or alternation of mouth position, the canal was not dug and development continued across the back barrier area and the barrier itself. BEGG (1984) reports that the flood risk was greatly reduced by the canalization of the mouth and estuary in its present position in 1982. However, a major flood in 1987 produced a water level in the estuary near the mouth of approximately 2.6 m relative to land levelling datum. The canal banks were sandbagged to prevent the banks bursting; and if the water level had risen to the critical level estimated to be 3.5 m elevation, little could have been done to prevent the flood waters from flowing along the old channel, through the CBD and into the harbour (HUGHES and BRUNDRIT, 1990). At this stage in Durban's development, such a flood would have been devastating.

The rising and falling limbs of the flood hydrograph were relatively prolonged, increasing the damage potential of the flow (PERRY, 1989) which lasted over several tidal cycles. It was fortunate that the flood tides were within a few days of their mean neap values (at present Mean High Water Neaps (MHWN) are at 0.45 m above land levelling datum) and there was no appreciable storm surge. Thus, the tidal influence, which usually extends for a distance of 2.5 km upstream, played a minor role in accentuating the flood. Had the flood occurred during spring tide or high surge and low atmospheric pressure conditions, the critical level of 3.5 m might have been reached. Indeed the highest predicted tides of the year, 87 cm higher than MHWN, occurred just three weeks earlier.

On the shorefront, landward displacement has been slowed by retaining walls and sea walls along much of the southernmost distal part of the spit. The dominant swell direction is from the south and northwards longshore transport of sediment necessitates significant beach nourishment. Annual rates of sediment loss for the Durban seafront have been estimated to vary between 0 and 300,000 m^3/year (CSIR, 1989). This extreme variability underscores the inherent instability of such barrier spits. The Umgeni river's average contribution to the sediment budget is unknown, and although the net transport direction is northwards, under extreme conditions some fluvial sediment is deposited to the south. The presence of an underwater mound located in an area east of the harbour mouth, caused by years of dumping of dredged material, tends to focus wave energy around the Central and North Beach areas, leading to sharp variations in longshore transport potential. Small changes in the incident wave conditions can alter the wave energy foci and cause significant variations in rates of sediment transport (CSIR, 1989). The use of average rates of sediment transported in sediment budget calculations must therefore be treated cautiously.

Preliminary investigations into the impacts of sea level rise on Durban have been made (Hughes and Brundrit, 1990) and the vulnerability of the drift-aligned delta, with its estuary mouth in the "short channel" position, can be highlighted by concentrating on the impacts of increased coastal erosion and reduced protection from extreme storm and flood events.

Increased coastal erosion was modelled by application of the Bruun Rule (1961) to the 9 profiles shown in Figure 6. Extreme water levels were modelled simply by adding sea level rise to the MHWS (at present 1.06 m above land levelling datum) combined with storm surge, wave set-up and river flood components. Surge and set-up components for a 1 in 10 year storm were taken to be approximately 1.4 m (Hughes and Brundrit, 1990) whilst the component from a major flood such as that of 1987 is taken conservatively to be 2.15 m above river level.

Under a 0.5 m sea level rise scenario almost the entire length of coastline from the harbour mouth to the Country Club Beach would be seriously affected by increased coastal erosion (Figure 6). To the north of the Country Club the impacts will be less severe as the beach is wider and the foreshore less developed. In most cases, the beach profile will be lowered landward of the development and at locations 2 and 4 (Figure 6) the beach will disappear completely at mean high water springs. Sea walls in these areas would need to be up to 6 m high and during major storms (return periods of approximately 1 in 10 years) would be seriously overtopped by wave action. Retaining walls along other sections of the shore would need to be up to 3.5 m high and may be subject to some wave attack during extreme storms.

Within the estuary, a 1 in 10 year storm during MHWS could raise the estuarine water level to approximately 3 m elevation, just less than the critical 3.5 m level. The occurrence of a 1987 size river flood could raise the water level to approximately 3.7 m. Estuary water levels higher than the critical 3.5 m level would break the banks and flow along the golf course, NMR and major roads and railway, through the CBD and into the harbour. The coincidence of a 1987 size river flood and a 1 in 10 year sea storm at MHWS could raise the water level to 5.1 m elevation, far in excess of this fateful limit. Combinations of smaller and more frequently occurring storms and floods will clearly be capable of exceeding this limit. Under a 1.0 m sea level rise scenario, the entire coastline will be seriously affected by erosion and some 7 km of protection or retaining wall would be required, due to lowering of the beach profile. Sea defences will be required to protect existing development between locations 1 and 4 (Figure 6) and around location 6, where the beach will effectively disappear completely and MHWS will be adjacent to the wall.

Without increasing the height of the sea walls to provide additional protection from storms, these walls will have to be up to 9 m high and, even so, severe overtopping will occur. In the region of Profile 4, the shoreline water level during a major (1 in 10 year) storm will be 0.4 m above the ground level of existing development. In the absence of development and coastal protection, the barrier would most likely have been overwashed at this location.

Within the estuary, the problems for potential "mouth switching" are more serious. After a 1.0 m rise in the sea level, MHWS will be at 2.06 m elevation. Only a 1.5 m increase in estuary water level would be sufficient to overflow the bank protection and flood the city centre. The occurrence of a *mean* high spring tide with *either* a river flood smaller than that of 1987 *or* a major (1 in 10 year) sea storm with tidal background level flow would be sufficient to raise the water level to the critical 3.5 m elevation. Although the extreme water level probabilities for the estuary have not yet been accurately assessed, there is a strong likelihood that the critical bank bursting water level would be reached by combination of river floods and sea storms long before their individual occurrences.

Durban's shore protection requirements for the two sea level rise scenarios are shown in Figure 6, together with the area of the old river course below approximately 5 m elevation. Clearly, the consequence of estuary "mouth-switching" and long-term erosion will have disastrous effects on the City of Durban, both in terms of flood damage potential and changes to the beachfront, which in turn will impact on the local tourist industry.

CONCLUSION

Drift aligned deltas are characteristic of shoreline with high rates of longshore sediment transport and reduced river flow. These types of deltas produce longshore parallel spits, backed by long shallow lagoons and wetlands, and are commonly found along the South Africa coast. These are usually dynamic sedimentary environments in which the process of spit barrier growth is often punctuated by river flood or sea storm events which cause the mouth of the estuary to shift location.

The back barrier lagoons and wetlands formed by these deltas provide shelter from coastal winds and waves and their biodiversity and aesthetic appeal make them attractive locations for development. Around the South African coastline, there are numerous examples of locations where development has taken place in these inherently unstable environments. Worldwide there are many more, *e.g.*, St. Louis and La Petite Côte, Senegal and Abidjan, Ivory Coast (BIRD and SCHWARTZ, 1985). Because of the relatively short history of human settlement in South Africa, these locations appear to have some "relative stability" and development in them is flourishing. Major floods in Natal in recent years have served as a reminder of their instability and focussed attention on town planning in dynamic coastal settings.

Sea level rise will enhance the dynamic nature of these environments by increasing the frequency of spit barrier washovers, the potential for estuary mouths to switch location and rate of mouth migration. The two examples cited highlight the vulnerability of existing development in these environments and underlines the need for effective coastal planning.

The first on the Diep river delta, north of Cape Town, demonstrates how increased long-term coastal erosion can form a new estuary mouth with a shorter channel. This new channel will be cut in a partially developed spit barrier. The increased coastal erosion will seriously affect development on the spit and the new mouth will expose previously sheltered development on the landward bank of the back barrier lagoon to direct wave action. Much of this area will be vulnerable to future storm damage and flooding. An increase in storm damage potential with sea level rise is evident. Development pressure is increasing rapidly in the study area and far-sighted planning in this and other similar locations is essential to reduce the potential impacts of sea level rise.

The second example, the Umgeni river delta at Durban, demonstrates how a rise in sea level can induce the opposite response and lengthen the channel. A chance combination of river floods and sea storms can, at present, raise the water level in the estuary sufficiently to cause it to break its banks and flow down its longer, older channel, through Durban's central business district. Sea level rise will drastically increase this risk, making it feasible for smaller and therefore more frequently occurring storms and floods, or their combinations, to do such damage. Even if this longer channel were only temporarily functional, the effect would be devastating. Increased coastal erosion on the sea-side of the highly developed barrier will reduce the area of beach available for recreational purposes unless current nourishment efforts are intensified. Tourism is an important local industry and the character of the beachfront may change to such an extent that its touristic value may be substantially reduced.

The two case studies are not the only examples of extensive development in drift-aligned estuaries along the South African coast. These attractive locations have increasingly been developed and often form potential growth points for future development. Coastal management in South

Africa is a relatively new practice and development has, in places, gone ahead with little cognizance of coastal processes. Consequently, there are probably many more examples of development in vulnerable sites that have yet to be documented. The identification of these locations and mapping of their geomorphological features is essential. River mouth changes and the potential impacts of sea level rise within these locations and environments yet to be developed must be considered as a town planning imperative, both locally and internationally. Until such studies have been completed any further development or stabilisation of these environments should be carried out with extreme caution. Sea level rise hazard tests should form an integral part of town planning procedure in all drift-aligned deltas.

ACKNOWLEDGEMENTS

We gratefully acknowledge the Department of Environment Affairs and the Foundation for Research Development for providing financial support for this study.

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