

**TOWARDS THE MANAGEMENT OF MARINE SEDIMENTATION
IN SOUTH AFRICAN ESTUARIES WITH SPECIAL
REFERENCE TO THE EASTERN CAPE**

EH Schumann

WRC Report No. 1109/1/03



Water Research Commission



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Report prepared for the Water Research Commission

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EXECUTIVE SUMMARY

Introduction

Areas adjacent to estuaries represent some of the most desirable land estate available. This has led to the establishment of growing communities in estuarine environs, and the associated developments have inevitably impacted on their natural functioning. In particular, constructions such as bridges, jetties, groynes, hardening of channel walls and canalization have modified flow and restricted natural channel movement. Construction of dams in the catchments of parent rivers has reduced freshwater inflow to estuaries, while agriculture and forestry activities have also altered such flow characteristics.

The popular perception of an estuary is of open channels, freely-flowing water and a healthy ecology, with access to the sea through an open mouth. Even though this is seldom the case, when changes in sedimentation patterns cause the establishment of unwanted sandbanks which affect accustomed uses of an estuary, then it can be expected that demands will be made to rectify the situation. However, reasons for the changes are often not apparent, and the most effective methods to manage such sediment movements are consequently also not necessarily self-evident.

With the reduction in fresh water flow, the mouths of many small estuaries have become closed for longer and longer periods, some even permanently. This has resulted in ongoing demands to breach the offending barriers, particularly if houses are in danger of flooding.

Many estuaries in South Africa experience these types of sedimentation problems, in particular in the Eastern Cape. This has led to a requirement for an analysis of the causes of such sedimentation, coupled with a consistent approach to manage the problems.

This report investigates one particular aspect of estuarine sedimentation, namely that associated with the ingress of marine sediment. Such sediment is assumed to be non-cohesive, with sand grain sizes in the range from about 0.1 mm to 2 mm; it specifically excludes silts, clays and coarser gravels.

Objectives and Programme Accomplishments

The initial stage of the programme requires the compilation of available and relevant information, and applicable legislation, to enable practical management steps to be formulated. In order to do this, the following stages were proposed:

- Analysis of known sedimentation characteristics of South African estuaries, and a review and evaluation of the extent of the associated problems*
- Review and evaluation of methods available for managing marine sediment accumulation in estuaries, including legal requirements*
- A synthesis of the management of marine sediment in South African estuaries, with special reference to Eastern Cape estuaries.*

These three objectives represent desk-top studies, and a team of experts was appointed to analyse and

report on these aspects. However, it was recognised that the extent of the sedimentation problems could not be established without in situ investigations.

A further objective was to

- Produce a research programme description for marine sediment management in Eastern Cape estuaries.

In support of this objective, specific estuaries in the Eastern Cape were to be identified for in loco feasibility studies, and appropriate survey and monitoring procedures initiated for these selected estuaries. Thus while the report would be prepared by the appointed experts, their expertise and experience would be transferred to groups directly involved with the management of estuaries.

It proved impractical to initiate the survey and monitoring procedures. In particular, no specific follow-up programme was set in place to continue the work, and it was not considered feasible start measurements and not continue. Nonetheless, over a longer period the work, and the capacity-building component, will continue in other WRC-sponsored programmes.

Contents

A primary objective of this report is to provide an explanation why marine sediment enters an estuary. As such, the geological setting of South African estuaries forms the basis of their characteristics, though there are substantial differences in type and size around the coast.

To understand the geological estuary type, it is necessary to analyse their structure in relation to past sea level changes, and the associated erosion and deposition cycles. Most estuaries occupy drowned river valleys, and establishment of the erosion base determines the maturity of the estuary and the manner in which sediment is scoured during floods. Similarly, the nature of the river and estuary valley will determine the length and width of the estuary, its tidal prism and the flow characteristics of river floods. Such floods need to be analysed in conjunction with local weather and climate patterns.

The influx of marine sediments into estuaries depends on their mouth characteristics, the availability of sediment, the extent of the tidal prism, and the wave climate and nature of the associated longshore sediment drift. In South Africa most estuaries are flood-dominant, which means that, on average, the stronger flood tides are able to move in more sediment than is taken out on the slower ebb tides. The accumulation of marine sediment in estuary inlets often constricts the mouth, limiting further tidal exchanges, and sometimes closing the mouth completely.

In the past, this excess sediment was scoured out of the estuaries by regular floods. However, because dams have been built in river catchments the frequency and discharge of these floods has been reduced or even eliminated entirely. Consequently it is only the very large floods that are effective in scouring out sediment, and in these situations sandbanks and developmental structures also serve to dam up such flows, often leading to extensive damage.

At the start an assessment needs to be made if sedimentation in an estuary is a real problem. For this

assessment full community participation is required, and agreement must be reached on a vision for the estuary. Goals and objectives must be set, and should form part of an overall Integrated Development Plan as specified in the Local Government Transition Act.

An integral part of this management plan is to create monitoring structures to understand the processes and changes occurring in the estuary. This should include gathering past information such as photographs or notes of mouth closures and breachings, and then keeping careful records of any subsequent changes; all relevant available geological, climate and oceanographic information should be sought. If possible, measurement systems should be set up, such as water level recordings, bathymetric cross-sections, water flow, photographs etc. It is very important that judicious monitoring should be started as soon as possible in all estuaries where sedimentation problems exist, or may develop in the future.

Once a reasonable understanding of the sedimentary functioning of the estuary is achieved, steps can be considered to remedy problems that may arise. If this involves the breaching of the mouth, then protocols have been established and must be followed; nonetheless, if feasible, breaching should be allowed to occur naturally. Otherwise there are specified optimum seasons, water levels in the estuary, and tidal conditions at which artificial breaching should take place. The actual position can vary, and expert advice should be sought in this regard, and in the actual techniques used.

In most other cases remedying sedimentation problems will involve removing sediment bodies. The standard method of doing this is by means of a dredger, and several types of dredgers are available. However, dredging costs are high, dredgers generally tend to be unsightly and noisy in operation, and disposal of dredged material can present a problem: here the easiest option is to discharge on beaches and allow the longshore drift to move the sediment away. If the dredging option is chosen, then it makes economic sense for nearby estuary communities to share the costs of a single dredger, and then operate on a rotational basis in the different estuaries.

Other options are available. In particular, agitation dredging raises sediment into the water column and allows ambient currents to remove it. On the other hand, fluidization liquifies the sediment by pumping water into it and then allowing the resulting mixture to flow as a density current to specified lower areas; this is unlikely to be suitable for the generally shallow South African estuaries.

In estuaries with multiple channels, diversion of flood and/or ebb flows into different channels can have the effect of selectively moving sediment, although careful control must be exercised. An untried method, but one with potential under specified conditions, is that of tidal flooding. Here the flood tide is dammed at some point, after which the wall is collapsed and the resulting enhanced ebb flow can scour out unwanted sediment.

However, none of these remedies can be applied before all the legal requirements have been met. At the present time (March-2002) several applicable Acts are being revised, but legislation can be found in the Bill of Rights in the Constitution of the Republic of South Africa, the National Environmental Management Act (NEMA), the Environmental Conservation Act (ECA), the Sea-Shore Act (SSA) and the National Water Act (NWA). Other legislation such as the Minerals Act and some provincial planning ordinances may also be relevant.

At present NEMA establishes principles for the proper management and planning procedures for ecosystems "subject to significant human resource usage and development pressure". The issues of compliance, enforcement and protection make it possible to prosecute any person who causes significant pollution or degradation of the environment.

The ECA aims "to provide for the effective protection and controlled utilization of the environment". Sediment removal activities will generally be subject to the Environmental Impact Assessment (EIA) regulations, which require that specific reports by independent consultants be produced, as well as public participation before the relevant authorities can authorize an application with or without conditions, or reject it.

Additional regulations apply to the permitting of activities in Sensitive Coastal Areas. The SSA declares the State President to be the owner of the "water and the bed of any tidal river and of any tidal lagoon". Consequently a lease must be entered into to permit "the removal of any material"; i.e. dredging or similar activities would fall directly under the provisions of this Act.

The NWA lays the basis for regulating water use, which includes "altering the bed, banks, course or characteristics of a water course". This Act also deals with the estuarine reserve, which is the minimum fresh water flow which has to be maintained to comply with specific, specified needs. The criterion directly relevant to the subject of this report is the requirement that flood levels are not reduced to such an extent that natural scouring of sediments is adversely affected. However, the manner in which these regulations are implemented still needs to be clarified, and a strong recommendation is made that the concerned government and provincial departments cooperate in setting specific guidelines.

Any proponents seeking to alter an estuarine water course through movement of sediment should collaborate fully with the appropriate environmental authorities in obtaining permission for such activities. This will ensure that cognisance is taken of the latest applicable legislation.

Finally, the Appendix gives an example of the effect of a flood in the Nahoon Estuary, and deals with relevant background information and the sedimentation problems in the Kowie Estuary.

CAPACITY BUILDING

Capacity building allows knowledge and experience to be passed on to interested people, groups or organisations who may not have had the opportunity to acquire it in the normal course of their activities. This report, as a compilation of expert knowledge and opinion, should therefore be seen primarily as an attempt to consolidate experience in estuarine sedimentation and management, and to make it available to concerned users.

As such, the report presents an integrated review of marine sedimentation in estuaries in South Africa, and sets out associated management structures to cope with problems that may arise. The contents cover a wide range of topics, and it aims to bridge the gap between researchers, managers and interested lay people. An understanding can be built up of the processes involved in estuarine sedimentation, and the possible technological remedies available to solve the problems are described. Nonetheless, it is also important that any activities comply fully with the latest regulations.

*The groups which should benefit from these results include the WRC, DEAT, provincial authorities, local authorities and NGOs involved with the management of estuaries. This report complements the recently published report on **Managing Estuaries in South Africa: An Introduction** (Breen and McKenzie, 2001), in assisting the transfer of knowledge to regions and groups where it is required.*

As indicated in the Executive Summary, this project was not aimed at any specific estuary in terms of initiating management or monitoring structures, principally because there was no follow-up project in place. However, there are other associated projects which are fulfilling some of these functions, in particular the Eastern Cape Estuaries Management Programme run by the Institute of Natural Resources: this is aimed primarily at enabling management structures, as well as developing monitoring and rehabilitation protocols. Estuarine reserve determinations being carried out on selected estuaries can also be seen as adding to management structures, while the information given here should allow other groups to identify the procedures to tackle estuarine sedimentation problems successfully.

1

INTRODUCTION

1.1 AIMS

South Africa has a total of some 250 listed estuaries spread along a coastline of over 3000 km, as well as a number of minor river outlets (Whitfield, 2000). These fall into markedly different climatic and oceanographic regimes, from subtropical in the east to warm temperate in the south and cool temperate in the west. In addition, the different geomorphological characteristics of the catchments and coastlines mean that there will be correspondingly large variations in estuarine types.

As in most parts of the world, estuaries form some of the most desirable land estate available. People have been attracted by the pristine beauty of estuaries, the rich biotic diversity, and the availability of fresh water. In many cases estuaries have also proved favourable for the location of protective harbours and the siting of commercial and industrial enterprises.

As more people have migrated to these areas of natural beauty, consequent developments have spoilt and detracted from these assets. Developments have also impinged on the natural functioning of the estuaries, ranging from dams in the catchments of the parent rivers limiting freshwater input, to roads, bridges, buildings and other structures restricting natural flow regimes. Exploitation of biological resources has led to destruction of habitats and reduction or even elimination of some species of biota.

Nonetheless, estuaries continue to provide facilities for recreation and commercial enterprises. In particular, they provide a haven from storms at sea for ships and boats, while the sheltered waters afford safe and enjoyable expanses of water for a variety of water sports. Many of these activities are centred around fishing or other exploitation of the natural resources.

South African estuaries are small by world standards (§2.2.2), in part because of the limited fresh water runoff from rivers in a generally semi-arid interior. This has meant that big ships can only use those few estuaries kept open by artificial means, namely Richards Bay, Durban and East London. Boats used in other estuaries are smaller commercial fishing vessels and various recreational craft, and in many places these depend on changing mouth conditions for access to the sea. Within the estuaries themselves fluctuating channel structures and the occurrence of sandbanks has caused problems with navigation. Such variations in channel positions have also on occasion caused jetties to become redundant as the sediment accumulation has caused previously deep channels to shallow. The mouths of many smaller estuaries are closing for longer periods, with the result that artificial breachings of their mouths are now commonplace.

In many cases the movement of sediment in estuaries can be considered natural, in that it would have occurred irrespective of whether or not human developments had taken place. In other cases the sediment movement can be attributed to some man-made changes in the estuary itself, or on a

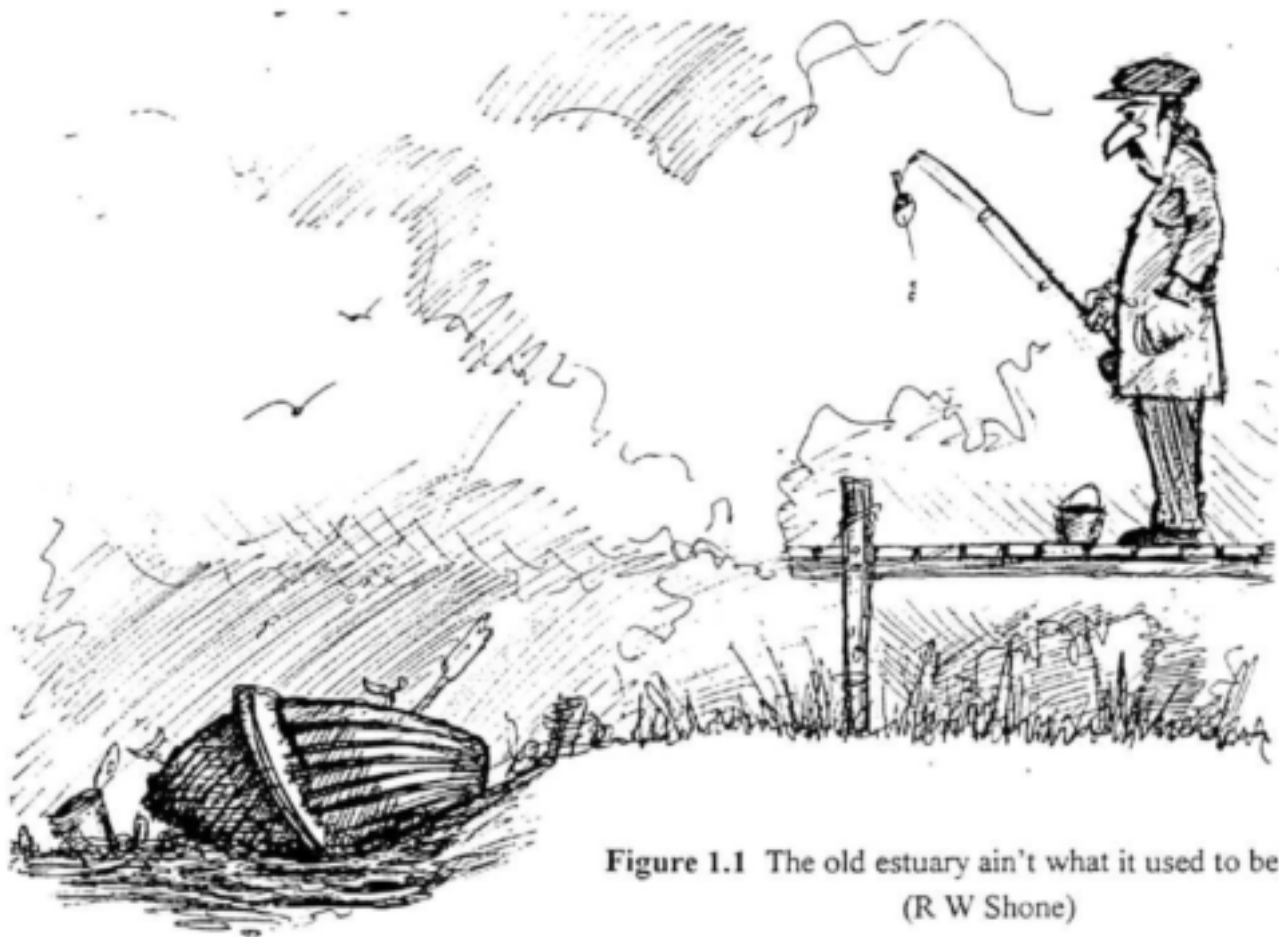


Figure 1.1 The old estuary ain't what it used to be!
(R W Shone)

broader scale such as in the parent river catchment. Whatever the reason, such changes are inconvenient and affect property characteristics and values, since unknown longer-term variability is seldom considered in property transactions.

It has meant that affected parties have attempted to remove such accumulated sediment, with dredging the generally used technique. Such attempts have invariably been expensive, and in situations where the underlying causes are not understood, have often failed or only been partially successful. In some circumstances they have exacerbated the problems, with derelict structures a testimony to these efforts. Concerns also exist about the environmental and economic consequences of dredging, and there are requirements that other techniques be investigated.

It is with this background that the South African Water Research Commission (WRC) commissioned this report to investigate possible solutions to one particular aspect of sedimentation in South African estuaries. It must be recognised at the outset that there are two primary sources of sediment in estuaries: the first is fluvial, i.e. it originates in the parent rivers, whereas the second is marine, i.e. it originates in the sea and progresses into the estuary from that region. A third source, namely intra-estuarine sediment, is mainly organic and typically contributes only a minor component to the overall sediment supply.

Fluvial sediment is associated with freshwater inflow at the head of an estuary, and comprises material eroded in the catchment. This sediment consists primarily of clay, silt and very fine-grained sand, with a component of sand and granular bedload. A small fraction of the mudload accumulates in the upper

reaches of estuaries, with most remaining in suspension and when it reaches the sea is deposited in deep water.

The sediment fraction deposited on beaches and the nearshore region is reworked and abraded by wave action, and resulting finer particles are also carried farther offshore. It is generally only quartz or quartzite grains that survive for any significant period. Biogenically-derived components, composed of broken-up mollusc shells, generally contribute between 25 and 50% of beach sediment; these fragments are continually replenished, keeping the resulting percentages fairly constant.

The sediment on South African beaches resulting from these processes can generally be classified as *sand* (Dyer, 1986), with grain sizes varying from about 0.1 mm (very fine sand) to 2 mm (very coarse sand). In this size range the sand is generally non-cohesive, and is referred to here as *marine sediment* (most grains will not be round, but will have various degrees of angularity). Finer sediment falls into the range of *silt* and *clay*; in the latter category the ionic charges on the particle surfaces are much stronger than gravity, and cause them to stick together. These are cohesive forces resulting in a fundamental difference in the sedimentary behaviour between sand and clay or mud.

Beaches are dynamic, coming under the influence of waves and winds, and marine sediment is moved on and offshore, and alongshore by these agents. Along most coastal areas marine sediments are a ubiquitous component of the seabed and shore, although in rocky areas and along coastal cliffs this may not be obvious.

At low tides sediment on beaches dries out and can be easily moved landward and into adjacent dunes by onshore winds. Such wind reworking can be very energetic, and mechanically-weak grains can be broken up and blown away as dust. Larger waves may erode the dunes again, taking the sediment grains back into sea. Alongshore winds can also deposit sediment directly into estuaries.

This report will consider only non-cohesive marine sediments in the ocean/beach/dune system, and their movement in the lower reaches of estuaries.

In a typical estuary, a range of sediment types will be found, ranging from mud at the head to marine sediments at the mouth. The distribution and character of these sediments is never stagnant, coming as it does under the influence of wind, rain, runoff and ocean processes. An understanding of these dynamic interactions is essential for overall proper management of sediments in estuaries.

Generally South Africa is a semi-arid country with only a section in the east, and limited coastal regions, receiving more than 600mm rainfall on average per annum (Tyson, 1986). In addition, the rainfall is erratic, with marked seasonal variations. Consequently most estuaries occur on the east coast, but there are few rivers which rank on a world scale in terms of volume flow. Put into a world-wide context, the present average flow of the Tugela River varies from about $25 \text{ m}^3\text{s}^{-1}$ in winter to $160 \text{ m}^3\text{s}^{-1}$ in summer (Huizinga and Van Niekerk, 1997), though prior to recent developments it was probably about 25% higher. South Africa's largest river, the Orange River, averages about $370 \text{ m}^3\text{s}^{-1}$, while in the USA the Mississippi River averages $18\,400 \text{ m}^3\text{s}^{-1}$, with the Amazon River an order of magnitude greater. Many South African estuaries have freshwater inflows averaging around $1 \text{ m}^3\text{s}^{-1}$, while others receive no inflow in their dry season.

As a consequence, and because of the different river and sedimentary characteristics of the KwaZulu-Natal coast, most estuarine sedimentation problems have occurred in the Eastern Cape. The emphasis of this report therefore falls into this region.

1.2 STRUCTURE OF THE REPORT

This report provides a background description of the processes involved in the movement and accumulation of marine sediment in South African estuaries, and then provides guidelines for solutions to problems caused by such sediment. The target audience covers a wide variety of expertise and experience, from interested individuals to managers. As such considerable effort has been taken to describe the background processes and procedures involved in the understanding and management of marine estuarine sedimentation; references point to further information on specific issues.

Chapter 2 describes the known physical processes involved in the movement of marine sediment in and out of estuaries. This includes the geology and geomorphology, climate and meteorology, and relevant aspects of ocean waves, tides and coastal morphological processes. On the practical side, chapter 3 gives examples of sedimentation problems, including the impacts of various structures, while recommendations are made for remedial measures such as mouth breaching, as well as monitoring that is required to assess changes in an estuary.

Chapter 4 discusses various techniques to move undesirable marine sediment from estuaries. These techniques include retaining walls, dredgers, and agitation and fluidization of sediment, while the utilisation of natural tidal flows also shows some potential. It is suggested that cooperative solutions in several estuaries may be feasible to reduce capital and operating costs.

Removal of sediment from an estuary using artificial means requires approval in terms of environmental legislation, and an outline of relevant statutes is presented in chapter 5. This should give proponents of sediment removal initiatives a clear understanding of their legal obligations, and adequate provision can then be made during the planning stages of any activity to obtain the necessary permissions.

Chapter 6 integrates the procedures and techniques of the preceding chapters to outline a coherent management strategy for estuaries. However, it is important to understand that each estuary is unique, and that a procedure that is successful in one estuary will not necessarily be the best in another.

It is therefore very important that responsible local authorities and interested NGOs recognise their role in management of estuaries. In many cases towns have become established because of the presence of estuaries, with the result that it is in their own interests to establish proper management structures. These will involve regular monitoring, as well as considered responses to any adverse sedimentary changes that may take place: remedies can then be selected from the range of technical solutions discussed in this report.

Case studies in the Nahoon and Kowie Estuaries illustrate the effectiveness of monitoring an estuary to determine sedimentation patterns and processes (Appendix).

References and a glossary of terms used in the text complete the report.

1.3 AVAILABLE INFORMATION AND DATA

There is a shortage of available good data and general information on the physical characteristics of South African estuaries. In particular, this refers specifically to sedimentary and morphological data over long periods. Thus many estuaries have had short-term topic-specific investigations done on them, most with a biological emphasis, but with little attention given to longer-term changes.

In assessing sedimentation it is these longer-term changes that are important, because they give an indication of the natural functioning of estuaries. The discussions in Chapter 3 identify time scales of 10 years and longer in sedimentation patterns, particularly those associated with floods and storms. To obtain information on these time scales photographs are invaluable, in particular since human memory is in many cases very fallible.

A comprehensive recent publication list on South African estuaries, including sedimentation studies has been compiled by Whitfield (2000), and this should serve as a start for assessing an estuarine situation. Heydorn and Tinley (1980) summarized the known environment of estuaries in the then Cape Province, and this was followed up by more detailed multi-disciplinary investigations by the CSIR of various specific estuaries.

Sediment data exist for a number of estuaries. Work was done during the 1980's under the Research on Sedimentation in Estuaries (ROSIE; Department of Geology, University of Port Elizabeth) and Sedimentation in Estuaries and Lagoons (SEAL, Department of Geology and Applied Geology, University of Natal, Durban) programmes under the auspices of the estuaries programme of SANCOR, while other projects were carried out by the Institute for Coastal Research at the University of Port Elizabeth in the 1980's and early 1990's. Two reports were prepared by the Council for Geoscience in the mid-1990's, and follow-up data exist for some estuaries: these include the Nahoon, Mgeni and Gamtoos estuaries. Data references include Cooper (1986, 1987, 1988, 1989, 1993), Cooper and Mason (1985), Cooper *et al.* (1990, 1999), Esterhuysen (1982), Esterhuysen and Reddering (1985), Reddering (1988a, 1988b, 1994), Reddering and Esterhuysen (1981a, 1981b, 1981c, 1982, 1983a, 1983b, 1984a, 1984b, 1984c, 1986, 1987b), Reddering and Scarr (1990a, 1990b), Reddering *et al.* (1986) and Wright (1995), .

Bathymetric survey data were collected for many important estuaries in the Western Cape and Eastern Cape as part of a monitoring programme undertaken by the CSIR for the DEAT. These data are stored in a database developed by *WAMtechnology* and the CSIR which will in the future be accessible via the Internet. All the data are also included in special data reports (CSIR 2000a and CSIR 2000b). It is very important that all new data collected on South African estuaries is properly archived, so that it becomes available for any future investigations.

A number of additional references are cited in the text, and give specific information relevant to that section; some general books are also referenced. For South African estuaries the book by Allanson and Baird (1999) has sought to describe present levels of understanding; this concentrates on biological aspects, but does give very good overall perspectives. On the other hand, the recent publication by Breen and McKenzie (2001) seeks to promote the wise and sustainable use of estuaries by making relevant information on a wide range of topics accessible to ordinary users and managers. The report

compiled by Boyd *et al.* (2000) resulted from a workshop to ensure that management and research in South Africa are carried out in a nationally co-ordinated fashion; it also gives details of a national plan for managing estuaries and setting guidelines for research initiatives.

All these publications add further to the growing awareness and importance of estuaries. Correspondingly, legislation is also changing, and any group or organisation involved with estuaries is strongly encouraged to obtain the most recent information on regulations that have been promulgated.

1.3.1 Resource Directory

For further assistance and expert advice on sedimentation problems in estuaries, the following organisations can be consulted:

Consortium for Estuarine Research and Management

This is a voluntary grouping of estuarine scientists in the physical, chemical, biological and engineering fields who are involved in basic research in estuaries, and also in management aspects. Of specific importance is the management and implementation of the resource directed measures of the Water Act.

Web Site: <http://www.upe.ac.za/cerm>

KwaZulu/Natal Department of Agriculture and Environmental Affairs

P/Bag X89 3838 Ulundi

Tel 035 874 3291/2; fax 035 874 3293

Western Cape Department of Environmental and Cultural Affairs and Sport

PO Box 659 8000 Cape Town

Tel 021 483 3911; fax 021 483 4372

Northern Cape Department of Agriculture, Land Reform, Environment and Conservation

P/Bag X5018 8300 Kimberley

Tel 053 831 4049; fax 053 832 4328

Eastern Cape Department of Economic Affairs Environment and Tourism

P/Bag X0054 5605 Bisho

Tel. 040 609 3233; fax 040 609 3201

1.4 LOCATION MAPS

In the course of the report, various locations and estuaries in South Africa are mentioned and discussed. Figure 1.2 consists of two maps identifying such locations: the first is of South Africa as a whole, while the second is an enlarged map covering the eastern and southern coasts (specifically the Eastern Cape). It should be noted that many estuaries are not shown, but that no measure of importance or otherwise must be attached to those that are shown.

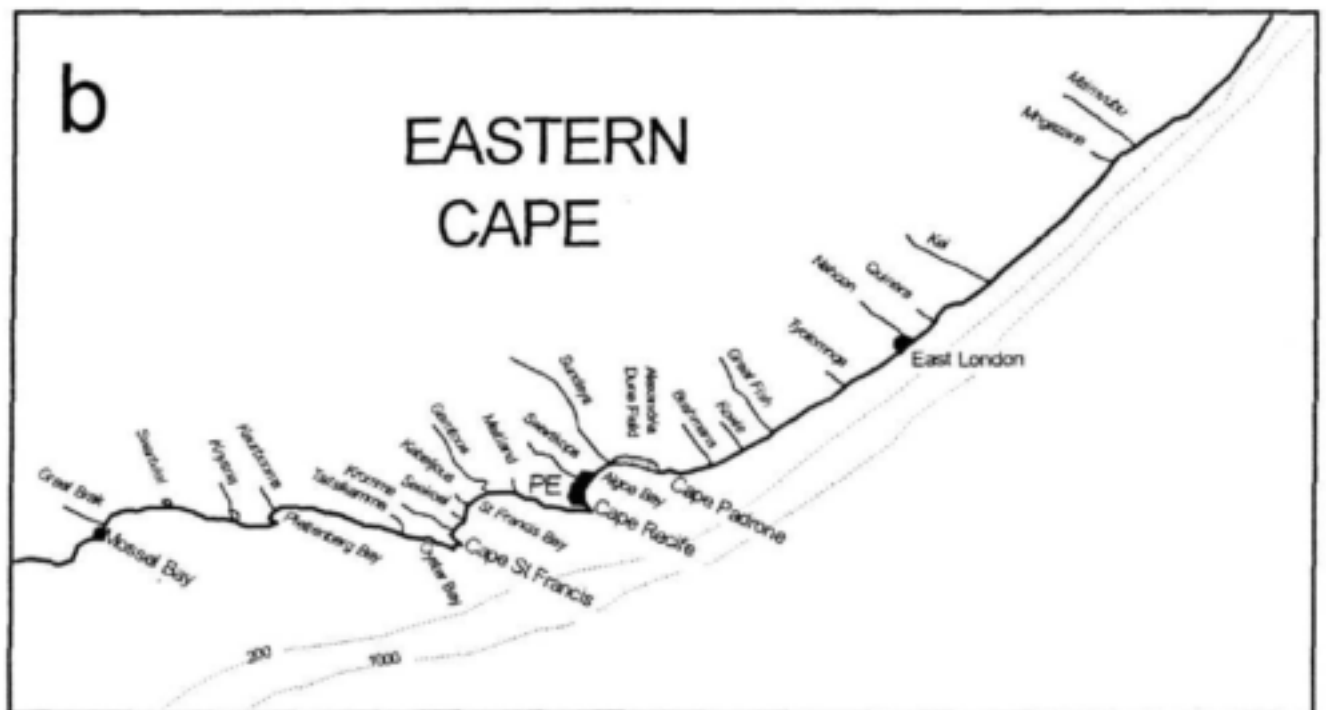
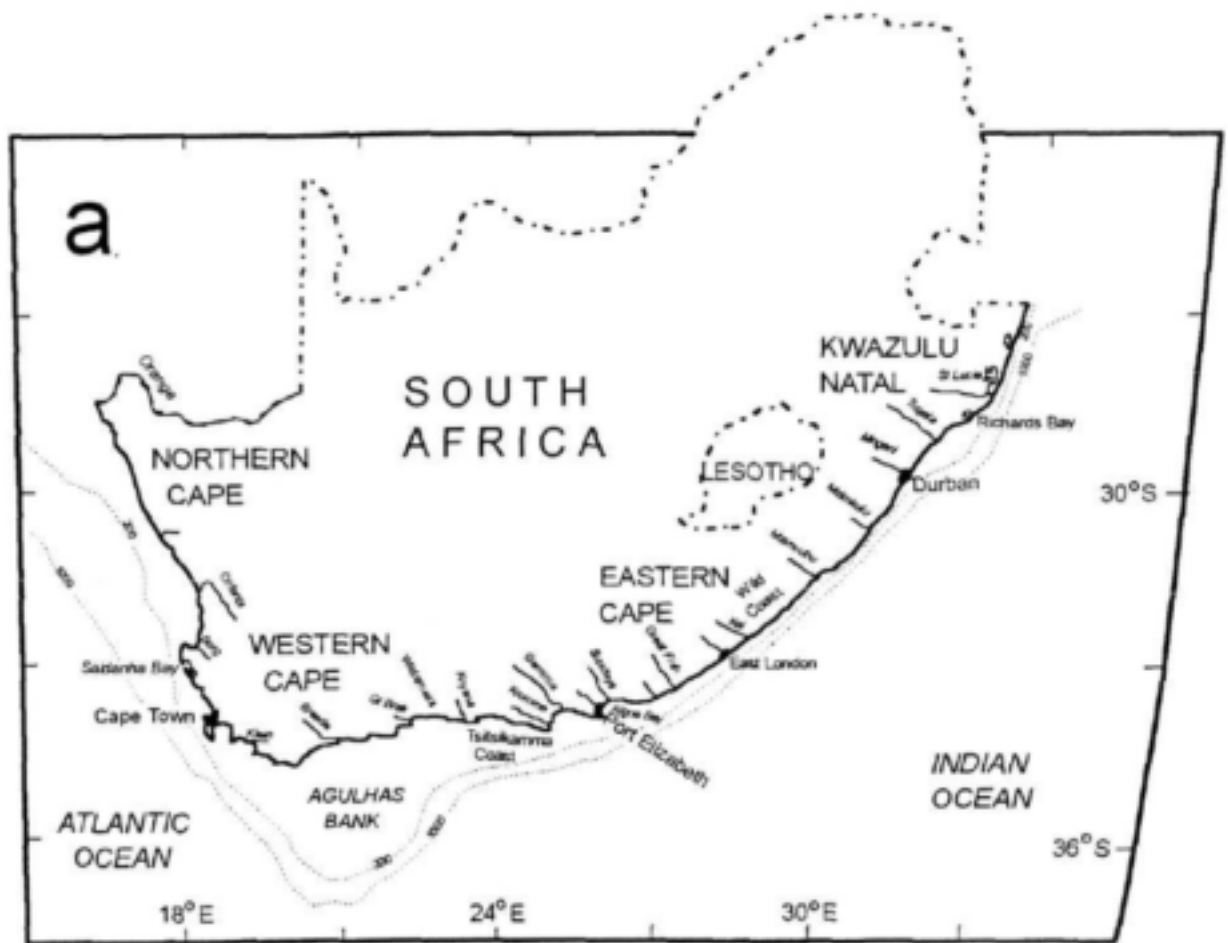


Figure 1.2 Maps identifying locations discussed in the report. (a) is a general map of South Africa, and (b) a more detailed map of the eastern and southern coasts.

2 SEDIMENTATION: CAUSES AND PROCESSES

2.1 INTRODUCTION

This chapter gives the background on physical processes which affect the movement of non-cohesive marine sediment into and out of South African estuaries. Such an understanding is essential to enable good management decisions to be made.

As indicated already, it is the unwanted accumulation of marine sediment which gives rise to the problems encountered in many estuaries. Many factors are involved, including geomorphology, the manner in which sediment is moved, various marine processes (tides, waves etc.), fluvial effects, the hydrodynamics of estuary mouths, cycles of erosion and deposition, and the characteristics and sources of marine sediment.

All these relevant components of the physical environment are covered. Though it is clearly not possible to go into great detail, the descriptions should provide an understanding of the many facets that need to be considered in assessing marine sedimentation in estuaries.

2.2 GEOMORPHOLOGY

The geomorphology and topographic development of the southern African subcontinent has had a significant influence on the development and function of South African estuaries. Development of the subcontinent and its river basins and the geomorphic evolution of the coast have played a significant part in how present-day estuaries function. This section includes relevant geological aspects and begins with the large picture, and then zooms in to the geomorphology of estuaries. Rather than following the more conventionally descriptive approach to geomorphology, the emphasis here is on landscape processes.

2.2.1 The Southern African Subcontinent

The coastal outline of Southern Africa originated from the breakup of the Gondwana supercontinent during the Mesozoic, about 135 million years ago.

The east coast northeast of Cape Padrone was formed by translational faulting of the South American land mass laterally past its African counterpart (Figure 2.1). As a result the coastline is almost linear, even after 135 million years of erosion. The fault contact was almost vertical and very steep bathymetric slopes prevail along this coast: the Mzimvubu Estuary mouth lies only 12 km from the 1 000 m depth contour. The southern and western outlines of the coast were formed by extensional faulting and have more gentle slopes and irregular outlines (Figure 2.1). Exceptions do exist. Along the Tsitsikamma coast, for example, the very hard rock preserved the steep local slopes. Gondwana-

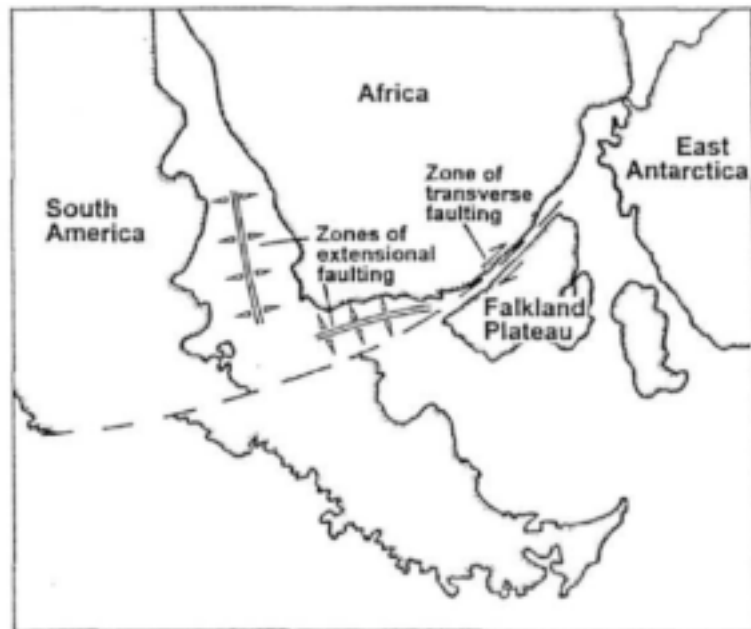


Figure 2.1 The southern African coastline still shows the effects of the breakup of the Gondwana supercontinent about 135 million years ago. As the land masses separated, different situations developed in different parts of the supercontinent (only those aspects affecting South Africa are shown). Two areas of extensional faulting were present where the continents pulled apart, and these produced coasts with ragged outlines and bays and moderate bathymetric slopes. An area of translational faulting was also present where the Falkland Plateau sheared past Africa: such faults are almost linear and extend very steeply down into the crust. When the Falkland Plateau eventually pulled free, it left a linear coast with steep and very deep bathymetric slopes. Despite natural modifications over time, these coastal types have remained much the same since the breakup of Gondwana and affect their estuaries differently (diagram modified after Cole, 1998).

related fractures produced several basins in the crust, and these were filled with Mesozoic sediment masses. These deposits are prone to erosion and weathered into bays such as Algoa Bay, St. Francis Bay and Plettenberg Bay.

Southern Africa occupied a central position in Gondwana before it broke up, and as a result the land surrounded by the new sea afterwards consisted of a high central plateau surrounded by steep seaward slopes. These steep slopes redefined the drainage that had previously been directed northward. The new rivers carved the landscape downward to attain equilibrium with the newly established erosional base level, and sculpted the landscape landward causing the escarpment to retreat inland. The Great Escarpment is the present-day position of this retreating scarp and it separates the smaller rivers that drain seaward from those tributaries that still drain inland towards the Orange River basin and other large inland river systems. By the end of the Cretaceous, about 65 million years ago, the coastal landscape was in equilibrium with the sea level of the time and very gentle slopes prevailed along the South Africa coastline (Maud, 1996).

Since the Miocene, about 18 million years ago, crustal uplift raised the coastline, in places by as much as 350m. This landscape rejuvenation produced the incised river valleys now occupied by estuaries in the coastal zone. Because the fault-bound post-Gondwana coast still had steep gradients below sea level where erosion could not reach it, the uplift produced a steep relief along much of the coastline.

Rock types along the coast influence the rate of coastal erosion. Where a significant difference exists between the erosion competence of adjacent rock suites, embayments can be formed. The most prominent embayments lie along the southern coast of South Africa between Cape Town in the west and Port Elizabeth in the east. Bays, by having sandy shorelines and providing a degree of protection against wave attack, have a significant influence on the type and behaviour of estuaries.

Coastal plains, where the coastal sedimentation rate exceeds the erosion rate, appear to be associated with the erosion-prone Cretaceous deposits. These coastal plains are rare and are present as stunted features in some bays (Plettenberg Bay, Algoa Bay). Only one large coastal plain is present on the coast and lies at Maputaland in northern KwaZulu Natal, and continues northward into Mozambique. Several smaller coastal plains are underpinned by dune and beach rock and are therefore not entirely composed of unconsolidated sediment; the coastal plain in the Wilderness-Sedgefield area is reinforced in this manner.

2.2.2 Coastal Geomorphology and Global Sealevel Change

Steep gradients characterize the coastal relief of South Africa, and rivers draining most catchment basins are incised in the coastal area to form distinct valleys. Sea level was lower during cold-climate periods when glaciation on land removed water from the global ocean, and most rivers cut into the landscape to well below present-day sea level. The last ice age ended 10 000–15 000 years ago. During interglacial (high-sealevel) intervals, such as the period leading up to the present, sea water filled the coastal sectors of the river valleys, in the process forming estuaries (Figure 2.2). By analogy, this effect



Figure 2.2 The Kaaimans Estuary in the Western Cape Province is an example of an estuary that occupies a drowned river valley. The flat top above the valley is a marine-cut surface eroded before the Miocene, and valley incision took place subsequently. In many places incision took place to below present-day sea level during glacial low-stands of the world oceans. The original valley floor of the Kaaimans estuary lies well below sea level and the valley filled with water during the present interglacial high-stand of the sea, and is also filled almost to capacity with sediment. The low local marine sediment supply prevents a barrier from forming here. (Photo: J S V Reddering)

can be viewed as water filling a river valley after construction of a dam wall. By further analogy, both basin types are effective sediment traps. Estuaries occupying drowned river valleys, which is the most common setting for South African estuaries, are termed rias. A concept important to the understanding of the processes involved is that of the erosion base (Box 2.1).

To follow the development of an estuary, consider the historical effect of rising sea level on a typical South African incised river valley.

As sea level rose to enter the incised valley, the erosion base rose. Existing erosional conditions in the valley ceased and changed to a phase of deposition after the valley became 'drowned'. The estuarine basin formed during valley drowning had become a sedimentary reservoir where marine and fluvial sediment accumulated. During the initial phases of sediment accumulation in the estuarine basin, the erosion base lay above the sediment bed and sediment accumulated. Floods passing through the estuary were not erosional, allowing bedload and coarser-grained suspended sediment to accumulate. Marine sediment also accumulated in a deep seaward reservoir and river floods caused only superficial erosion of marine deposits. Estuaries in this condition are immature and few present-day South African examples remain: the Knysna Estuary is probably the best example.

Although rapid in geological terms, the valley-drowning process was gradual. The estuarine basin filled with sediment, and as sea level rose, it was abandoned as the estuary moved landward up the continental slope to successive new positions where the tidal envelope coincided with new levels within its host valley. Sediment levels probably never quite reached the base levels during the rising sea level stages. At present estuarine sediment probably fills much of the remnant palaeovalleys on the continental shelf and the shallow-marine slope between the present-day shoreline and the landward edge of the continental shelf.

After sea level stabilized following the last global rise in sea level, sediment filled the estuarine basin established at present-day sea level. The sediment level approached and eventually met the erosional base level (Figure 2.2). Such an estuary has reached maturity. River sediment entering such a system during floods passes through the estuary into the marine environment where it accumulates. Most present-day South African estuaries are of this mature type.

If sea level were to fall again, the river will erode the accumulated sediment, and a new mature estuary will establish itself seaward and at a lower level than is now the case. Should sea level rise even more, estuaries will migrate landward and become less mature. Estuaries are inherently ephemeral and mobile features of the coastal landscape, as are beaches, coastal dunes and small coastal plains.

The effects of severe flooding, of the type associated with flood events with return times of twenty years or more, are to scour accumulated sediment from the channel reach of an estuary. The erosional

Box 2.1 *The erosion base*, as it applies to erosion and deposition by water, is a theoretical level above which erosion takes place and below which deposition occurs. In the proximity of the sea, including in estuaries, this level is taken as sea level. In detail the depth of erosion depends on the vigour and depth to which erosional scour takes place. During severe river floods passing through estuaries, this level may decrease to tens of metres below sea level, depending on a variety of factors, mainly discharge rate, flow confinement and sediment cohesiveness. During periods of low flow the erosion base rises to very near the theoretical level, which is sea level.

base level of an estuary is lowered during such an event to the level of effective scour, which may vary from about two to ten metres below the fairweather base level. This relatively minor adjustment to the sediment level makes a big difference to local conditions in terms of circulation, tidal exchange, recreational appeal and the perceived general well-being of the system.

Because the South African coast generally has a steeply sloping coastal geomorphology and a similarly steeply sloping nearshore bathymetry, sediment moves offshore rather than alongshore. Since sediment generally does not build up at the coast, coastal plains are therefore poorly developed. As a result the coast is characterized mainly by rocky shorelines with localized pocket beaches. Shorelines composed of unconsolidated sediment, mainly sand, are present in larger bays and small embayments, where a combination of gentler bathymetry and favourable wave diffraction patterns promote sand accumulation on beaches. Even so, many beaches consist of a thin veneer of sand overlying bedrock.

A few exceptions exist to the prevalence of rocky shorelines. Gently sloping, soft-sediment coasts are present at Maputaland in northern KwaZulu-Natal, in the Wilderness-Sedgefield area along the south coast and in the sheltered sectors of the bays between Saldanha Bay and Cape Town, and extending east to Port Elizabeth. These are coastal plains similar to many coastlines of the world. The coastal-plain components in the bays are very narrow. Estuaries crossing these coastal plains differ in several respects from those occupying steeply incised river valleys. Coastal-plain estuaries generally have wide flood plains that are poorly developed in incised valleys. As a result, coastal-plain estuaries inundate their flood plains during floods whereas floods are laterally confined in incised valleys.

Coastal geomorphology with its generally distinctively steep topography and incised valleys has a further influence on estuary development. Since most estuaries occupy drowned river valleys with seaward sloping valley floors, the intertidal capacity of an estuary depends on the valley shape. A valley with a gently sloping valley floor allows the tidal envelope of an estuary to extend a long distance up the valley. Where rocks are tectonically folded, a river flowing along a valley controlled by fold axes could display a gentler slope than that dictated by the shortest route, by following an indirect route to the sea. Such a valley would extend the tidal reach of its estuary. Conversely, a valley with a steeply sloping floor would hold a short estuary.

Using a similar argument, a valley with steeply sloping sides will contain a narrow estuary, confined between rocky banks. Open valleys can contain wider estuaries. These characteristics of the tidal length and width of the basin contained by the host valleys determine the maximum size of an estuary. In addition, the valley characteristics also control the flow characteristics of river floods passing through an estuary. In many places the cross-sectional profile of a valley depends on the erosion-competence of the host rock. The valleys cut into poorly consolidated Cretaceous deposits north of Port Elizabeth, for example the Swartkops valley, produced gentle valley slopes. In nearby hard-rock valleys, such as the Baakens (at the Port Elizabeth harbour) these are incised into quartzite, and slopes are very steep.

A feature of the South African coast that influences estuaries is the comparative effect of waves and tides. Tidal variations fall into the microtidal category (§2.3), whereas surface gravity wave activity in South African coastal waters is very vigorous. Thus while the coast would be classed as wave-dominated, tidal exchanges are nonetheless significant in estuarine-sediment exchanges.

2.2.3 Estuarine Features and Processes

In geological terms, few South African estuaries meet the internationally accepted definition of a 'true' estuary. Almost all South African estuaries are mature, which excludes them from some geomorphic definitions that consider true estuaries to be in the immature, valley-filling phase of development. Many have intermittently blocked estuary mouths that fail these systems from meeting the criterion of being permanently tidal. Furthermore, few South African estuaries receive perennial freshwater inflow, another defining criterion of estuaries. This situation leaves many South African freshwater-marine interfaces in an uncertainty of geomorphic classification. However, it is necessary to define, at least loosely, what geomorphic features along the coast are locally considered to be estuaries; these definitive criteria may differ from those used, for example, by life scientists.

1. It is surprising that few definitions, even those by geomorphologists, specify that an estuary must have a basin composed of unconsolidated sediment. Some of the rivers entering the sea on the Tsitsikamma coast, for example, lack a significant sedimentary component and are therefore elongated marine bays where freshwater runs directly into the sea. Estuaries must have a predominantly sedimentary basin, especially a seaward barrier must be present.
2. The feature that the estuarine basin must be semi-enclosed as dictated by several definitions is essential. Without the narrow estuary mouths of South African systems, the tidal dynamics in the systems would not be recognizable as estuarine, which is why some Tsitsikamma systems fail the test. South African conditions dictate that these conditions be expanded to include systems that are totally enclosed from time to time. Equally important, such systems must at least intermittently be tidal, since the name 'estuary' is derived from the Latin 'aestus', meaning tide.
3. The freshwater requirements of estuaries are equally important. The mixing of fresh water and sea water is fundamental to estuaries, and river floods are vital to the functioning of all aspects of an estuary. Saldanha Bay, one of the most prominent tidal embayments on the South African coast, fails the freshwater test, and is therefore not an estuary. In the South African context the perennial freshwater requirement of most international definitions must be watered down to meet at least an ephemeral freshwater supply to the tidal system.

Considering their common origin and general setting, a surprisingly high geomorphic diversity exists amongst South African estuaries. Some are large, others small. Some have permanently open tidal mouths whereas others are intermittently cut off from the sea. Most lie in rocky valleys but some lie on coastal plains. Some have narrow channel systems with steeply-sloping banks whereas others are wide and laterally unconfined. Some extend inland for tens of kilometres, others are very short.

Figure 2.3 shows features of a typical estuary. Almost all estuaries have a subaerial sandy barrier that extends across the seaward section of the estuary, and separates it from the sea. A barrier is a wave-built sand ridge that lies parallel to the prevailing wave fronts. Barriers consist of unconsolidated sand, or rarely in South Africa of gravel, and extend from well below sea level to above this datum. Bedrock barriers are present in a few places (e.g. Knysna and the Soutrivier, east of Plettenberg Bay) but are rare. Barriers may be short, of the order of 200 m long, if the host valley is narrow; others, by contrast, may be several kilometres long along coastal-plain lagoons, e.g. the Keurbooms Estuary shown in

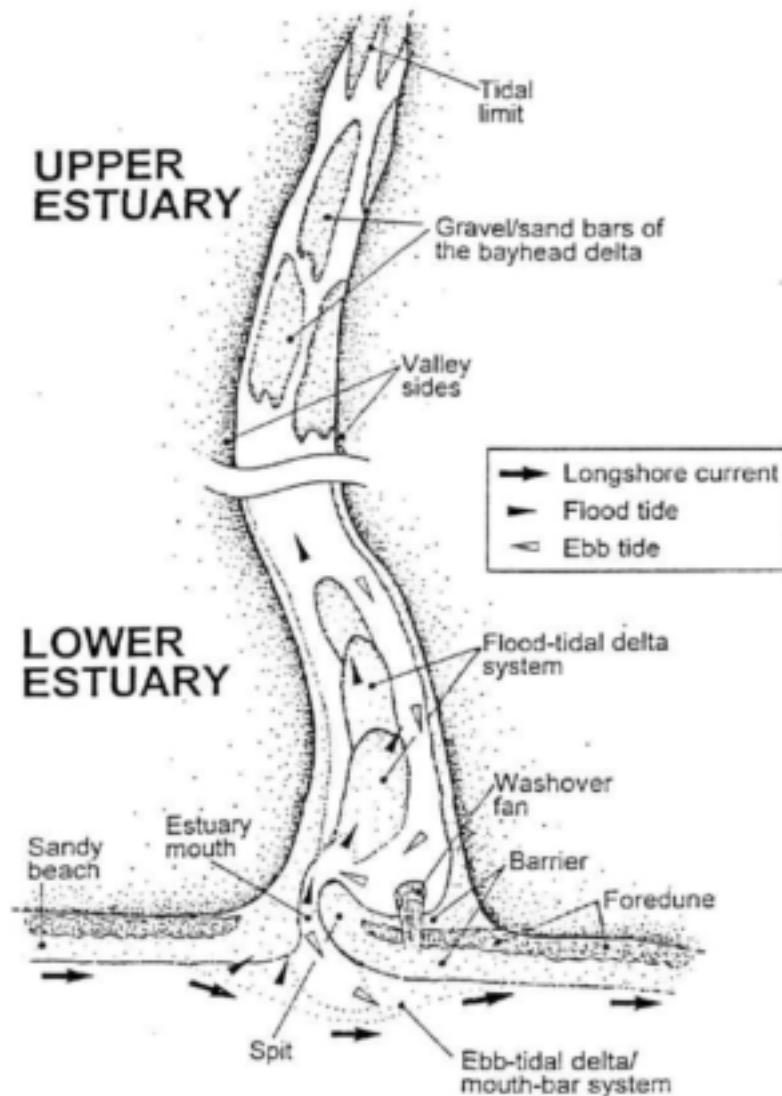


Figure 2.3 A schematic estuary typical of the kind found in the Eastern Cape, illustrating geomorphic features. The estuary is split to show the lower and the upper reaches, with the middle reaches omitted. It occupies a valley with steep sides, and the sand barrier at its seaward end is a natural extension of the adjacent sandy beach. The estuary mouth is a tidal channel through the barrier that connects the estuary with the sea. In many estuaries this tidal mouth is intermittently closed off as the barrier blocks off the whole valley and merges with the adjacent beach. Foredunes on the beach extend seamlessly onto the barrier, except where a storm event eroded a subaerial washover channel through the dunes and deposited a washover fan into the estuary behind the barrier. The ebb-tidal-delta/mouth-bar system lies below lower tide level just offshore from the mouth and acts as a conveyor for longshore-drift sand transport past the mouth. The small ebb-tidal deltas shown are typically a summer feature when wave activity is relatively subdued; during winter storms the mouth bar moves shoreward where it plays a part in mouth closure, if that were to take place. The end of the barrier, known as a spit, bends inward into the estuary as a result of wave-refraction effects. Sand diverted into the estuary from the longshore-drift conveyor during the flood tide accumulates on sand bodies known as flood-tidal deltas. These deltas extend into the estuary as lobe-like sand bodies that grow up the main channel by sediment accretion at the landward end of the deltas. Sand on the flood-tidal deltas is main accumulation of marine sand in the lower estuary. The upper estuary near its tidal limit is characterised by accumulation of sand or gravel bars at the slope change where the river flows into the estuary at the tidal limit. The sediment body, called the bayhead delta (§2.2.3), consists of river sand or gravel, and is the other major potential source of sediment in estuaries. The effects of river sedimentation are not covered in this report.



Figure 2.4 The late-1980's barrier of the Keurbooms Estuary with the estuary mouth in the middle. A small ebb-tidal delta has developed seaward of the mouth and a prominent flood-tidal delta lies landward of the mouth. The mouth has migrated towards the bottom of the frame over the past 60 years so that the established vegetation is undercut and removed, and the newly established barrier in the distance has a younger vegetation cover. Several evenly-spaced washover channels are present on the distant part of the new barrier and the washover sand has widened the barrier there. This washover sand is an important local source of marine sand in the estuary. (Photo: J S V Reddering)

Figure 2.4. The upper level of a sand barrier lies at about the spring-tide, upper-wave-swash zone, and because this barrier surface is dry for much of the time, the surface is commonly reworked by the interplay of wind and vegetation. As a result many barriers host an associated dune ridge.

Composed of unconsolidated sand, barriers are prone to erosion during severe river floods, especially if the host valley is narrow and the barrier short. It is also a common observation that the barrier is the first mobile geomorphic facies to be reestablished after a flood.

The mouth of an estuary (Figure 2.3), also called a 'tidal inlet', is a channel cut through the barrier, and allows tidal exchange to take place between the estuary and the sea, and allows river discharge to reach the sea. The wave-driven, bar-building process generally prevails in the wave-dominated barrier environment and continually seeks to block the mouth channel. The processes of bar construction involve spit growth by sand derived from longshore drift and landward bar migration in the breaker zone. Under the sole influence of wave action and in the absence of tides, the bar would grow to merge seamlessly with the barrier, closing off the estuary from the sea.

The longshore current carrying sand entrained in wave-generated turbulent suspension constitutes the longshore drift (§2.4, Figure 2.3). Wave-built sand bars, present in the surf zone of most estuary mouths, are shallow corridors along which sand in the longshore-drift conveyor bypasses an estuary mouth. That fraction of the longshore-drift conveyor diverted into the estuary by the flood tide is the largest source of marine sand in South African estuaries.

Tides moving through an estuary mouth have the capacity of eroding wave-deposited sand from the mouth channel and, depending on their erosive capacity, are able to keep the estuary mouth open. Despite this erosion, most South African estuary mouths are constricted, that is the mouth channels have smaller cross-sectional areas compared with the channels of the lower estuaries.

The capacity of the tides to maintain an estuary mouth open depends mainly on two factors:

1. The extent of wave activity: higher waves tend to force closure, and many permanently open estuary mouths lie on the more wave-sheltered shores of bays.
2. The volume of tidal water passing through the estuary mouth: most estuaries with permanently open mouths are larger systems, whereas smaller estuaries in the same area of the coastline have *intermittently or nearly permanently blocked estuary mouths*.

The water volume passing through an estuary mouth is its tidal prism, and depends principally on the intertidal water capacity of an estuary and the resistance to tidal flow at the narrows and shoals of an estuary mouth (§2.5). The intertidal capacity of an estuary depends on the length and width of the estuarine basin. A system such as the Bushmans Estuary extends 32 km from the sea (Reddering and Esterhuysen, 1981a), and it occupies its valley from bank to bank. As a result it has a large capacity to accommodate tidal water and this large tidal prism maintains the estuary mouth in a permanently open state. Along the coastline adjacent to the Bushmans Estuary, many other estuaries are shorter and narrower, and although under the influence of similar wave conditions to that experienced by the Bushmans system, these estuaries have mouths that are blocked for long periods.

Additional factors influence the mouth conditions, like the presence of sand on the coast, the mouth configuration and the presence of bedrock at the mouth. For example, along the Tsitsikamma coast, the steep nearshore bathymetry promotes offshore rather than alongshore sediment movement. The small Tsitsikamma estuaries are permanently open because insufficient sand is available to block their mouths. Some have so little sediment that they are not true estuaries. Where the least bit of sand is present, like at the Tsitsikamma Estuary itself, the estuary mouth is blocked for long periods.

Geomorphic features in the middle and landward channel reaches of estuaries are commonly the

product of the sediment type. In mud-dominated estuaries, the banks are coherent, and are able to maintain steep banks. As a result such systems have narrow intertidal areas and deep, narrow channels. Sand-dominated systems have unconsolidated banks, and these banks are reworked by tides, floods and local wind-driven wavelets. As a result the sandy estuaries have wider intertidal areas, in places tidal flats, and wide, shallow channels. The significance of these geomorphic features is that mud-dominated estuaries with deep narrow channels tend to display salinity stratification and long tidal residence periods. The basin capacity of the steep-sided channel is roughly proportional to the tidal range as it varies during the spring-neap tidal cycle. A sandy estuary, being shallower, generally displays better tidal mixing and its residual water has a shorter residence period. In addition the intertidal profile significantly widens upward so that the spring-tidal prism is disproportionately larger than its neap-tidal counterpart.

Many estuaries occupy steep-sided valleys (Figure 2.2), and the sedimentary fill of the valleys is restricted by the bedrock valley sides. Especially the upper reaches of such estuaries have rocky banks. Because the valley floor of such an estuary slopes seaward, the estuary occupies a higher, wider section of the valley near its seaward end. Because the valley is filled with sediment in this broader seaward reach, the channel almost invariably lies on a sediment floor, but tends to abut one rocky bank or another.

The channels of estuaries that occupy drowned river valleys, especially those in narrow, steep-sided valleys, cannot migrate sideways, nor can river floods disperse by moving onto a flood plain. Such estuaries display confined flow during river floods, focussing their discharge along the channel, and their erosive power is concentrated there. Such estuaries are effective in removing accumulated unconsolidated sediment from their channels during river floods. Some mud-dominated estuaries with steep estuary banks display similarly confined flow. In estuaries where a significant flood plain is present, floods disperse onto the flood plains, reduce the flow speed and reduce the effectiveness of erosion.

The effect of flow confinement is well illustrated by estuaries where downstream variation of confinement is evident. Possibly the best example of such a system is the Keurbooms Estuary. Upstream of the N2 road bridge, the flow is confined in a gorge, and erosional scour in the gorge during river floods is very efficient, owing both to flow confinement and because the sediment consists of unconsolidated sand. Sandy banks are rare and several deep scour pools are present along this section; one pool is 24 m deep. Where the Keurbooms passes onto the coastal plain downstream of the N2 bridge, flood flow is unconfined (Figure 2.5). The abrupt reduction in flow speed has caused deposition to take place on a mid-channel bayhead delta (§ 2.6). Sand shoals and shallow water prevail from there on to the estuary mouth, which lies along the 3,5 km long sand barrier that separates the estuary from the sea (Figure 2.4). Similar but less accentuated flow-confinement effects are evident in the Kromme Estuary, 150 km to the east.

Most South African estuaries display a flood-tidal dominance (§ 2.5), and on average more marine sand enters these systems during flood tides than is removed during ebb tides. The sand accumulates in flood-tidal deltas which grow by lateral extension (§ 2.6), and are common features in South African estuaries with permanently open or intermittently closed estuary mouths. In near-permanently-closed-



Figure 2.5 The change in estuarine landscape in the Keurbooms Estuary from a confined drowned-valley situation landward of the N2 road bridge (top left in photo) to an open floodplain condition seaward of the bridge. The lack of flow confinement has caused deposition of sediment bodies, called bayhead deltas, during river floods. Such unconfined flow is much less effective in naturally scouring sediment from affected estuaries than confined flow. The channel in the foreground is the much smaller Bitou Estuary tributary that joins the Keurbooms Estuary at the right of the photograph. (Photo: J S V Reddering)

mouth estuaries these flood-tidal deltas are not developed because tidal action, critical to their growth, is limited by the closed-mouth condition. Flood-tidal deltas are also not prominent in river-dominated estuaries, such as many estuaries of KwaZulu-Natal and the Orange River Estuary. Examples of river-dominated estuaries from the Eastern Cape include the Mzimvubu Estuary at Port St Johns and the Great Fish Estuary. The dominance of river flow in these estuaries reverses the usual flood-tidal dominance to one directed seawards so that marine sediment does not readily enter the estuary. These systems are also more prone to seasonal flooding so that whatever little marine sediment has accumulated, is quickly scoured out of the system.

In some estuaries of the world, the sand removed from the estuary during the ebb tides accumulates in elongate intertidal bars that grow out into the sea, normal to the coast. These features are not well developed in South African waters because little sand is eroded from the predominantly flood-dominant estuaries and the very active wave action along the shoreline rapidly reworks any sand deposited in the surf zone. Some estuaries have stunted ebb-tidal deltas during the summer months when surf energy is somewhat lower, but these sand bodies are invariably eroded during the winter storms.

2.2.4 Aeolian Sand

Aeolian dunes are large-scale bedforms produced at the air-sediment interface formed when wind blows across dry, unconsolidated sand. Coastal dunes form where the dominant wind blows onshore and the sediment source is dry beach sand. Dunes unconfined by vegetation cover migrate in the direction of the dominant wind direction.

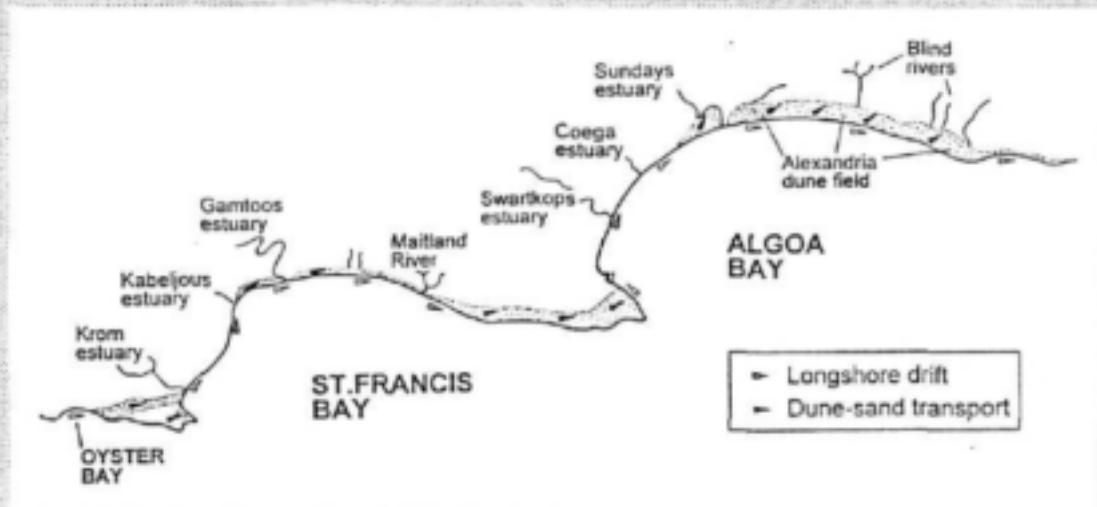
Sand dunes can transport huge sediment volumes. Movement of dune sand is closely associated with longshore-drift corridors and related sandy beaches. Several transport corridors involving dunes, beaches and longshore drift systems exist along the southern coast of South Africa. Possibly the best example in the Eastern Cape is the one that originated to the southwest of Cape St. Francis and extending to Cape Padrone (Box 2.2), before human intervention led to large-scale dune stabilization. The results of these stabilization activities now severely curtail sand transport along critical sectors of the transport corridor.

An unusual situation exists along the East London coastline where both the prevailing and main subordinate winds blow parallel to the almost linear coast. The coast there consists mainly of bedrock eroded to form gently inclined wave-cut terraces that extend from the high-tide level into the low-tide-level surf zone. A thin fringe of sand is present along the high-tide level during favourable conditions but storms often erode this sand. Permanent sandy pocket beaches are present in small embayments at the mouth of each estuary along the coast. These beaches form the source of parabolic dunes that blow obliquely onshore and migrate parallel to the coast to terminate in the next estuary to the northeast. River floods there scour accumulated dune sand from the lower estuary, and the source of another narrow parabolic dune lies at the downwind end of that embayment. This pattern repeats itself between every estuary between the Tyolomnqa and Quinera estuaries, and is repeated farther to the northeast.

In many places, especially along the east coast of South Africa, the prevailing wind direction has an offshore component and the transported sand is trapped in vegetated dune ridges during periods that subordinate winds blow onshore. In such situations dune sand is not a significant threat to the sediment balance in the associated estuaries. Some sectors of the coast, notably the rocky-shore-dominated Wild and Tsitsikamma Coasts display a distinctive coastal geomorphology, in which steep sea cliffs abut wave-cut platforms near sea level. Sandy beaches are uncommon in these settings and are restricted to pocket beaches. The small supply of sand and the steeply sloping sea cliffs provide unfavourable conditions for dune development, and estuaries in these settings generally do not experience significant sand accumulation from coastal dunes. The Tsitsikamma Estuary is a notable exception.

In most estuaries the volume of dune sand entering the estuaries is small, and episodic river floods readily scour the sediment from the estuary channel. Even the oldest known post-Gondwana coastal palaeo-dune, now dune rock, extended into an Early Cretaceous estuarine palaeochannel at the Mngazana proto-estuary, 135 million years ago. River floods eroded away at the toe-end of this palaeo-dune, so the present-day processes are not new.

Entry of dune sand into lower estuaries is neither unusual nor unnatural. Unless unusually large rates of deposition prevail, such as those observed in the Alexandria dune field, natural erosion by river floods scour the unconsolidated sand from the estuary. In most estuaries, natural conditions seldom



Historically a sediment transport corridor existed that extended from Oyster Bay to the Alexandria coastal dunes northeast of Port Elizabeth. The continuity of this corridor has been broken by human intervention. Sandy beaches at Oyster Bay southwest of Cape St. Francis are aligned east-west, facing the sea to the south (see figure), so that the prevailing southwesterly wind blows onshore there. Dune sand crossed the headland of Cape St. Francis along a dune corridor termed a headland-bypass dune field. On the shore of St. Francis Bay the wind is offshore and the dune sand enters the beach-longshore-drift corridor there; this drift is driven by prevailing waves from the southwest (§2.4.2). The curvature of the bay changes the alignment of the coast and at the northern sector of the bay, around the Kabeljous Estuary mouth, the prevailing wind has an onshore component. The beach provides sand for development of a beach-dune corridor that extends from the Kabeljous Estuary to the Maitland River mouth southwest of Algoa Bay. From the Maitland River eastwards a headland-bypass dune field extends inland and across the headland to Algoa Bay. In the bay the prevailing westerly winds blow offshore and move the sand into the surf zone where it enters another beach-longshore-drift corridor that follows the coast line to where the curvature of the bay causes the southwesterlies to blow onshore. Along the northern sector of the bay this onshore sand transport produces the beach-dune corridor that extends to the easternmost extent of Algoa Bay at Cape Padrone (the

Alexandria dune field).

The coastal dune-beach-longshore-drift conveyor at Cape St Francis passes several estuaries. The Sand River, a small river draining the headland-bypass dune field at St. Francis Bay, carries significant quantities of sand into the Kromme Estuary. Before dune stabilization and diversion of the Sand River during the 1960's, the sand moved shoreward near the mouth of the Kromme Estuary. The dune corridor at the northern sector of St. Francis Bay deposits sand into the Gamtoos Estuary, where it continues to affect the sediment balance of that system. On Algoa Bay most of the estuaries lie in the area where the southwesterlies blow offshore, and the influence of dune sand is minimal. Where the dunes represent a significant sand volume at the northern end of the bay, only the Sundays Estuary has sufficient discharge during floods to scour and maintain a valley through the dune corridor. Dune sand blows into the lower 3.5 km of the Sundays Estuary at a rate of about $39 \times 10^3 \text{ m}^3 \text{ a}^{-1}$ (Illenberger, 1992). East of the Sundays Estuary, where the very large Alexandria coastal dune field prevails, several so-called blind rivers flow into the dune (see figure). The porous sand absorbs the discharge sponge-like from the almost-lagoonal wetlands to the landward side of it. As a result no rivers join the sea for a distance of 55 km. Two blind rivers are also present at the dune field east of the Gamtoos Estuary.

prevail, and discharge patterns of host rivers are commonly disrupted by freshwater impoundment and extraction. The result is that dune sand, like tidally deposited sand, may accumulate to unnatural levels to cause shoaling of the lower estuaries, compromising the natural circulation that drives the whole estuarine system.

2.2.5 Barrier Overwash and Estuarine Spits

Barrier overwash is a process whereby storm waves erode channels through the normally subaerial dune ridges on barrier surfaces. These channels normally do not cut down to form proper mouth channels but are more specifically channel-like corridors that extend from the high-tide level of the barrier beach, across the barrier surface to the back-barrier estuary (Figure 2.4). These corridors allow the swash of storm waves, carrying entrained sand, to wash across the barrier surface into the back-barrier estuary. On some barriers, the overwash process carries considerable sediment volumes, and can contribute significantly to the marine sediment load of the associated back-barrier estuary. Reddering and Esterhuysen (1983a) suggested that more than half the sand accumulated in the Keurbooms Estuary between 1915 and 1979 entered the system by storm-driven barrier overwash. The total sediment volume that had entered the Keurbooms Estuary during this period was calculated at $1 \times 10^6 \text{ m}^3$, but floods and mouth migration have since removed much of the accumulated sand.

Barrier overwash is a common phenomenon in the estuaries along the KwaZulu-Natal coast. It is a storm-wave-driven process and represents an episodic event accumulation, in contrast to tidal sand accumulation in estuaries, which is gradual. Episodic events, especially those with significant impact, have a far greater impact on the perception of change than gradual processes.

The even spacing between overwash channels during an overwash event in 1978 in the Keurbooms Estuary (Figure 2.4) suggests that edge waves (§ 2.4.5) played a significant part in eroding gaps through the barrier foredunes.

Waves moving into an estuary mouth become refracted to tend parallel to the mouth banks on both sides. The associated longshore drift commonly generates small spits that extend into the host estuary (Figures 2.3 and 2.4). This process only takes place during the upper half of the incoming tide but can accumulate sediment bodies of significant dimensions. In the Keurbooms Estuary these spits commonly exceed 100 m in length, especially during the storm season. The mouth banks have a distinctive funnelled shape that extends into the estuary. Where an estuary has one rocky bank, a situation very common in the South African rias, only half the funnel is developed. Overwash also takes place across these spits, which naturally lie at or just below the high-tide level.

2.2.6 Closed Estuaries

An important aspect of an estuary, which has gained multidisciplinary prominence over the past decade, is the condition of the estuary mouth, whether it is permanently open or whether it closes intermittently (see also §3.4). Estuaries with permanently open mouths enjoy the advantages of exchange of water, electrolytes, sediment and a host of biotic components between the estuary and the open sea. When an estuary mouth closes, these exchanges are stopped or significantly curtailed. In such closed-mouth systems, a number of chemical, physical and biological changes take place during the closed-mouth periods. These mouth states also influence the influx and dispersal of marine sediment.

While an estuary mouth is closed, a barrier blocks off all tidal circulation into the lagoon, and sediments carried by the longshore drift pass the estuary along the barrier beach. Marine sediment that forms part

of the barrier or enters the lagoon by barrier overwash remains in the lower estuary. This overwash sedimentation is generally localized and does not pose a widespread sedimentation threat to the estuary, unless the barrier is very long, e.g. more than about 500m. Barrier overwash has the potential to block subtidal channels inside an estuary.

While an estuary mouth is open the flood tide carries sand from the barrier beach zone through the mouth channel into the estuary to accumulate on the flood-tidal deltas (see § 2.6). The influx of marine sand therefore depends on the periods during which estuaries have open mouths, as well as conditions within the river itself.

2.2.7 Estuarine Classification: Geomorphology and Processes

This report is confined to the management of marine sediment accumulated in South African estuaries with the emphasis on estuaries of the Eastern Cape Province. It is therefore necessary to categorize the estuaries into management classes where the influence of marine-sediment accumulation is significant. The first step is to identify classes of estuary where deposition of marine sediment is insignificant. The remaining estuaries receive significant quantities of marine by tidal, wave or aeolian processes. Amongst these estuaries it will be useful to identify those systems that suffer excessive sedimentation owing to human activity.

Three categories of estuary (or other fluvio-marine interfaces) do not inherently experience an influx of marine sediment:

1. River-dominated estuaries. Estuaries like the Great Fish and Mzimvubu estuaries, and many KwaZulu-Natal estuaries, experience river-dominated sedimentation and little or no sediment enters these systems from the sea. The Orange River Estuary also falls into this category. In the case of the Great Fish Estuary, this river-dominance is partly attributable to the Orange River transfer scheme, a human influence, but its river dominance predates the introduction of the large-scale interbasin water transfer. The most significant difference is that the mouth of the Great Fish Estuary is now permanently open whereas there are reports that it had closed in the past.
2. Estuaries with almost permanently closed mouths have a physical sand barrier across the lower estuary, which prevents tidal exchange with the estuary. As a result flood tides cannot carry marine sediment into the system. In the absence of dunes entering the system, such estuaries receive very little marine sediment. Many Kwazulu-Natal estuaries fall into this category, as do a number of Eastern Cape and Western Cape estuaries. Many estuaries where the closed-mouth state is less prevalent do not necessarily fall into the category of estuary where marine sedimentation is insignificant. The Piesang Estuary at Plettenberg Bay (Figure 2.6) is possibly one of the worst-affected estuaries in terms of marine-sediment accumulation, yet its mouth is closed about half the time.
3. Those fluvio-marine interfaces, particularly along the Tsitsikamma coast, where fresh water enters the sea along elongated marine embayments without interaction of an estuarine interface receive almost no marine sediment. These bays are not semi-enclosed and are not estuaries, even in the South African context.



Figure 2.6 The Piesang estuary at Plettenberg Bay during the early 1990's. The flood-tidal delta system composed of marine sand occupies almost the whole lower estuary. Sediment bodies have enlarged since the photograph was taken. Despite the estuary mouth lying sheltered behind a rocky island and being only intermittently tidal, the influx of sand has been very vigorous, possibly the result of a prominent flood dominance of the tide. (Photo: J S V Reddering)

All other categories of estuary receive significant quantities of marine sand and fall into the management class that could require remedial sand removal from the lower reaches.

2.3 SEDIMENT MOVEMENT

Water moving over a sediment bed exerts a frictional drag on the sediment grains at the water-sediment interface. If the water speed is great enough, this drag can initiate grain movement in the direction of the current, and if strong enough, may even lift grains into suspension within the water column.

The details of these processes are complex, and in many cases poorly understood. Measurements are also difficult to make since details occur at the molecular level. Nonetheless, the concepts are well established, and are reported in a number of books, e.g. Komar (1976), Allen (1984, 1985), Dyer (1997), Open University (1989). The discussion in this report will only present the concepts relevant to the movement of non-cohesive sediments.

2.3.1 Water Flow and the Bottom Boundary Layer

Water flowing over a stationary, smooth, bottom boundary has a theoretical speed of zero where it is in contact with the bottom. The shear produces stresses at the bottom, and affects the velocity profile in the water column. That part of the flow where the influence of the bottom is felt forms the *bottom boundary layer* (bbl). In shallow water such as in estuaries, the bbl commonly extends to the water surface.

If the flow is slow enough, there will be a linear increase in current speed above the bottom, and the flow is said to be *laminar*. If the speed increases beyond a critical value, the flow becomes *turbulent*. This turbulence produces random movements and small eddies within the water, the instantaneous situation being complex and ever changing. Unlike laminar flow which is characterized by rectilinear downstream flow, turbulence has sideways, upwards and downwards components. In most natural situations water flow is turbulent.

The eddy movements of turbulent flow are much larger than the molecular movements involved in laminar flow, and consequently the turbulent shear stresses are also greater. Experimentally, these shear stresses have been observed to be proportional to the square of the time-averaged water velocity, and this leads to the definition of the *shear velocity* u_* . Thus the boundary shear stress τ_o is given by

$$\tau_o = \rho u_*^2 \quad (2.1)$$

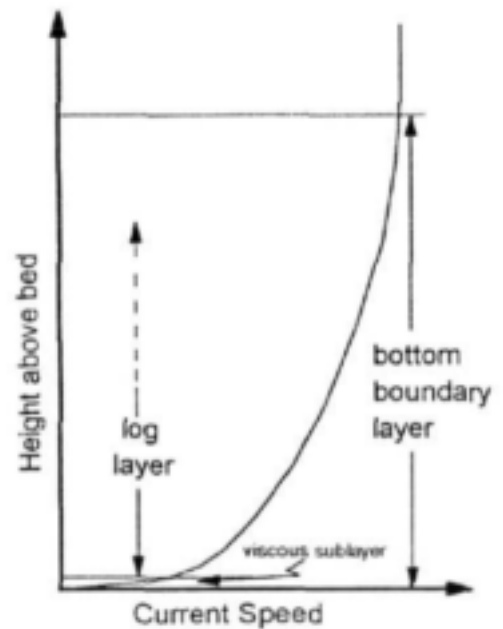
where ρ is the density of the water. In practice it is not possible to measure u_* directly, though many results are expressed in terms of this parameter.

A schematic picture of the boundary layer for a steady flow over a smooth bed is shown in Figure 2.7, i.e. the velocity profile increases from zero to a constant value outside of the layer. Various structures occur within the bbl, with the *viscous sublayer* occurring at the interface between the water and the sediment bed. It is very thin (a few mm), and within this layer conditions approach laminar flow because of the slower current speeds. Above the viscous sublayer lies a transitional layer where u increases approximately as the logarithm of the height above the sediment bed, and this is consequently called the *log layer*.

Increased current speed has a marked effect on sediment movement at the bed. As speed increases, the viscous sublayer becomes thinner, allowing turbulent flow to reach closer to the bottom. In practice the bed is not smooth, but consists of sediment with differing grain sizes. Consequently, as the viscous sublayer becomes thinner the larger sediment grains protrude through into the turbulent flow regime, and the grains themselves will begin to disrupt the flow in the layer.

Eventually, with increasing current speed the grains protrude so far that the layer breaks down altogether, and turbulent conditions can effectively reach right down to the bed. This condition increases the potential for sediment movement across an unconsolidated sediment floor.

Figure 2.7 The bottom boundary layer is that part of the flow influenced by the bottom bed, i.e. the current speed increases gradually to the maximum undisturbed value outside of the layer. The viscous sublayer is generally only a few mm thick and flow here is slow enough to be laminar. The log layer occurs above that, with an indistinct transition to flow above the bbl.



2.3.2 Sediment Movement

The extent to which loose sediment is moved depends on the current structures in the bbl above the sediment bed, the size and shape of the sediment grains and the density of both the grains and the water. Additional complicating factors are the bottom profile, i.e. bedforms (Box 2.3), and that a time-varying current exerts different forces to a steady current. Thus sand ripples can greatly increase the bed roughness, causing added drag, and thereby reducing the capacity of the flow to move sediment.

The movement of sediment begins when the shear stresses and lifting forces from the turbulent current become sufficiently great to overcome the frictional and gravitational forces holding the grains on the bed; this threshold is termed the *critical shear stress*. The critical shear stress is generally least for the lightest, smallest sediment grains, and these will move first. Generally, this movement starts with the grains beginning to roll, slide or bounce across the bed, occasionally also undergoing short hops (*saltation*). This type of sediment movement is termed *bedload* transport.

If shear stresses increase, sand grains are lifted off the bottom and into the water column as *suspended load*. Under these conditions the turbulent fluid forces are sufficient to keep the grains suspended, and they move with the current flow. Water movements in nature are not steady, and when currents slow down the turbulence that kept sediment in suspension decreases. Consequently, deposition out of suspension occurs. The grains then settle out of suspension at their *settling velocity*, which depends on their size, shape and density, and on remnant water turbulence. Very small particles settle significantly slower than coarse ones, and if the current slows down there will be a settling lagtime before they reach the bed. The rate of deposition will also be greater if the suspended sediment is concentrated close to the bed, rather than higher up in the water column.

A special case of suspended load common to estuaries is when a transverse rolling vortex develops under vigorous flow conditions in the water just above a rough sediment bed. The vortex may then detach from the bottom as a hairpin vortex and extend upward into the water column, taking with it

sand scooped up from the bedload carpet and forcefully propelling it upward. In places the vortices break the water surface and suspended sand is evident in the 'boils'. Once a vortex dissipates, the sand settles to the bottom, but because the water mass moves rapidly downstream, the sand in the boil may land several hundred metres downstream from where the vortex entrained it.

Sediment suspended in the water column effectively increases the density of the water. This sediment concentration increases near the bottom, and the increased density makes it more difficult for turbulent eddies to move the denser water upwards. The net result is that turbulence is dampened, causing lower than expected shear stresses at the bed.

The movement of sediment therefore involves the interplay of a number of different factors, and Figure 2.8 portrays these general results for steady currents. It shows the different stages of sediment movement for different grain sizes under different current speeds, as well as the settling velocities of the different grain sizes. Of interest is the fact that finer grains of sand can be lifted straight into suspension without going through a bedload phase. Note that this figure depicts trends, and that no clearly defined boundaries exist between the different phases.

The current speed in Figure 2.8 is the shear velocity u_* . As indicated above, it is not directly related to a measured current speed at any particular depth, and its value is therefore not easy to determine

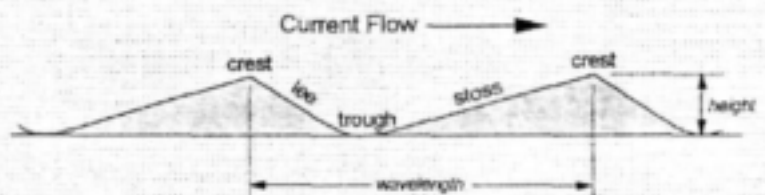
Box 2.3

Bedforms

Bedforms are regular geometric surface shapes in loose sediment formed at the bed surface by flowing water or air. Bedforms include depositional features such as ripples, dunes and plane beds, and erosional features such as scour marks.

Current ripples are small ridges that form transverse to sluggish water flow, and are the first bedforms to develop once the critical shear stress is exceeded. These straight-crested current ripples are asymmetrical and are roughly triangular in cross section with a gently sloping upstream or stoss side and a more steeply sloping downstream or lee side (see Figure); this pattern repeats down-current. Under more vigorous flow, the ripple crest surfaces become three-dimensional, and viewed from above the crest lines become sinusoidal or linguoid (U-shaped) with even stronger currents. Ripple heights range from 0.5 to 3 cm and have typical wavelengths between about 0.5 and 60 cm, and only occur in sediment finer-grained than about 0.6 mm in diameter.

Asymmetrical underwater dunes are larger bedforms than ripples and are produced in coarser sediment under more energetic flow conditions and in sufficiently deep water. Dune wavelengths range from about 0.6 to 1000 m, depending on flow conditions, water depth and sediment particle size, while heights can vary from 0.1 m to around 20 m. In the subtidal zone of estuaries dune wavelengths are generally less than 10 m with heights less than 1 m, while heights are less than 0.5 m



in the intertidal zone where these dunes are most readily observed

Sand grains are transported as bedload up the stoss side of a ripple or dune, and then over the crest where they accumulate on the steep lee side before moving on. In this way both the bedform and sediment migrate across the bed in the direction of the dominant flow.

When the flow is sufficiently strong, it wipes out high-relief bedforms altogether, and sediment is moved in sheet-like layers over a plane bed. Under conditions of vigorous flow in very shallow water, such as the swash zone of a beach, all ripples and dunes are washed out and replaced by plane beds.

It is common for smaller bedforms to be superimposed on larger bedforms. In this way the surfaces of flood-tidal deltas are commonly ornamented with dunes that themselves have superimposed ripples. The equilibrium or fully developed shapes of the bedforms are determined by complex interactions between the flow, the bed geometry and the sediment: the bedform is created by the flow, and the flow is in turn acted on by the bedform.

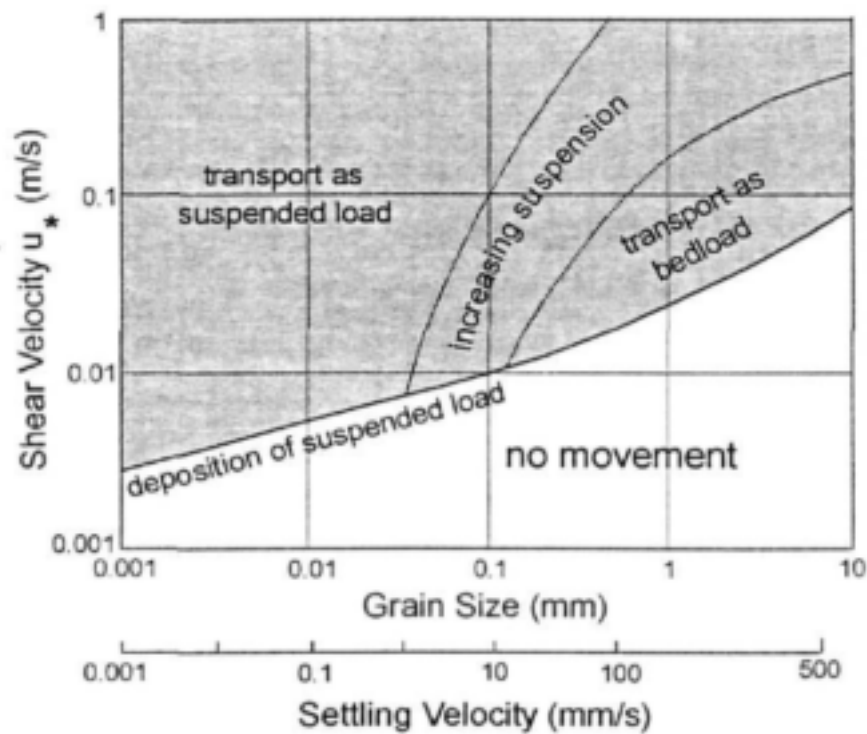


Figure 2.8 Empirical graph showing sediment behaviour for different grain sizes under varying current speeds. Finer grain sizes (silt and clay) move directly into the suspended load phase, while larger grains first go through a bedload phase. Note that silts and clays can be non-cohesive and are subject to compaction. The settling velocities are also given in relation to grain size (Open University, 1989).

precisely. As an example, experiments have shown that for a flat bed and sediment grain sizes of 0.25 mm, $u_* \sim 0.03 u_1$ (approximately), where u_1 is the water speed at a height of 1 m above the bottom. Bedform roughness increases the effective u_* , and where bedforms are present $u_* \sim 0.07 u_1$.

The rate of sediment transport is simply the mass of sediment that is moved over a given distance in a set time. Such movement includes both bedload and suspended transport, while if the current speeds drop, then the bedload will stop moving, and the suspended sediment will settle out again.

Bedload Transport Rate Measurement of the bedload transport rate is subject to inherent uncertainty because it takes place at, or very close to the interface between the bed and the overlying water. Nonetheless, provided that the critical shear stress is exceeded, it has been found experimentally that the bedload transport rate, q_b , is proportional to the cube of the shear velocity, i.e.

$$q_b \propto u_*^3 \quad (2.2)$$

This relationship is important because very small changes in current speed or bed roughness can have significant effects on the rate of bedload transport.

Suspended Load Transport Rate The suspended load transport rate q_s can be calculated directly from sediment concentrations in the water column, c_s , and the current speed, u , i.e.

$$q_s = c_s u \quad (2.3)$$

Determination of both c_s and u in the water column involve uncertainty, particularly because of the variability with height.

All these factors lead to the concept of *fining down the transport path*. This means that, where a current flows over a sediment source, the mean particle size of transported sediment decreases from the source. Bedload and suspended load effects inherently cause the finer fractions to be transported farther, leading to the gradation of sediments.

2.4 MARINE PROCESSES AND WEATHER

Marine processes affect an estuary in a number of different ways. The most obvious phenomena are those which are immediately visible, namely the waves at the surface of the sea and tidal variations. Marine sediment is moved by the associated forces, but there are also other relevant processes which are less obvious and which are responsible for moving sediment over very different time scales.

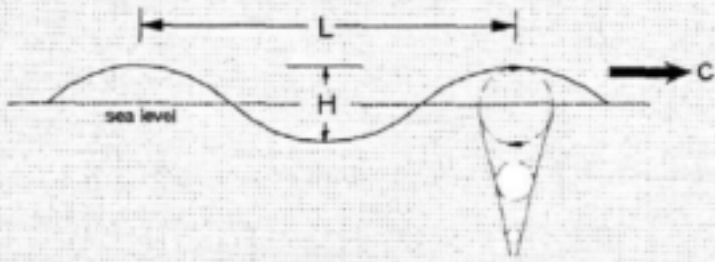
These processes are described below, with an outline of their possible impact on marine sedimentation in estuaries.

2.4.1 Surface gravity waves

These waves occur at the surface of the sea, and depend on gravity as the restoring force (Box 2.4). The period of surface gravity waves varies from less than a second up to about 20 seconds, with the corresponding wavelengths varying from about 0.02 m to more than 500 m.

Wind is the primary generator of these waves, and the stronger the wind the longer and higher the waves. However, the size of the waves can also be limited by the distance over which the wind blows (the *fetch*), and the duration of the wind. Waves can travel many thousands of kilometres from a generating storm, eventually reaching land as smooth, long-crested *swell*. Local winds tend to generate a shorter-period choppy *sea*.

Box 2.4 **Wave Parameters**

Wave Height	H	
Wavelength	L	
Wave Period	T	
Wave Frequency	$1/T$	
Wave Steepness	H/L	

Wave Speed: $c = L/T$

The wave period **T** is the time taken for one wavelength to move past a stationary observer, e.g. the time from one crest to the next.

Waves transport **energy** from a source region to an eventual destination. The disturbance is propagated through the water without any substantial loss of energy or overall motion of the water itself, i.e. when the wave is past, the water returns to its former position.

In deep water the orbital motion of water particles is in the form of a circle under the wave profile, with the size of the circle decreasing with depth. At a depth of $L/2$ the motion is about 4% of that at the surface. In shallower water, the motion is deformed into an ellipse, with a backward and forward movement at the bottom.

Most swells reaching the coast of South Africa have their origins in the Southern Ocean, approaching the continent from a southwesterly direction. The increased influence of extreme weather conditions in the winter months means that high wave conditions are generally more frequent in winter than in summer (Roşsouw, 1984).

When waves move into shallow water, they react with the bottom and the associated orbital velocities have the potential to move sediment. As soon as the bottom velocities exceed the critical shear stress sediment starts to move. The maximum orbital velocities are related to wave height and period, whereas the movement of sediment depends on grain size, shape and density; the shear stress is also greater for short period waves because of the rapidly changing velocities at the seabed. The effect of waves can be felt at a considerable depths, and large storm waves can move sediment in depths exceeding 100m.

Beaches are the most visible marine sedimentary deposits but are seldom in an equilibrium state, as they come under the influence of continually varying wave fields (§2.4.2). An estuary mouth situated in a section of beach is affected by this sediment movement, particularly if the accretion of sediment leads to mouth closure. Recent investigations of the closure of selected South African estuaries have indicated that the wave-driven on-and-offshore movement of sediment is the primary mechanism for mouth closure. Differences in wave climate, sediment sizes, beach slopes and the presence of rocky headlands or outcrops lead to different mouth closure conditions. Thus the Great Brak Estuary can remain open under river discharges as low as $0.4 \text{ m}^3 \text{ s}^{-1}$, whereas the Mgeni Estuary has been known to close when river discharges are as high as $10 \text{ m}^3 \text{ s}^{-1}$ (§3.4.2).

Surface gravity waves are also responsible for changes in sea level at the shore, through the process of *wave setup*. Here the wave momentum effectively pushes water towards the shore, and under high wave conditions the sea level can increase by more than 0.1 m.

2.4.2 Marine Sediment Movement by Waves

The wave field impinging on a coastline varies substantially in time and position. Large waves with a range of periods can be generated by winds, and will have a dramatically different effect on sand movement compared to the calm conditions which may follow some days later. Seasonal changes have longer-term effects, and differences in the width of the beach at the Great Brak Estuary of up to 100 m have been observed between summer and winter. These variations can have major implications for the stability of an estuary mouth.

There are two ways in which waves move marine sediment, namely on and offshore, and alongshore. These will be described separately below.

2.4.2.1 On and Offshore Movement of Sediment

Small, gentle waves and regular swell tend to build up beaches by bringing sand onshore, whereas storm waves erode and flatten beaches by moving sand offshore.

The wave orbital velocities are responsible for moving the sediment. Waves change shape in shallow

water, acquiring sharper peaks and longer, shallower troughs. As a consequence, the onshore velocities are stronger though lasting for a shorter period, and the offshore velocities are weaker, but last longer. In the same way that flood-tidal currents move sediment preferentially into an estuary (see §2.5), so regular, moderate waves will move sediment onshore.

In contrast, storm waves tend to be much higher and steeper than swells, and comprise a much broader spectrum of periods. Consequently the offshore orbital velocities are strong enough to move sediment offshore, and since they last longer there is a net offshore transport. Moreover, waves arrive much more frequently and large volumes of water are thrown onto the beach face on a continuous basis and erosion occurs, particularly at the base of the beach face. As sediment is put into suspension and moved offshore, so erosion of the beach face continues farther.

Wave currents decrease in the deeper water offshore, and consequently the sand eroded from a beach during a storm is deposited in an offshore sand bar. The smaller waves following the storm then serve to bring this sand back to shore, provided it hasn't been moved too far away. Occasional extreme storm events may erode a beach to the extent that it may take years to recover. Such on and offshore movement of sand is a normal feature of beaches.

Beaches tend to be eroded more in winter when winds are stronger and waves bigger. However, this is not the case for the western sections of the large bays along the South African south coast because of a greater percentage of easterly winds in summer.

The resulting beach profile depends on the waves as well as the sand grain sizes. When a wave breaks sediment is pushed up the beach by the swash, and is dragged down again by the backwash. Due to percolation into the beach face, the backwash tends to be weaker, leading to a net onshore movement of sediment and the slope becomes steeper until an equilibrium is reached. Greater percolation occurs with greater sand grain size, which leads to coarser beaches being steeper. The water table level will also affect the extent to which percolation occurs.

2.4.2.2 Longshore Sediment Drift

Depending on their origin, wave crests can approach a coast at a range of angles. The process of *wave refraction* will serve to orientate these crests more nearly parallel to the coast, but nevertheless in most cases the crests will not be entirely parallel to the local shoreline. Consequently a component of wave momentum lies parallel to the coast, and drives a longshore current (Figure 2.9).

The longshore current lies within the surf zone, with typical speeds between 0.3 and 1 m/s. The actual position of the peak current depends on the conditions, e.g. for spilling breakers the maximum longshore current velocity occurs inside the breakers, whereas for plunging breakers it occurs at the breaker line. The longshore current itself can transport sediment, but it is also in the surf zone that the turbulence caused by breaking waves and surf lifts sediment into suspension, and this is then carried alongshore as suspended load.

Further movement of sediment occurs on the beach face. Thus the swash from a wave approaching a shore obliquely moves up the beach face at an angle, carrying sediment with it. However, the backwash then flows straight down the beach face, again carrying associated sediment with it. The continual

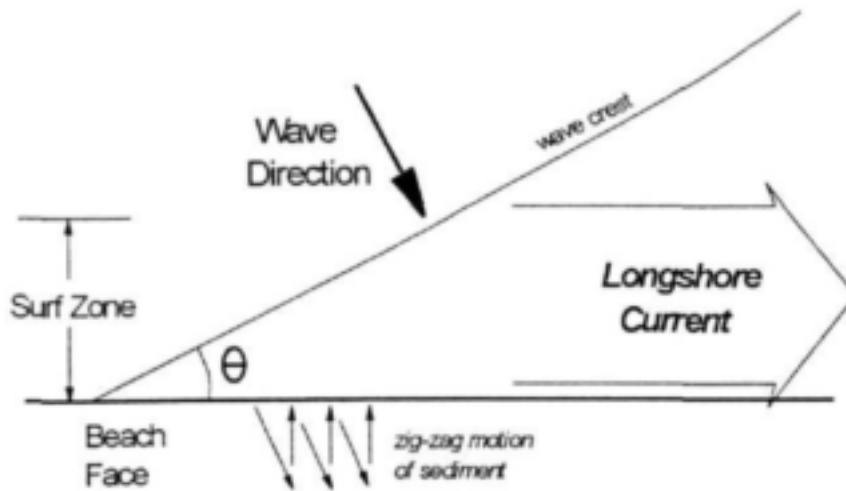


Figure 2.9 Oblique wave approach to a beach, and the resultant components of sediment transport. The longshore current moves sediment within the surf zone, while the swash of waves on the beach face also moves sediment in a zig-zag motion.

succession of such wave swash action moves sand in a zig-zag motion on the beach face in the same direction as the longshore current in the surf zone (Figure 2.9).

In most situations the longshore current is the dominant transporter of sediment, with the zig-zag motion of sediment on the beach face making up less than 20%. However, on steep-faced beaches where there is limited energy dissipated in the surf zone, transport by swash and backwash can be more important than by longshore currents.

It has been found in practice that the potential rate of sediment transport (q) depends on the wave energy, which is proportional to H^2 , the angle at which waves approach the shore (θ), and the density of the water (ρ) and that of the sediment (ρ_s). This can be expressed as

$$q \propto \left(\frac{\rho}{\rho_s - \rho} \right) H^2 \sin\theta \cos\theta \quad (2.4)$$

The actual volume of sediment moved depends on the sediment actually being available. Nonetheless, the resultant longshore transport of sediment can be substantial, e.g. along sections of the KwaZulu-Natal coast it is estimated to be between 500 000 m³ and 800 000 m³ per annum.

Other wave-driven phenomena may impact locally on this average longshore transport of sediment. In particular, rip currents are strong, narrow currents with speeds up to 4m/s which flow seawards from the surf zone. They form part of cell-like circulation structures which can locally move sediment offshore.

Note that a beach is not necessary for the alongshore movement of sediment. Thus sediment can be moved in deeper water offshore, and can for instance be moved along a coast at the base of a cliff, or a rock sill. On the East London coast substantial volumes of sand move alongshore in the surf zone of wave-cut platforms cut into bedrock. These platforms may have a thin veneer of sand along their upper fringes to form ephemeral beaches.

2.4.3 Shoreline Morphodynamics

Coastal geomorphology has already been discussed in §2.2, and in this section the consequences of sediment movement on coastal landforms will be described. This can broadly be described as shoreline morphodynamics, and is necessary in order to understand the processes operating on estuary mouths.

Beaches tend to build up transverse to the direction of the most important beach constructing waves. Headlands of a more erosion-resistant rock are often interspersed with beaches, and the orientation of the resulting bays is an excellent indicator of the direction of net sediment movement along the coast (§2.2.3).

Movement of sediment driven by wave-induced longshore currents can be blocked by a headland. On the other hand, if the headland is not too acute, sediment can be taken around by refracted waves, while it can also be transmitted through the succeeding bay by longer period swell that does not undergo appreciable refraction or diffraction. It means that a headland is not necessarily a blockage point for the movement of sediment along a coast; it can also be moved across the headland by the wind in a by-pass dunefield (§2.2.4).

Prominent headlands on the south coast of South Africa, e.g. Cape Recife and Cape St Francis, form the large associated bays to their north, in these cases Algoa Bay and St. Francis Bay. Waves from the southwest are refracted around the capes and erosion has taken place so that the orientation of the local shoreline in the bays is approximately parallel with the wave crests. At the downcoast extremity of the bay the headland has no effect, and the beach orientation is approximately normal to the average oceanic wave direction. The bays that form as a result of the existence of headlands have been called a variety of names in the literature, such as zeta bays, halfheart bays, crenulate-shaped bays, log-spiral bays, spiral beaches, curved or hooked beaches, headland bay beaches or pocket beaches.

The stability of the resulting shoreline can be assessed in terms of beach erosion or accretion and longshore currents. Essentially, if waves break simultaneously around the periphery of a bay it is a confirmation of a stable situation, though sediment can move through such systems. Moreover, it is important to realise that **the direction of sediment movement can change with season along different sections of coast**. Changes can also result from man-made developments in altering the defining characteristics of such bays. Typical structures are extensions of headlands (e.g. to form a breakwater), or construction of groynes.

Tidal inlets form the exchange routes with the adjacent ocean for systems such as estuaries and harbours; these are discussed in greater detail in §2.5. They serve to disrupt the direct longshore transport of sediment. A certain amount of the transport may become incorporated into the flood and ebb-tidal deltas of the inlet structures, while some sediment may traverse the inlet (Figure 2.3). This movement can occur in two ways, firstly individual sediment grains may by-pass via the channels or along the shoal margins. Secondly, large masses of sediment may migrate downdrift by channel-switching. The mobility of the inlet is then related to the by-passing ability of the sediment. If all the sediment arriving at the updrift side can be bypassed successfully, then the position of the inlet will be stable. If bypassing cannot handle the volume of sediment delivered, then updrift accumulation will occur in the form of a spit and the mouth will migrate downdrift. If the bypassing is over-efficient then

the updrift side will erode and sediment accumulating on the downdrift side will cause the inlet to migrate updrift.

2.4.4 Tides

Tides are caused by the gravitational attractions between the earth, moon and sun, and their resultant orbital motions. Using planetary values, it can be shown that the direct gravitational attraction of the sun at the surface of the earth is about 177 times that of the moon, but at the surface of the earth this is actually negligible compared to the Earth's own gravity.

Tidal forces associated with both the moon and the sun therefore originate from imbalances between their gravitational and centrifugal forces at any point on the surface of the earth; these tide-producing forces vary with latitude. It is the resultant horizontal components of these forces which act to cause the tides observed in the world's oceans, and in this situation the tidal force of the moon is almost twice that of the sun.

Precisely-determined periodicities are associated with the planetary motions, and the resulting tides therefore also have very specific periods. The moon revolves around the earth in the same direction as the earth rotates on its own axis, and this means that the time the moon is directly overhead increases by approximately 50 minutes each day, giving a period of 24hr 50min. However, because the force imbalances occur on both the side of the earth facing the moon or sun and on its opposite side, the observed period is halved, i.e. 12hr 25min. Correspondingly, the resulting tides occur approximately twice per day, and they are therefore *semidiurnal*.

This is the dominant tidal component, and is called the principal lunar M_2 component. Tidal forcing occurs at a whole range of other periods, associated with aspects such as the moon and sun's declination and elliptical orbits. Other major components are listed in Table 2.1

The tide-producing forces of the sun and the moon also interact in producing *spring* and *neap* tides. Thus spring tides occur at new and full moon, when the tide-producing forces of the moon and the sun combine, while neap tides occur at first and third quarter, when the forces oppose each other. The period, or time between two consecutive spring tides, is approximately two weeks.

The ocean does not respond directly or uniformly to the tidal forcing from the various tidal components. Instead, each ocean or sea has its own characteristics - latitude, depth, shelf widths, coastline shape etc. - and therefore responds in different ways to the regular forcing that comes from each of the tidal components. The response generally occurs in the form of Kelvin waves (§2.4.5) propagating in the southern (northern) hemisphere with the coast on the left (right) in the direction of propagation. Consequently Kelvin waves propagate around an ocean basin in the component period, e.g. in 12.42 hours for the M_2 component, while there is an amphidromic point in the centre region where no tidal variations occur. For the M_2 tide there is an amphidromic point south of Africa, and tides therefore propagate from west to east along the coast, with the tidal phase at Cape Town leading that at Port Elizabeth by about 20 minutes.

Name of Tidal Component	Symbol	Period (hours)	Relative amplitude
Principal lunar	M_2	12.42	100
Principal solar	S_2	12.00	46.6
Larger lunar elliptic	N_2	12.66	19.2
Luni-solar semi-diurnal	K_2	11.97	12.7
Luni-solar diurnal	K_1	23.93	58.4
Principal lunar diurnal	O_1	25.82	41.5
Principal solar diurnal	P_1	24.07	19.4
Lunar fortnightly	M_1	327.86	17.2
Lunar monthly	M_m	661.30	9.1

Table 2.1 The major tidal components. The theoretical amplitude is determined relative to the dominant M_2 tide, but actual responses depend on the locality considered.

In practice, the responses at all the different periods determines what the total resulting tides will be at any one place. These responses are generally mixed, ranging from semidiurnal tides to diurnal tides, and often varying over spring and neap tides. South African tides are dominantly semidiurnal, but with a diurnal inequality (see Figure 2.13).

Tidal amplitudes around the world vary from a few centimetre to a maximum of over 15 m in the Bay of Fundy in North America. They are roughly classified by their spring tidal ranges into the following categories:

- Microtidal: less than 2m
- Mesotidal: 2 to 4 m
- Macrotidal: Greater than 4m.

Microtidal and mesotidal ranges are generally found on the open coasts of the world's ocean as well as the landlocked seas such as the Mediterranean, Black and Red Seas. Macrotidal ranges are found locally in gulfs and embayments along coasts. Tides around the South African coast can be classified as semidiurnal microtides (amplitudes < 2m), although at times the spring tidal amplitudes are greater than 2m, which would place them at the transition between the micro- and mesotidal regimes.

2.4.5 Coastal Trapped Waves

The effects of this class of waves are generally not immediately evident to an observer on a beach, in particular because they have periods longer than surface gravity waves (§2.4.1). Nonetheless, they are apparent in measurements made in the surf zone, and can have substantial effects on beach morphology and sediment movement. Beach cusps are typical consequences of the effects of some of these waves.

The first of these waves to be considered are *edge waves*. Here the periods are derived from the field of surface gravity waves present at the time, e.g. they can originate in the groupiness of two or more incident wave trains, or they may be subharmonics (e.g. twice the period) of one wave train. Other

means of generation of edge waves have also been reported, e.g. Shillington (1984) described edge waves along the South African coast originating from pulses in air pressure: these had periods between 30 minutes and 1 hour and amplitudes up to 0.6 m. Typical edge wave periods vary in the range from seconds to hours.

Edge waves depend on reflection from the beach face, generally with an oblique wave approach. The trapping mechanism can be envisaged from the concept of wave refraction, namely that waves in deeper water travel faster. Thus on a shoaling coastal profile a wave moving obliquely offshore will refract around until it is again moving towards the coast, i.e. it is effectively trapped against the coast. The amplitude of such trapped waves is greatest at the coast, and decreases exponentially offshore.

At longer periods the effects of the earth's rotation become important - incorporating the so-called Coriolis force. Those waves where both gravity and Coriolis force are significant include *Kelvin waves*, which are typically the manner in which tides propagate (§2.4.5). At even longer periods rotational effects dominate, and variations in bottom bathymetry associated with the Coriolis force result in *shelf waves*. In all these cases the waves travel with the crests perpendicular to the coast, with a maximum amplitude at the coast and an exponential decrease offshore. The direction of propagation is also fixed, and in the southern (northern) hemisphere the coast lies to the left (right) in the direction of propagation. As an example, on the South African coast the waves travel from Cape Town to Port Elizabeth.

Shelf waves are generated primarily by the longshore component of wind stress, and therefore have periods lying in the weather band, i.e. from about 2 to 10 days. On most coastlines of the world their impact is relatively minor, and shelf waves amplitudes vary around 0.1 m. However, along the South African south coast a condition of near-resonance between moving wind systems and characteristic shelf waves speeds leads to much higher amplitudes (Schumann and Brink, 1990).

2.4.6 Weather

Rainfall in the catchments of rivers provides the freshwater input for estuaries. As already indicated (Tyson, 1986), South Africa is predominantly a semi-arid country, with only the eastern and southern sectors receiving appreciable annual rainfall totals (Figure 2.10a). The 40 cm isohyet divides South Africa into wetter eastern and drier western halves, with over 100 cm in some eastern areas, and almost complete aridity in places in the west.

However, rainfall is particularly erratic, and is also highly seasonal (Figure 2.10b). More than 80% of the rainfall in the north occurs in summer, while in the southern part of the Western Cape the situation is reversed with over 80% of the rain falling in winter. The narrow southern Cape coastal belt is a transition region, with rain falling more uniformly throughout the year; in parts of the southern Eastern Cape peak rainfalls tend to occur in autumn and spring.

Incident solar radiation (insolation) is important for estuaries since it determines air and water temperatures, and consequently also the extent to which evaporation that occurs. Clouds reflect insolation, and there is therefore also a marked seasonal variation in evaporation associated with the

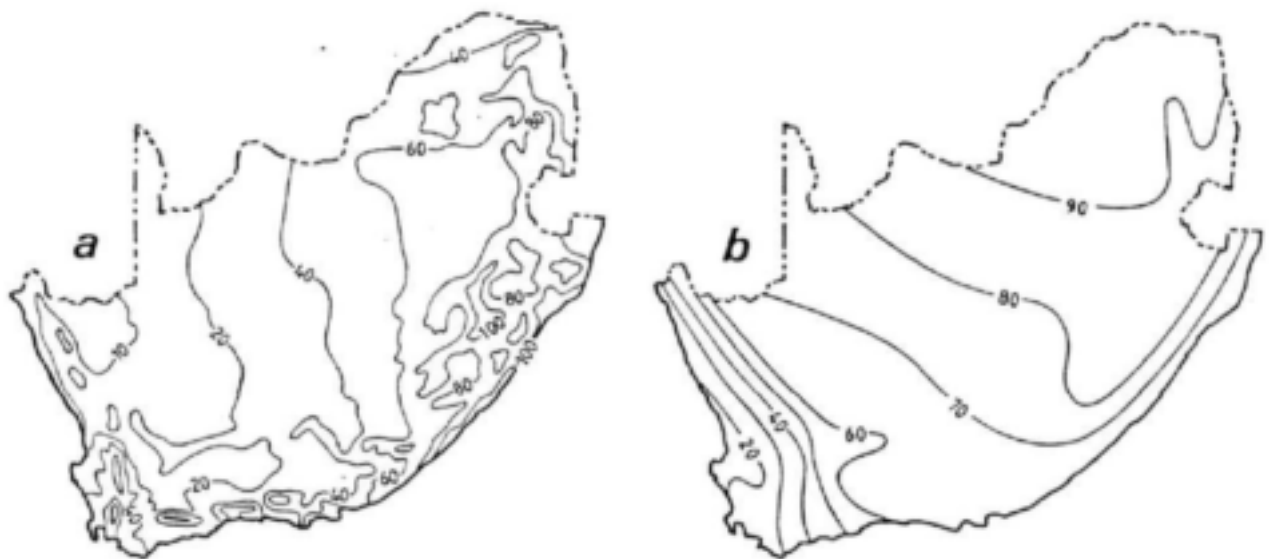
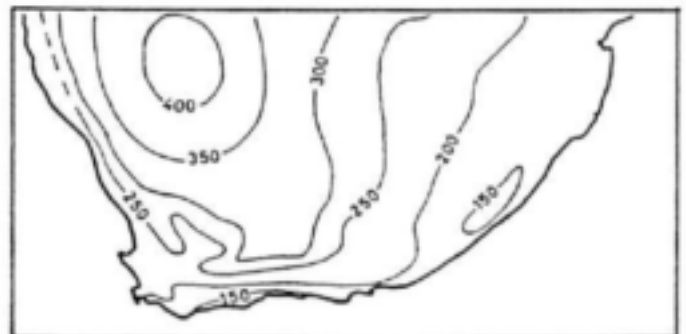


Figure 2.10 (a) Mean annual rainfall for South Africa (isohyets are given in cm).
 (b) Seasonal rainfall over South Africa, with the summer rainfall (October to March) given as a percentage of the annual rainfall (from Schulze, 1984).

seasonal rainfall. shows The highest average annual evaporation occurs in the west of the country (Figure 2.10c), particularly in the dry season and during the often prolonged droughts that occur there. Rainfall, with evaporation, to a large extent determines the average freshwater runoff into catchments and therefore also into estuaries.

Figure 2.11 Average annual evaporation contours (in cm) from Class 'A' pans over southern Africa (from Schulze, 1984).



The rainfall statistics (Figure 2.10) do not present the full picture, and rainfall is a highly variable quantity, particularly over the dry western parts (Tyson, 1986). In general, percentage variability is least in the season of greatest rainfall and in areas of highest rainfall. On longer time scales, periods of above average rainfall and droughts follow one another, and Tyson (1986) has identified 18 year oscillations in the northeastern regions, while a 10 to 12 year oscillation was evident in the south. With the probability of climatic changes, the forecasts are that the intensity of droughts and wetter periods will intensify.

Floods are important in scouring out accumulated sediments in estuaries (§2.2.3). The intensity of the floods has decreased because dams have been built in catchment areas of rivers, and a 1-in-20-year flood may now only have the same impact as a previous 1-in-10-year flood. Nonetheless, an extreme event may have more catastrophic consequences, since after filling dams the constrictions caused by

developments and extensive sediment accumulation may result in extensive flooding before the sediment is removed and old channels are re-established.

Winds have been shown to be important in moving sediment (§2.2.4), as well as in the generation of surface gravity waves (§2.4.1). Around South Africa, the coastal winds are generally the result of the large-scale circulation systems both in the tropics to the north and the temperate latitudes to the south. In addition, smaller-scale systems such as coastal lows play an important part in localised weather patterns. Land and sea breezes, caused by differential heating of land and sea, vary seasonally, and can also be important locally.

Around South Africa the dominant winds blow approximately parallel to the general trend of the coastline. There are marked seasonal variations, and at Cape Town around 80% of the summer winds blow from the southeast, with over 60% of the winter winds from the northeast. Off Port Elizabeth the dominant winds throughout the year blow from the west-southwest, though in summer almost 50% are from the east-northeast; of interest is that the variability is greater in the east. Off Durban there is little seasonal variability in direction. At all the sites strongest winds occur in October/November, with the calmest periods in June (Schumann and Martin, 1991).

Barometric pressure can also have a direct effect on sea level. The *inverse barometer rule* states that a 0.01 m change in water level will be caused by a 1 hPa change in air pressure, i.e. water level will go up 0.01 m for a decrease in air pressure of 1 hPa, and vice versa. However, this must be seen in relation to the presiding air pressure systems, and whether equilibrium has been reached. In general, for the South African situation air pressure will not directly change sea level by more than a few cm.

2.5 ESTUARY-MOUTH PROCESSES AND HYDRODYNAMICS

2.5.1 Flood-Dominant Estuaries

Most estuary-mouth channels on South Africa's wave-dominated coast are constricted by wave-deposited sand (§ 2.2.3), and a constricted estuary mouth modifies the ocean tide as it moves into and out of an estuary. As a result the estuarine tide has markedly different qualities from its oceanic counterpart (Figure 2.12). The cross-sectional area of a constricted estuary mouth is very small at low tide, significantly retarding ebb-tidal flow owing to high frictional drag. At high tide the channel cross-sectional area is considerably larger, and the flow encounters much less drag during the flooding high tide than during the ebbing low tide. The resultant tidal curve in the estuary is significantly asymmetric, exhibiting a long, slow ebb and a brief, fast-flowing flood tide.

In mathematical terms, estuary mouth processes generate an overtide at half the M_2 period, i.e. the so-called M_4 tide with a period of 6.21 hours. Superposition of the M_2 and M_4 tides at the correct phase leads to the tidal profiles shown in Figure 2.12 (Schumann *et al.*, 1999).

Since bedload sediment transport varies as the cube of the current speed (Equation 2.2) and sediment suspension also increases with current speed (Figure 2.8), the faster-flowing flood tide transports more sediment per unit time than the more sluggish ebb tide. In general, even though the ebb tide lasts for

a longer time (Figure 2.12) the greater speed of the flood tide ensures that more sediment is transported into the estuary than out of it; such estuaries experience a flood-dominant sediment transport.

Shorter period waves can also contribute to this net influx of sediment. Thus the inflowing flood tidal currents allow surface gravity waves to penetrate into the estuary, and the additional orbital velocities serve to put further sediment into suspension and be transported landwards. On the other hand, the outflowing ebb tide inhibits the penetration of such ocean waves into the estuary, and this means that less sediment is put into suspension for transport seawards with the ebb flow.

Slightly longer period waves, such as edge waves, penetrate the mouth constriction even more effectively than surface gravity waves, particularly at flood tides. These waves pass through the estuary mouth in pulses dictated by the parent gravity waves (§ 2.4.4), and can be observed as spikes on

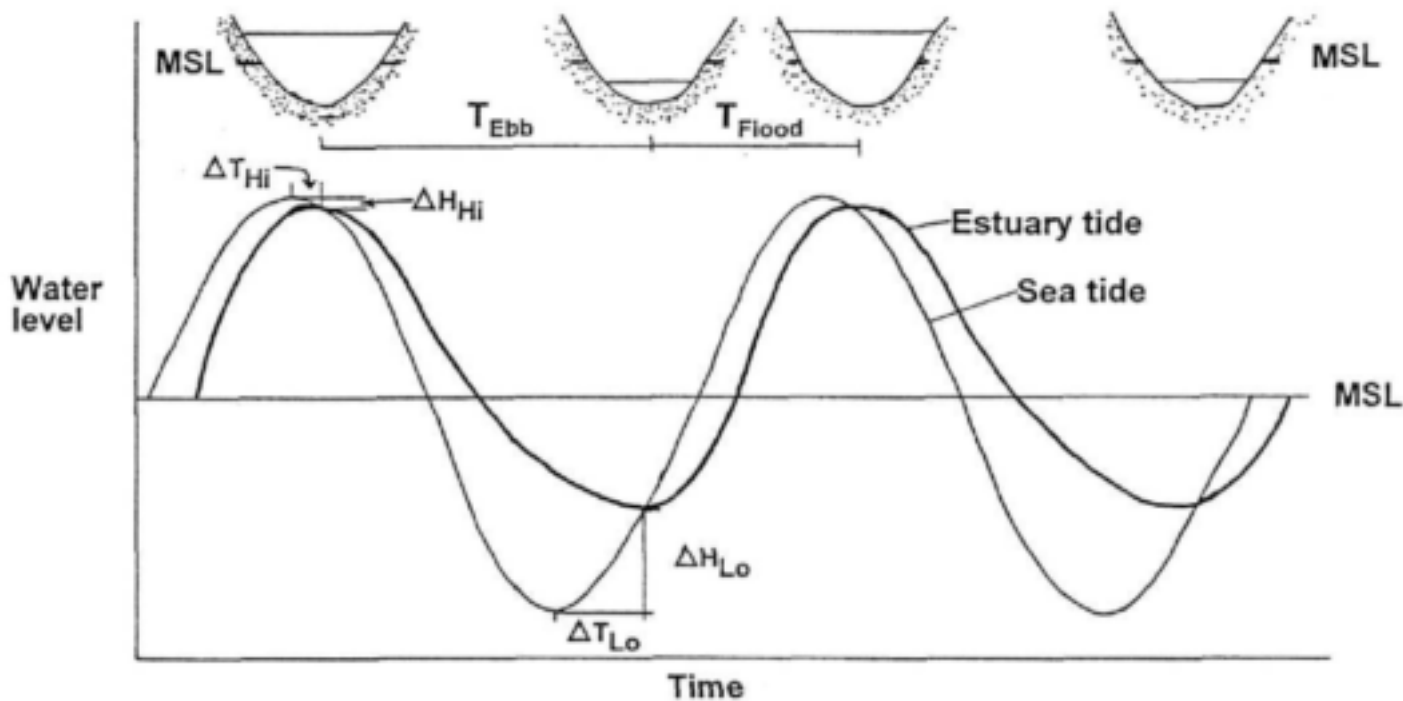


Figure 2.12 The effects of a constricted estuary mouth on the tide in an estuary (winds and waves are not considered). As the sinusoidal ocean tide rhythmically rises and falls, the cross-sectional area of the constricted mouth changes dramatically; this is illustrated at the top of the diagram. At high tide the cross-sectional area of the mouth channel is large, allowing a comparatively free exchange of water, resulting in a short tidal lag time (ΔT_{Hi}) and a small elevation difference (ΔH_{Hi}) between the sea and the estuary. As the tide falls, the channel cross section gradually becomes smaller, exerting progressively more drag on the water flowing out through the mouth. Consequently the estuarine ebb tide is still active when the sea tide has already reached ebb and has in fact turned into the next rising tide. At a certain stage the water levels are the same, and after a very brief estuarine slack ebb tide the estuary tide rises. A considerable lag time (ΔT_{Lo}) and elevation difference (ΔH_{Lo}) occur at low tide. After slack tide in the estuary, the channel cross-sectional area quickly increases owing to the rapidly rising sea tide so that the water level in the estuary also rises rapidly. The total time taken for the estuary tide to ebb (T_{Ebb}) is longer than the time to flood (T_{Flood}). If the effects of freshwater inflow on the estuarine tide are ignored the same volume of water enters the estuary during T_{Flood} as leaves during T_{Ebb} , and the flood tide has to flow faster than the ebb tide. (After Reddering and Rust, 1997)

unfiltered water level records. Edge waves themselves are likely to have stronger forward currents than backwards currents and will also contribute to a net influx of sediment.

In this flood-dominated environment the flood tidal currents therefore transport more sediment into the estuary than that removed by the less vigorous ebb tidal currents. This current velocity asymmetry causes the characteristic sand body distribution typical of the estuaries along the South African coast - the flood tidal deltas (§2.6). In the mouth channel the fastest flowing currents occur at low tide but mouth deposits seldom display a net ebb dominance.

Figure 2.12 demonstrates these estuary mouth processes. Note that the areas under the flood and ebb curves are equal, signifying that equal volumes of water enter and leave the estuary through the estuary mouth over one tidal cycle (this equality ignores the inflow of fresh water at the tidal head of the estuary). The volume of water exchanged over a tidal cycle is called the *tidal prism*, and varies with the tidal amplitude. Longer-period coastal trapped waves will also alter the prism, since they can change the vertical position of the tidal range and hence flood different areas of the estuary.

In the estuary, tidal currents very commonly segregate into zones dominated by either ebb-directed or flood-directed currents (Van Veen, 1950). Subtidal channels usually segregate into ebb and flood sectors, but a dominance in one direction normally prevails. Flood tides commonly dominate on intertidal areas because the water level drops below the level of the sand flats before the ebb currents reach a velocity capable of transporting sand. Therefore ebb currents concentrate themselves in the deeper ebb-dominant sections of the mouth channel complex, whereas flood currents flow in shallower flood-dominant sectors.

2.5.2 Water Level Variations in the Bushmans Estuary

As an example of tidal and longer-period sea level variations and their impact on an estuary, records taken in the Bushmans Estuary and Port Elizabeth harbour are shown in Figure 2.13. The latter record can be taken to be approximately the same as the sea off the Bushmans Estuary, since past records indicate a delay of less than 10 minutes between the two.

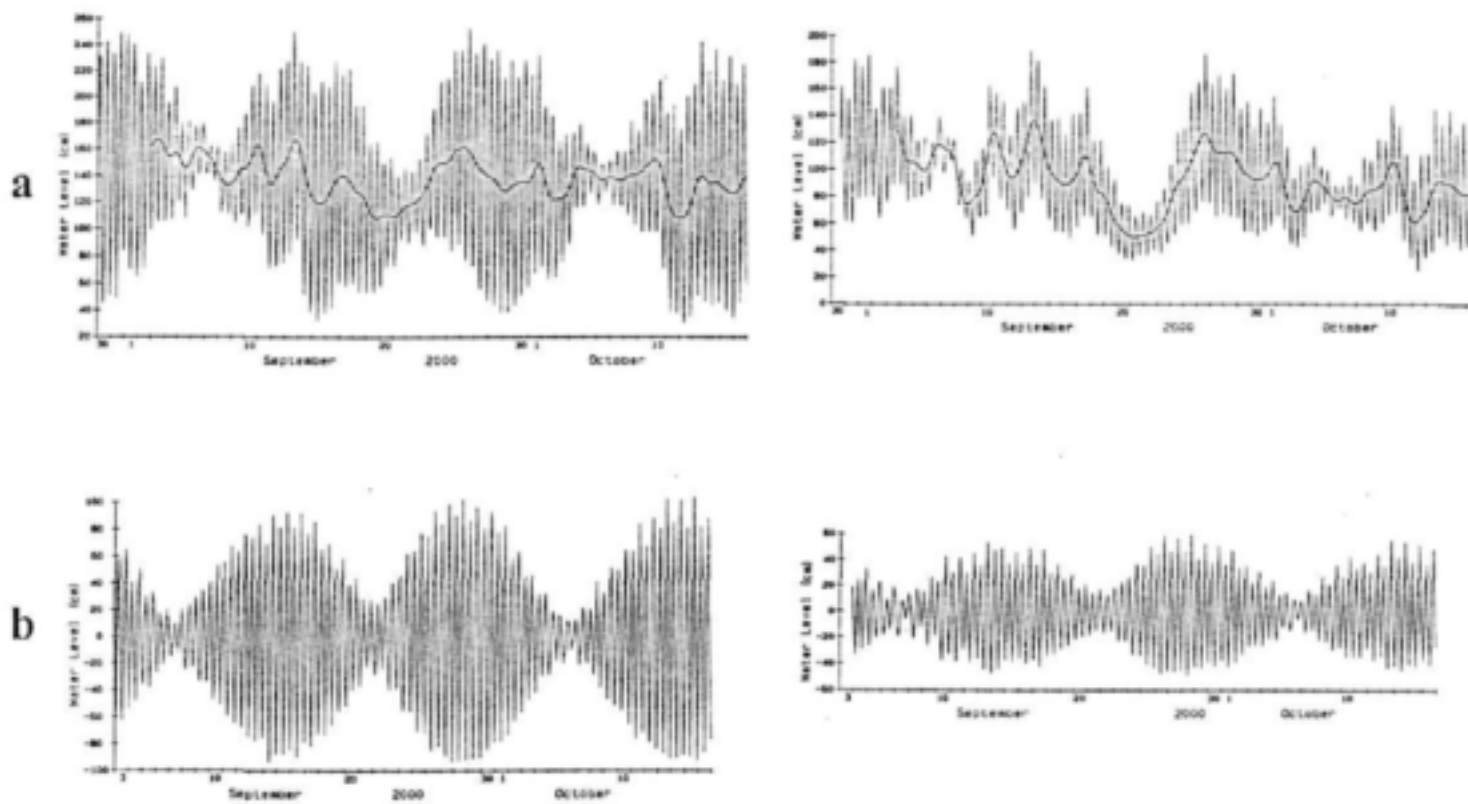
Figure 2.13 shows the actual measurements made at the two sites during September and October, 2000, as well as filtered and longer-period fluctuations. It is clear that substantial water level variations occurred during this period, with the regular tidal oscillations modified by the longer period changes.

The effect of longer period fluctuations can be substantial, and Figure 2.13a shows that on 8 September the high tide water level in the Bushmans Estuary was actually lower than the low tide water level on the previous day. Such fluctuations originate in the sea, and are probably driven by weather events, in particular the longshore component of the wind (§2.4.5). It can be expected that shorter-period water-level fluctuations will be restricted to a greater extent within an estuary, but it is interesting to note that the longer-period fluctuations appear to be amplified in the Bushmans Estuary.

Figure 2.13b shows the tidal variations at the two sites with the longer-period fluctuations removed. The constrictions in the estuary mouth reduced the tidal amplitude, with maximum tidal heights of almost 2 m in the sea, and less than 1 m in the estuary. The spring-neap tidal cycle is clearly evident,

Port Elizabeth Harbour

Bushmans Estuary



Spring Tide

Neap Tide

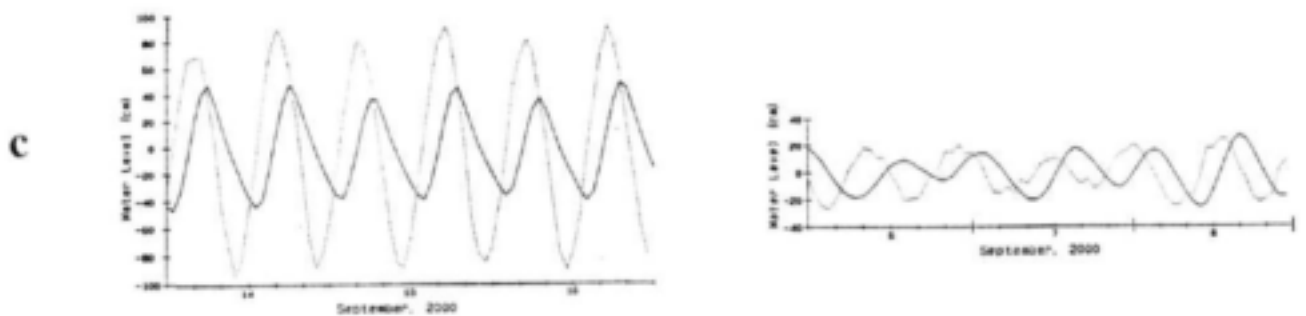


Figure 2.13 Water level measurements at the Port Elizabeth harbour and at the marina in the Bushmans Estuary. (a) shows the raw readings with the long-period variation superimposed as a darker solid line, (b) the tidal oscillation only, and (c) more detailed tidal oscillations at spring and neap tides, with the light dotted line representing the harbour and the solid dark line the estuary. Note that the relative levels are arbitrary.

while there is also a diurnal inequality in the dominantly semidiurnal tidal signal. An approximately 14-day signal is apparent in the alternating neap tides.

Figure 2.13c depicts the tidal variations in greater detail, with the left hand graph covering the spring tide period and the right hand graph the neap tide period. In both cases the tidal asymmetry is evident in the estuary, with the flood tide taking something like 5 hours, and the ebb tide about 7.4 hours. It is clear that the estuary mouth constriction inhibits water exchange at spring tides to a much greater extent than at neap tides, since the neap amplitudes in the sea and estuary are very similar: this is because the constriction does not allow sufficient water through at spring tides.

2.6 ESTUARINE SEDIMENTATION-EROSION CYCLES

Estuaries receive sediment from two main sources, namely the sea and from river catchment areas. Marine-derived sediment, the subject of this report, consists mainly of beach and wind-blown dune sand. In some exceptional cases marine sediment may enter an estuary via an indirect route or by local sheet wash. In the Kromme Estuary, for example, marine-derived sediment enters the middle estuary via a small river, but such situations are rare. Many environmental factors influence the extent to which sediment from different sources accumulate in estuaries. Similarly, a number of factors influence the way in which natural erosion scours accumulated sediment from estuaries. In general, sedimentation and erosion take place in cycles, processes that have been operating since the formation of the post-Gondwana coast of what is now South Africa during the Early Cretaceous Period, 135 million years ago.

The *longer-term cycles* involve the global changes in sea level, mostly by glacially induced transfer of water from the sea to land and the reverse process during glacial retreat. Longer-term cycles are important in two respects. Some estuarine systems have not yet filled to capacity with sediment since the last rise of sea level about 10 000 years ago, and these systems behave differently to others where a sedimentation-erosion equilibrium exists for present-day sea level (§ 2.2.2). In the immature Knysna estuary and a few other similar systems which have not yet filled to capacity with sediment, the erosion base (Box 2.1) lies well above the sandy estuary floor. River floods cause little or no erosion in such a system, and the management of sedimentary challenges requires a fundamentally different approach.

The second, more general respect in which global sea-level changes are of interest is that the biota which have evolved into this system of long-term fluctuation in sea level since the beginning of the Cainozoic (65 million years ago) are robust. The little palaeo-ecology carried out on these populations shows remarkably little variation in the estuarine populations despite at least five major fluctuations in global sea level since the Pleistocene, 1,6 million years ago.

The *medium-term sedimentation and erosion cycle* in estuaries is more readily recognized, and is more directly responsible for the sedimentation challenges facing present-day estuaries: these cycles take place at constant sea level on a time scale that varies between ten and 1 000 years. Erosion is typically an event caused by a high-discharge flood, the scour of which removes sediment to the depth of a temporary erosion base dictated by the depth to which turbulence effectively acts on the sediment

bottom. This erosion base lies at a level below that of the calm-weather erosion base. Estuaries are therefore natural sediment traps during periods of relatively subdued tide-dominated flow.

In the classification of Dalrymple *et al.* (1992), estuaries have a tripartite division of sedimentary transport energy. River processes prevail near the head of an estuary and decrease seaward. Marine processes (tides and waves) dominate the area near the tidal mouth but diminish up-estuary. In the middle estuary relatively low levels of both tidal and river processes prevail. The model of Dalrymple *et al.* (1992) really applies to immature estuaries, but can be applied in the fairweather, tide-dominated facies of most South African estuaries. It excludes river-dominated systems where river processes prevail throughout the system into the mouth areas.

In response to this tripartite division, sedimentation typically takes place in three estuarine facies. At the tidal head, the change in gradient from the sloping river channel to the almost horizontal tidal level in the estuary causes river-derived sediment to accumulate there. This sediment consists of river sand or gravel depending on detailed source conditions in the river environment. The river-deposited sediment facies accumulates on seaward-growing sediment bodies collectively termed the bay-head deltas.

Marine sediment enters at the tidal mouth of the estuary. Estuarine tides very commonly display an asymmetry of tidal current speed, and are usually flood-tide dominant (§2.5). Sediment, typically marine sand, enters the estuary and accumulates on laterally aggrading sediment bodies called flood-tidal deltas. These sand bodies typically grow landward by accretion (see below) at the delta fronts.

The third sedimentary facies lies between the bay-head and flood-tidal delta systems. This is the area where tidal mixing takes place between sea water and fresh water from land drainage. River water from most South African catchment areas carries suspended clay, and where the fresh and salt waters mix in the middle estuaries, mud flocculates and falls from suspension to accumulate in the middle estuaries. Selective transfer of flocculated mud from the turbulent to the viscous boundary layers plays an effective part in promoting rapid mud deposition during sluggish tidal flow in these middle reaches of estuaries (McCave, 1970). Estuaries therefore commonly display a pattern of coarser-grained sediment both at the head and the mouth, with a muddy zone between these extremities. This tripartite division of estuarine sedimentary facies corresponds to the tripartite depositional zones advanced by Dalrymple *et al.* (1992), and is a worldwide phenomenon.

The emphasis in this report is on the sedimentation in the seaward zone of the estuaries where marine sand accumulates on flood-tidal deltas, and where dune sand may enter the lower estuary. The facies of marine-sand deposition and mud deposition overlap in many estuaries, and the mixed sedimentary facies at the landward end of the flood-tidal deltas produces a sediment composition that causes the sediment to be more erosion-resistant than loose marine sand.

The natural, medium-term erosion-deposition cycle can be influenced by reduced river discharge, whether by natural climatic abnormalities or by artificial reduction of the natural flow (Reddering, 1988a). Such reduction in flow increases the accumulation of sediment in estuaries, including the marine sediment on flood-tidal deltas.

Migration of an estuary mouth is a relatively uncommon component of the medium term cyclicity of

estuaries. Where a barrier composed of loose sediment, usually sand, is part of the estuary-mouth system, it is possible for the estuary mouth to migrate laterally along the barrier. A number of conditions need to exist before migration will take place (Reddering 1983), but the basic process is caused by erosion of one bank of the estuary mouth and deposition at the other bank. Barriers are usually narrow across estuaries that occupy drowned river valleys. More extensive barriers are present where the estuary lies on a coastal plain, where valleys are wider and can accommodate longer barriers. Examples of such barrier systems are the Keurbooms, Gamtoos and Swartkops estuaries. Migration of the estuary mouth is a natural feature of these systems. In the case of the Swartkops estuary, migration ceased after the N2 road bridge was built 600 m from the sea during the 1960's (Reddering and Esterhuysen, 1981b).

In the case of the Keurbooms estuary the estuary mouth was situated against bedrock at the southwestern end of the barrier in the early 1900's (Reddering, 1981, 1983). At some time between 1912 and 1915 (different reports give conflicting accounts of the date), a severe flood breached a new estuary mouth at the northeastern end of the barrier after which the one at the southwestern end closed. The new mouth remained in the northeastern sector of the barrier for a long time and during the 1950's the estuary mouth started a rapid southwestward migration. It now lies 2,5 km from its immediate post-flood position of the early 1900's (Figure 2.4) and is still actively migrating towards the bedrock at the southwestern end of the barrier. Historical records and geomorphic evidence show that the Keurbooms estuary mouth has repeatedly migrated along the same route. In the process the estuarine section behind the Keurbooms barrier has become much narrower, all by deposition of marine sand along the landward edge of the back-barrier lagoon.

The Gamtoos estuary mouth (Reddering and Esterhuysen, 1984a, Reddering and Scarr, 1990a) has a tendency to migrate eastwards. In its most distal position during the 1960's the estuary mouth also tended to close. The severe flood of 1971 eroded four new, more direct routes through the dune covered barrier, up to 3 km to the west of its most distal position. All but the westernmost mouths subsequently closed. Although migration has resumed, it is slow and floods have tended to return the mouth position to its westernmost position. In this position, where the tidal channels of the lower estuary have a more direct route to sea, the estuary mouth has been permanently open. Reddering and Esterhuysen (1984a) suggested that aeolian sand deposition on the western bank of the estuary mouth driven by westerly winds has contributed to the tendency of eastward mouth migration.

The Swartvlei estuary mouth in the Western Cape Province shows evidence of having migrated in historical times, but appears to have remained stable for as long as charts of the area have existed.

In all cases but one (Swartvlei estuary) the estuary mouths tend to migrate in the direction opposite to that of the prevailing longshore drift. All the examples lie on those exceptional stretches of coast where coastal plains are developed, because that is where long barriers are able to develop.

The cumulative effects of *short-term, tidally influenced sedimentation* are produced by sediment entering the estuary from marine and catchment sources, and the flood-tidal dominance causes more sediment to enter the estuary than the ebb tides are able to scour. As a result the sediment bodies in the estuaries grow. This report concentrates on sedimentation in the marine, lower reaches of estuaries.

Development of a flood-tidal delta begins in the mouth area after a major flood has scoured the sediment bed of the estuary to a significantly greater depth than that existing before the flood (Figure 2.14). Prominent sand bodies, including a barrier, will have been removed from the estuary and the sediment swept to sea, especially where the river flood was confined between rocky valley slopes (§ 2.2.3). The channel of the tidal mouth will be deep and wide open immediately after the flood (Figure 2.15), but as soon as it has passed wave action operating on the sediment of the adjacent beaches starts a process of barrier reconstruction across the mouth. Sediment brought to the estuary by onshore bar migration and longshore drift is deposited in the mouth channel causing it to shoal.

The estuary mouth established in the newly reconstructed, post-flood barrier soon becomes constricted. Flood-tidal dominance of the estuary develops as a result of the bottleneck produced in the constricted mouth channel (§ 2.5). The net import of sand from the adjacent beach into the estuary begins as soon as this flood-tidal dominance is established. Sand entering the estuary from the sea first shoals the seaward end of the river-flood-scoured channel, and eventually a small sand body develops with its upper surface exposed during low tides. Because this sand body, called the flood-tidal delta, is shallow at high tide, flow across its surface is vigorous, especially during spring flood tides. As a result sand moves, mainly by migration of small dunes, from a sand ramp extending from the mouth channel, across the surface of the flood-tidal delta, to where the delta extends into deep water. At the edge of the flood-tidal delta the sand avalanches into the deeper water, and the continual addition of sand to this area causes the sand body to grow up-estuary by lateral extension.

Figure 2.14 *The estuarine sedimentary cycle in estuaries is reset during a high-discharge river flood (top right). Accumulated sediment is eroded from the lower estuary and transported out to sea. Within days after the flood the barrier is re-established and an estuary mouth connects the estuary with the sea. Within weeks the flood-tidal delta begins to grow (bottom right). As time passes the flood-tidal delta system grows by extending into the lower estuary (bottom left) and in time, say 10 to 20 years after the flood, may take up significantly more than half the tidal space of the lower estuary (top left). The accumulated sediment is scoured during the next high-discharge flood.*

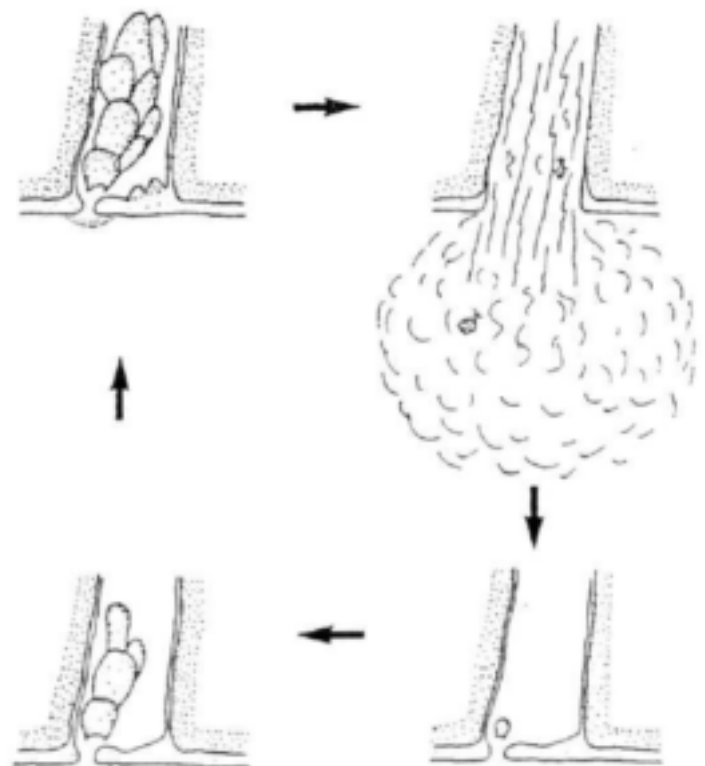




Figure 2.15 The Gamtoos estuary experiencing the waning stages of a flood in July, 1983, that eroded the barrier, all the flood-tidal deltas and the edges of the dunes. This type of flooding effectively scours sediment from the estuary. (Photo: J S V Reddering)

The detail of the growth of a flood-tidal delta depends in some measure on the shape of the estuarine basin. Flood-tidal deltas in confined valleys tend to be elongate normal to the coast whereas lagoonal flood-tidal deltas such as those developed in the Keurbooms estuary, for example, are forced to elongate parallel to the coast. The flood-tidal delta of the Knysna estuary is attached on to Leisure Island owing to flow confinement of the incoming tide.

Flood-tidal deltas start as a single lobe, which may grow by elongation. However, as the flow of the incoming tide finds a route of less resistance, it changes direction carrying its sediment load with it. A new lobe, fused to the original then branches off until yet another flow direction is located, maybe by a change in the orientation of the mouth channel, and a new lobe grows in that direction. Flood-tidal deltas commonly develop into multi-lobed sediment bodies in this way and fill the lower estuarine basin. In time the multi-lobed outline of the bedform may be blurred by tidal and wave reworking at the sediment surface, and by the effects of minor floods. Development of flood-tidal deltas in the Sundays estuary is well described by Illenberger (1992).

Flood-tidal deltas do not block the channel system altogether, although considerable channel constriction is possible after prolonged sedimentation. Even though much of the channel scoured after a river flood may be filled in by tidal deposition, a system of tidal channels that enables continued tidal circulation is maintained around the periphery of the flood-tidal delta. This system of channels usually segregates into flood-dominant and ebb-dominant sectors. Ebb channels usually display an ebb-dominant tidal asymmetry with ebb-directed bedforms, and the reverse applies in the flood-dominant

channels. Sections of flood-dominant channels are commonly exposed during low tide. These channels of opposing dominance occupy the same general area of an estuary, and inevitably interact, most commonly by flanking across each other (Robinson, 1960). Sediment carried by one channel is deposited into the other, causing local channel shoaling. A prominent sand bar then separates the ebb- and flood-dominant channel components. Since the channels tend to migrate laterally, these areas of shoaling are mobile, and a navigational nuisance.

As the flood-tidal delta system expands up-estuary, the length of the tidal channel system increases. These channels are scoured open and maintained by the tides. While the tidal channels are short during the youthful development of flood-tidal deltas, the scour is efficient. But as the channels become longer, the drag of the water along these channels increases, limiting the ability of the channels to maintain themselves. As a result the tide becomes gradually more sluggish, to the extent that an estuary that undergoes significant shoaling over a 10 or 15 year period, may suffer significant channel restrictions. At the same time the volume of water exchanged during each tidal cycle decreases, i.e. the tidal prism decreases and the tidal amplitudes in the estuary are only a fraction of those in the ocean.

In estuaries where the mouth condition is marginal, that is, where the condition could change from a permanently open state to one of intermittent closure, the effect of prolonged sedimentation can be significant. As the section of tidally maintained channels lengthens by extended sedimentation, the resistance to tidal flow increases. As a result the ability of the tides to maintain the estuary mouth in a permanently open condition is compromised. The probability then increases that wave action will close the estuary mouth.

During a detailed investigation of the lower Sundays estuary over three years (1986–1989) Illenberger (1992) calculated the sand budget for the lower Sundays Estuary on Algoa Bay. The lower Sundays estuary receives sand from dune and longshore-drift sources. Tidal deposition contributed 40,000 m³ per annum, whereas dune deposition contributed 39,000 m³ per annum. Sedimentation from other smaller and mixed sources was found to be low. Sediment measurably eroded from the system during a period unaffected by river floods was very low and intermittent. The total sediment influx into the lower Sundays estuary was about 83,000 m³ per annum, averaged over the three study years.

Illenberger (1992) measured sediment influx by monitoring fixed cross sections and comparing regular aerial photographs. Reddering and Esterhuysen (1987a) also measured fixed cross sections before and after the November 1985 flood in the Nahoon Estuary in East London and showed that 318,000 m³ of sand on the flood-tidal delta were scoured by the flood. Making assumptions later shown to be reasonable, Reddering and Esterhuysen calculated the mean annual tidal influx of marine sand into the estuary to be about 21,000 m³ per annum, or about one quarter of the sand entering the Sundays Estuary. This ratio appears reasonable considering the relative sizes of the estuaries and the added load of dune sand in the Sundays estuary. Most tidally-introduced sand accumulates on the flood-tidal deltas below the low-tide level.

Cooper *et al.* (1990) carried out a similar investigation in the Mgeni estuary but the sediment scoured from that estuary was mostly derived from the river and the results do not apply to this report.

In summary, the eventual state of an estuary after a prolonged period of sediment accumulation will

include the presence of extensive sand bodies extending well into the estuary. Shallow, narrow tidal channels will be prominent, especially at low tide, and navigation will be a challenge. Diminished tidal exchange will prevail, and a chance will exist under some circumstances of the estuary mouth being intermittently blocked. This estuary condition is not necessarily unnatural but can be part of a natural cycle. A severe river flood could then scour the sediment from the estuary and reset the cycle. If for some reason natural floods are prevented from reaching the estuary, or are seriously diminished in their effect over an extended period, sediment accumulation will continue in affected estuaries, and their natural function will be compromised.

2.7 MARINE SEDIMENT ORIGINS AND COMPOSITION

Marine sediment has various origins, but the sediment available for transport into estuaries generally originates on beaches and dunes, and for the purpose of this report the discussion will be restricted to beach and dune sand. This sand is generally a mixture of *inorganic* and *biogenically-derived* components.

Loose, inorganically-derived sediment is the product of weathering and erosion. The erosion could have taken place in the river catchment areas, and the sediment carried to the coast by rivers. Alternatively marine erosion, mainly by wave action, of coastal outcrops produces loose sediment.

Much sediment produced by erosion will not accumulate on beaches or dunes. The bulk of land-derived sediment consists of clay, silt and very fine-grained sand (Rooseboom *et al.*, 1992); coarser-grained granular sediment constitutes a minor component. The bulk, muddy fraction remains in suspension when it reaches the sea and is carried away to be deposited in deep water, usually below the wave base, and generally at a depth exceeding 40 m. Sand-dominated sediment enters the sea along the southern coast of South Africa, where rivers drain the quartzite-rich Cape Supergroup suite of rocks. The sediment load from this source is very low compared to other catchment areas of the subcontinent (Rooseboom *et al.*, 1992; sediment-yield map).

Fairly broad consensus exists that poor land management has increased the rate of erosion and therefore the sediment yield of the southern African subcontinent. This increase implies that more sediment should reach the marine environment. Although the sediment has increased since the start of large-scale agriculture in South Africa, dams have also been built on most rivers in the country. Dams trap sediment and are efficient in catching the coarser-grained fraction of the sediment. Much sand and gravel that would otherwise have travelled downstream towards the sea is retained by the dams and is unavailable for supplying suitable sediment to the beaches, dunes and, indirectly, the estuaries. The muddy fraction of river sediment that passes through the dams does not accumulate on the beaches but is deposited offshore.

Some sections of the coast, notably the south-central area of KwaZulu-Natal, receive very coarse-grained sand from the local catchment areas, composed of acid-crystalline basement rocks. As a result the beaches in these areas contain significantly coarser-grained sand than the rest of the coast. Since grain size influences the beach slope (§2.4.2.1), these coarse-grained beaches are steeply-sloping, high-

energy reflective beaches, with the tendency to concentrate their surf energy very close to the shoreline. The sediment composition there has a significant influence on the type and behaviour of the affected estuaries, especially those so typical of KwaZulu-Natal, where closure or near-closure of the estuary mouths is prevalent.

The sandy and pebbly fraction is generally deposited as part of the beach sand where it is reworked by wave action. The mineral fraction of the sand that is unstable in the marine environment is soon weathered or abraded, and turned into muddy sediment that joins the mud deposited offshore. Sand-sized grains composed of mudstone and most silicate minerals are unstable and weather into small grains. Of the inorganic fraction, it is generally only quartz or quartzite grains and heavy oxide minerals that are able to withstand the rigours of reworking in the surf zone for any significant period. Feldspar may last a while but also deteriorates.

Size sorting further reduces the sand fraction on the beaches. Very fine-grained sand (smaller than 0,125 mm in diameter) is usually also carried offshore to be deposited in deeper water, beyond the surf zone. The sand on beaches is commonly cycled between the water-reworked area and the dunes. Sand on dune fields undergoes further size sorting. In addition, the sand grains are subjected to much more energetic reworking on the dunes to become round, and mechanically weak grains are broken up and blown away as dust. Sand on dunes typically consist of grains in the narrow size range of 0,125 to 0,25 mm in diameter. Along many parts of the coast beach sand consists principally of recycled dune sand, and is available for entry into the estuaries. Beaches and dunes originally obtained their sand from the rivers, and then act as coastal sand reservoirs.

Many areas of the South African coastline receive sediment containing heavy minerals. These minerals originate in igneous or high-grade metamorphic terrains, or are derived from sedimentary rock suites that received heavy minerals during their initial deposition. These dense minerals, mainly ilmenite, rutile, zircon and magnetite, are chemically stable on the time-scale of medium-term estuarine sedimentation. Many beach-sand deposits contain these dark minerals, but their content is seldom more than about 5%. The beaches along the eastern and western coasts of South Africa contain heavy minerals whereas the southern coast between Cape Town and Port Elizabeth has beaches almost devoid of heavy minerals.

The biogenically-derived fraction of beach sand consists of sand grains composed of fragmented mollusc shells. This fraction generally makes up between 25 and 50% of the sand (Reddering and Esterhuysen, 1983b, 1984b; Esterhuysen and Reddering, 1985). The molluscan shell remains, mostly derived from marine bivalves and gastropods, are locally derived, but also enter the dune-to-beach sand cycling. Being much softer than the prevailing quartz sand the shell fragment probably abrade more readily, but are surprisingly resilient. Shells are also continually replenished and the shell content remains fairly constant. The size range of shell material varies from whole shells to limestone sand. (Limestone mud is unstable in cool-temperate waters of South Africa and dissolves.)

The final round of sorting arises when the tide transports sediment from a beach into an estuary. The turbulence generated by wave action in an estuary mouth area rapidly diminishes to a relatively subdued tidal turbulence inside the estuary. This diminished turbulence reduces the lift required to entrain sediment particles, and only sand-size particles are transported into the estuary to accumulate on the flood-tidal deltas. Any coarser-grained shell gravel and pebbles are present only in the mouth areas,

mainly in the area of direct wave influence.

So the composition of sediment entering an estuary from the sea consists typically of well-sorted, quartz-and-calcium-carbonate sand, possibly with a small content of dark ore minerals. This mono-granular size distribution of round, spherical particles means that the sediment mass is inherently unconsolidated (Allen, 1985). This looseness of the sand is caused by the low number of grain contacts between the evenly-sized particles (close to the theoretical minimum) and the lack of grain interlocking between the round particles. Under favourable conditions this sand readily liquefies or fluidizes to become quicksand (Allen, 1985).

The sediment composition changes in the area where marine deposition of the lower estuary overlaps with mud deposition of the middle estuary. Where sand and mud are deposited in the same area, and the sediment is thoroughly mixed by biogenic burrowing, the sediment character changes significantly. Open void spaces between grains are occupied by mud, which can become highly cohesive in an estuary. The mixture, which may contain as little as 20% mud, is also much more cohesive than loose sand. The potential for liquefaction and fluidization of the mixed sediment is significantly reduced.

3

MANAGEMENT OF CAUSES OF SEDIMENTATION

3.1 INTRODUCTION

This chapter deals with management of causes of sedimentation in estuaries and it is closely linked to Chapter 2, "Estuaries and Marine Sedimentation" and Chapter 4, "Options and Techniques" (about the removal of unwanted sediments from estuaries).

Three types of sedimentation problems in estuaries can be identified, namely:

- a. General sedimentation in the estuary as a whole.
- b. Sedimentation in local trouble spots.
- c. Closures and breachings of temporary open estuary mouths.

In some Eastern Cape estuaries, general sedimentation causing shoaling over extensive areas is a major concern and is the main problem to be addressed within this report. Sedimentation in local trouble spots within an estuary is often noticed and can be the reason for the perception that ongoing sedimentation takes place in the whole estuary. This chapter deals mainly with general sedimentation in an estuary, but aspects of sedimentation in trouble spots and closures and breachings of the mouths of temporarily open estuaries are also discussed.

A serious challenge in assessing sedimentation in estuaries is commonly the almost total lack of available information, making assessments of the perceived sedimentation problems unreliable, and therefore unlikely to justify expensive remedial actions. An important task that should be included in management of sedimentation in estuaries is therefore implementation of an effective monitoring program. A brief description of such a program is included.

3.2 SEDIMENTATION IN AN ESTUARY AS A WHOLE

Equilibrium between sedimentation and erosion in an estuary exists if, in the long term (which can be from decades to centuries), the volume of sediments flushed from an estuary is equal to the volume of sediments transported into the estuary.

Sedimentation challenges in estuaries arise when this long-term equilibrium is disturbed and when ongoing sedimentation takes place. The potential for removing sediments from estuaries artificially is described in Chapter 4, but it is necessary to investigate whether unnatural sedimentation takes place artificially and what the causes are. It may locally be possible to address unnatural sedimentation in estuaries by the management of these causes.

The sediment transport processes into and out of estuaries, which are extensively described in Chapter 2, are briefly discussed in this chapter.

3.2.1 Influx of Sediments

The influx of sediments in estuaries is caused by:

- (a) Sediments transported downstream from the catchment by river flow.
- (b) Marine sediments transported upstream from the mouth by tidal flows, sometimes under the additional influence of wave action
- (c) Lateral influx of sediments through slumping of dune slopes or through ephemeral streams.
- (d) Sediments transported by wind.

(a) and (b) are normally the dominant causes of sediment transport into estuaries. (c) and (d) may occur locally, but are often far less significant.

Unnatural net sedimentation in an estuary can be caused by an increase in transport by one or more of these processes or by a reduction of the scouring of sediments (§3.2.2). It may sometimes be more effective to manage these causes than to manage the resulting sedimentation problems inside the estuary. The four types of sediment transport into estuaries are therefore discussed and also the ways in which these can be managed.

3.2.1.1 Sediments Transported Downstream from Catchments by River Flow.

A major reason for ongoing sedimentation in estuaries in South Africa is increased erosion in catchments, resulting in an increase in sediment transport into estuaries. It is perceived that this is especially the case in estuaries in Natal, but it sometimes also plays an important role in other estuaries (eg Mzimvubu, Great Fish estuaries).

It is sometimes stated that erosion in catchments is one of the greatest challenges to be resolved in Africa. Topsoil is being lost on a large scale causing serious problems upstream in catchments and also downstream in estuaries.

Deforestation and ill-considered agricultural practices are commonly the main reasons for the erosion. **Effective land use planning and improvement in agricultural practices are needed to reduce the erosion in catchments.** The loss of topsoil will then be reduced and the additional benefit will be that the rate of sedimentation downstream in estuaries will be reduced.

Such fluvial sedimentation falls outside the scope of this project. However, it must be emphasized that comprehensive managements plans can only be developed if large-scale investigations are undertaken from river catchments to the sea on all the aspects of sediment erosion, transport, spreading and deposition.

3.2.1.2 Marine Sediments Transported Upstream from the Mouth by Tidal Flows.

The transport of marine sediments from the mouth into the estuary takes place by tidal flows (§2.5). Flood-tidal flows are normally stronger than ebb-tidal flows and have a larger sediment transport capacity causing the net upstream movement of marine sediments. Over periods of decades this process can cause significant shoaling, unless these sediments are naturally eroded and flushed out again during floods. Flushing of sediments will be discussed in § 3.2.2.

Upstream transport of sediments by tidal flows is a natural phenomenon and is in most cases not, or only in a minor way, affected by human interference. Examples of the effects of human interference are:

- (a) An increase in the supply of marine sediment near the mouth because of artificial coastal erosion or additional sand artificially fed into the littoral zone (e.g. at dumping of dredged sediments, mining). Coastal protection schemes can be implemented to address this erosion problem.
- (b) The construction of breakwaters at the mouth and of dredging to improve the navigability can have the side effect that the influx of marine sediments is reduced.
- (c) The effects of reduction in river flow.

3.2.1.3 Lateral Influx of Sediments through Dune Slope Slumping or Ephemeral Streams

In some places sediments enter estuaries because of slumping of adjacent dune slopes such as occurs at the Tsitsikamma and Sundays estuaries or through ephemeral streams such as the Sand River at the Kromme Estuary near Humansdorp.

These are largely natural phenomena, but in some places the effects can be reduced by dune stabilization (although this can cause deterioration of the dune environments), or by the construction of rainwater drainage channels.

3.2.1.4 Sediments Transported by Wind.

The volumes of sediments transported into estuaries by wind are normally much smaller than those transported by rivers from catchments or the marine sediments transported by tidal action. They can sometimes become significant, especially when large unvegetated dune fields exist near estuaries. Such dune fields sometimes already existed under natural conditions and remedial actions may then not be justified. However, revegetation may be justified if artificial destabilization of the dunes has taken place.

3.2.2 Flushing of Sediments from Estuaries.

Flushing of sediments from estuaries normally occurs in only two ways:

- (d) During floods.
- (e) During mouth breachings at temporary open estuary mouths.

3.2.2.1 Flushing of Sediments During Floods

The most important natural way of erosion and transport of sediments out of estuaries is normally by river floods. Large volumes of sediments can be removed in a very short time during major floods with a return period of 1 in 50 years and more. But smaller floods with return periods of 1 in 2 years to 1 in 10 years can sometimes also have a significant influence. Floods therefore play a major role in the equilibrium between sedimentation and erosion in estuaries.

Serious net sedimentation can occur in estuaries if the occurrence and magnitudes of floods is reduced. Construction of large dams can therefore result in a marked reduction in the flushing of sediments from estuaries leading to serious ongoing sedimentation. Dams can seriously disturb the long-term equilibrium between sedimentation and erosion. A large number of smaller dams could have a similar detrimental effect. Detailed investigations of the sediment-dynamics of estuaries are therefore required to ascertain if planned large dams will reduce the occurrence and magnitude of floods, and their scouring abilities.

3.2.2.2 Flushing of Sediments at Mouth Breachings

Many estuaries in South Africa do not have permanently open mouths and significant flushing of sediments can occur at mouth breachings at these estuaries. Mouth breaching only occurs under natural conditions when the water level in an estuary exceeds the level of the sand barrier. The berm of an estuary mouth in South Africa normally builds up to levels between + 2.5 m MSL (mean sea level) and +3.0 m MSL.

Large quantities of sediment are flushed from the berm during breaching, but significant volumes of sediment are often also flushed out from the area upstream of the mouth. More sediment is flushed out when the water level is higher before breaching, because the outflow velocities are then also higher. Not only are the velocities higher at higher levels, but there is also more water in the estuarine basin, which allows the flow to be sustained over a longer period. At some estuaries flushing of sediments at mouth breachings plays a significant role in the long-term equilibrium between sedimentation and erosion.

Developments on the flood plains of many estuaries in South Africa started in the nineteenth century. These were often at low levels and were threatened by inundation before the mouth was breached. Artificial mouth breachings were therefore undertaken at lower water levels to prevent this danger. Subsequent developments were often undertaken at still lower levels, resulting in serious further reductions in water levels at breachings.

Early artificial mouth breachings were undertaken by manual labour. A relatively narrow and shallow channel was excavated to cause the breaching and the reduction in flushing of sediments was limited compared to a natural breaching. Bulldozers and other excavators, which became available later, enabled mouth breachings at much lower levels, which strongly reduced the flushing of sediments.

By the end of the twentieth century mouth breachings were undertaken in several estuaries at levels between + 1.6 m MSL and + 2.0 m MSL, sometimes more than a metre lower than under natural conditions (Figure 3.1). The outflow velocities and the flushing of sediments were drastically reduced



Figure 3.1 Breaching the mouth of the Great Brak Estuary using a bulldozer (Photo: P Huizinga)

as a result and this has contributed to the problems with net sedimentation in these estuaries. These estuaries are among the greatest assets in their regions, but are gradually deteriorating by excessive sediment accumulation.

Detailed recommendations on mouth breaching are described in §3.4.2. The single most important recommendation is that ways should be explored to increase the water levels at which mouth breaching is undertaken. This recommendation implies that new developments should not be allowed at low levels necessitating premature artificial breaching. This recommendation also implies that ways should be explored to accommodate the needs of existing developments, and to explore whether measures can be taken to protect these developments and to enable mouth breaching at higher water levels. Mouth breaching should ideally again be undertaken or take place at water levels at which they would have occurred naturally. The benefits of high water levels just before mouth breaching are illustrated for two case studies.

The Great Brak Estuary The Great Brak is a small estuary near Mossel Bay on the Cape south coast (Figure 1.1). The Wolwedans Dam on the Great Brak River was constructed in 1990, about two kilometres upstream of the estuary. A grave concern about the dam was that it would indirectly cause further cumulative sedimentation in the lower part of the estuary because of a reduction in the occurrence of floods.

Studies and results of monitoring indicated that floods indeed flush significant sediment volumes from the estuary, but also that significant volumes of sediments were flushed from the estuary at mouth breaching. The results further indicated that the volumes of sediments flushed from the estuary increase strongly if the mouth is breached at higher water levels in the estuary.

Investigations were therefore undertaken of the potential to increase the water levels in the Great Brak Estuary before breaching.

The berm at the mouth builds up to levels of + 2.80 m MSL and under natural conditions mouth breachings would have occurred when this level was exceeded. Artificial breaching of the mouth started in the middle of the nineteenth century when the first developments on the flood plains took place. Before construction of the dam, mouth breachings were undertaken when the water level in the estuary was at + 1.62 m MSL. The volumes of sediments flushed from the estuary were probably strongly reduced at the artificial breachings and this probably resulted in net sedimentation in the lower estuary. The investigations also showed that the lowest house near the estuary has a floor level of + 2.26 m MSL. This indicated the potential for increasing the water level at mouth breachings.

Controlled breachings are presently undertaken to open the mouth for ecological purposes and water is released from the dam before breaching. These controlled breachings were initially also undertaken at water levels of + 1.62 m MSL. The breaching levels were later increased to more than + 2.0 m MSL, without affecting existing developments.

The result is that more sediment is now flushed out during breachings than ten years ago. Bathymetric surveys show that the state of sedimentation in the lower estuary remains similar to what it was before the dam was constructed and it is considered that the occurrence of a few floods plus the breachings at higher water levels were the reasons that the sediment equilibrium was maintained in the past ten years. Monitoring continues.

Local authorities at Great Brak still receive applications for developments below natural inundation low levels. Sometimes illegal developments are also undertaken below these levels and the owners complain bitterly when breaching of the mouth is not undertaken at a lower water level to prevent flooding.

Mouth breachings should primarily be undertaken to cause sediment scour and not to prevent inundation of ill-considered property developments.

The Klein Estuary Excessive sedimentation was also perceived to have occurred in the estuary of the Klein River southeast of Cape Town (near Hermanus). Developments there also took place below natural inundation levels and artificial mouth breachings started in the nineteenth century. Natural breachings would probably have occurred at water levels of about + 3.0 m MSL, but until five years ago breachings were sometimes undertaken at levels below + 2.0 m MSL.

The mouth of the estuary is normally breached once per year. Large volumes of water stored in the vlei flush the estuary out at a mouth breaching, but as at Great Brak, the mouth has been breached at successively lower water levels. Estimates indicate that the maximum flow at a mouth breaching of the Klein Estuary are similar to those of a 1 : 50 year flood in the Klein River. Flushing of sediments at mouth breachings is therefore very important for the equilibrium in sedimentation and erosion at this estuary. Five years ago statements were made that "the estuary has been destroyed already". Attempts were made to breach the mouth at higher water levels again, and several breachings were undertaken at levels of about + 2,6 m MSL. It is interesting to note that some of

the lowest houses on the banks of the estuary are being protected by temporarily installed straw bales to prevent damage by wave action. The first three breachings at this level seemed to have little effect on deepening the estuary and many more breachings were thought to be needed. However, breachings undertaken in 1999 and 2000 resulted in a noticeable deepening of the estuary and the general opinion is that the benefits of mouth breachings at higher water levels are already becoming apparent.

Conclusions Many temporarily open estuaries have been seriously affected by sedimentation because of artificial mouth breachings at too low water levels. Ways should be explored at these estuaries to reverse this trend and to undertake breachings again at higher water levels. These water levels should be as high as possible and, ideally, water levels should be reached which are similar to those at natural mouth breaches.

Any new developments necessitating artificial breachings at lower than natural water levels should be avoided. For many estuaries nothing less than their survival is at stake! Property owners should be informed that mouth breaching will be carried out to scour sediments from the estuary, not (necessarily) to prevent damage to property.

3.3 SEDIMENTATION IN LOCAL TROUBLE SPOTS WITHIN AN ESTUARY

3.3.1 Natural Processes

Complaints are often received about serious sedimentation in estuaries as a whole, while the concerns are mainly about shoaling in specific small areas, for example affecting boating activities. Sand banks developing in front of properties, especially at jetties, are a common reason for complaints because of the inconvenience of reduced access for boating. Such complaints are often accompanied by requests for dredging to restore earlier conditions with deeper water at desired spots.

Estuaries are, however, dynamic systems and sand banks and channels, especially near the mouth, are shifting continuously (Chapter 2). Deep channel stretches become shallow and new channels develop where sand banks were before. Natural channels are meandering all the time, sometimes faster, sometimes slower.

Property owners on the banks of estuaries, especially at the flood-tidal delta near the mouth, should expect the state of the channels and sand banks in front of their properties to change continually.

Remedial measures such as dredging, often at considerable cost, are therefore not automatically justifiable to restore previous conditions. Requests for such measures should be assessed on their merits and only be implemented if warranted.

Possible methods to address local sedimentation problems in estuaries are described in Chapter 4.



Figure 3.2 A jetty left high and dry by sedimentation processes near Leisure Island in the Knysna Estuary. (Photo: P Huizinga)

3.3.2 Local Sedimentation Caused by Human Activities

The natural morphology of an estuary is highly dynamic and, ideally, interference should not occur. However, developments take place and these can commonly affect the natural physical processes in an estuary such as current patterns and sedimentation and erosion. Some developments that can have these effects are:

- (a) Bridges and causeways
- (b) Bank protection
- (c) Groynes
- (d) Marinas
- (e) Mining, dredging and reclamation
- (f) Boating

Each will be discussed briefly.

3.3.2.1 Bridges and Causeways

Bridges commonly result in the position of the channel becoming fixed by the openings of the bridge spans. Natural meandering becomes restricted unless large bridge spans and wide openings are included. This situation is less constraining at new bridges, because their spans are generally much larger compared to older bridges.

Many old bridges only had significant bridge spans at the locality where the main channel happened to be during the design phase, while solid embankments were constructed across the flood plains. Examples of such bridges are the railway and N2-road bridges across the Knysna Estuary.

Span openings in most bridges are large enough for tidal flows, but can become bottlenecks during major river floods. Examples are the old railway and road bridges across the Swartkops Estuary at Swartkops village. This can cause inundation problems upstream and reduce the potential of flushing sediments downstream at such bridges. The sand shoal in front of the Zwartkops Yacht Club has arisen as a result of deceleration of flood water flow that has passed under the railway and road bridges at Swartkops village (Esterhuysen and Rust, 1987).

A causeway was constructed across the Seekoei Estuary to shorten the travelling distance between Aston Bay and Paradise Beach, situated on opposite banks of the estuary. The opening in the causeway is far too small to allow floods to pass through properly and even tidal flows are constricted. The result is serious net sedimentation in the Seekoei Estuary. The harmful effects of human influence on the estuary have been compounded by the construction of beach amenities and a parking area at the position where the natural mouth of the estuary used to be situated.

Large enough openings should be designed when bridges or causeways are constructed across estuaries. In some places remedial works are even warranted in cases of existing structures.

3.3.2.2 Bank Protection

Bank protection is commonly used to prevent damage to properties. Channel margins may become fixed and natural meandering may be reduced. Damage to bank protection schemes commonly ensues and it is prudent that these structures are properly designed and that maintenance work is undertaken when needed.

3.3.2.3 Groynes

Groynes are a form of bank protection designed to prevent the channel from becoming too wide and shallow. They also need to be properly designed and maintained.

3.3.2.3 Marinas

Marinas can also cause undesirable sedimentation in estuaries. An example is the marina near the mouth of the Kowie Estuary at Port Alfred. The channels of the marina are parallel to the main estuary channel and divert part of the flow through the marina. The reduction in flow speed through the main estuary channel has caused shoaling in that part of the main channel affected by the flow diversion.

Marinas should be designed in such a way, that their effect on sedimentation and erosion in estuaries is minimal. Proper hydrodynamic investigations are therefore essential for the design of marinas.

Sedimentation can also occur in the channels inside marinas and occasional maintenance dredging may be required.

3.3.2.4 Mining, Dredging and Reclamation

Mining, dredging and reclamation can strongly affect the sediment dynamics in estuaries. Proper Environmental Impact Assessments (EIA) are therefore required before such activities are undertaken.

3.3.2.5 Boating

Erosion of banks is sometimes caused by wave action generated by fast moving ski-boats. Restriction in speeds of these ski-boats can be applied to limit this erosion problem. The removal of vegetation such as reeds will exacerbate this problem.

3.4 CLOSURES AND BREACHINGS OF TEMPORARY OPEN ESTUARIES

3.4.1 General

Many estuaries in South Africa are only temporarily open to the sea (Chapter 2). The quality of the environment of these estuaries is largely determined by the frequency, duration and timing of open mouth conditions. Many estuaries are, unfortunately closed more frequently and for longer periods than in the past and their environment has deteriorated.

Open mouth conditions at large estuaries are mainly maintained by tidal flows. However, at smaller estuaries, it is commonly the river flow that keeps a mouth open.

The harmful effects of artificial mouth breachings at lower water levels than those at which natural breachings would occur, have already been discussed in §3.2.2.2. A more comprehensive set of guidelines for mouth management with brief explanations is given in §3.4.3.

3.4.2 Effects of Reduced River Flow on Mouth Closures

The ecological health of small, temporarily open estuaries depends strongly on the frequency and duration of mouth closures. Reliable data on open-mouth conditions in the past is not available for many estuaries, but it is perceived that many small estuaries are now closed for much longer periods than in the past.

Open-mouth conditions at small estuaries are principally maintained by river flow and especially by base flow. A reduction in minimum base flow therefore commonly results in an increase in closed mouth conditions.

Some estuaries, which were naturally open for most of the time have now, because of reduced river flow, changed into estuaries that are often closed. The Seekoei Estuary is an example. There are no major dams in the catchment of the Seekoei River, but many small farm dams are present. These dams do not normally affect high flows in the river, but they have almost completely cut off the low flows. As a result, the occurrence and duration of open mouth conditions has been drastically reduced, which has seriously affected the ecological conditions in the estuary.

Base flow in many rivers has been drastically reduced because of evapo-transpiration by alien vegetation in the catchment areas and especially in the river beds. Removal of alien vegetation, as part of the *Working for Water Programme*, will cause an increase in base flow, and can therefore also result in an increase in open mouth conditions for some estuaries.

The base-flow required to keep an estuary mouth open is different for each estuary, especially for those estuaries for which the extent that the mouth is protected against direct wave action is a controlling factor. Another important aspect is the size of the estuary. The larger the estuary, the more the mouth is kept open by tidal flows. The Mngeni Estuary near Durban, for example, closes even at spring tide and with a river flow of 10 m³/s, whereas the Great Brak Estuary normally stays open without river flow at spring tide, while a flow of only about 0.4 m³/s often keeps it open over neap tide.

The flow required to maintain an open mouth in an estuary is, because of the importance of an open mouth for acceptable ecological conditions, a crucial component of the environmental flow requirements of temporarily open estuaries. It therefore also needs to be included in the determination of the environmental reserve for these estuaries according to the National Water Act (No 36 of 1998).

In general, no simple correlation exists between river flow and mouth conditions, because of the specific flow requirements for each estuary to keep it open. Daily data on mouth openings and closures and continuous river flow data need to be collected to determine this relationship for each estuary. Continuous water level recordings normally automatically provide the information regarding mouth openings and closures and it is therefore strongly recommended that water level recorders be installed in all the important temporarily open estuaries in South Africa.

3.4.3 The Breaching of an Estuary Mouth

The methods used for the breaching of an estuary mouth can be of crucial importance for the maintenance of healthy environmental conditions (§3.2.2.2). A number of general recommendations on the methods to breach estuary mouths are therefore listed below.

1. The water level in the estuary should be as high as possible and if possible breaching should occur naturally, so that as much sediment as possible will be flushed from the estuary (§3.2.2).

The potential of flushing of sediments increases exponentially with the increase of outflow velocities after breaching (e.g. §2.2), and the outflow velocities increase with the increase in water levels before breaching. At higher water levels there is also more water in the estuary so that the outflow is sustained for a longer period. As described already, natural breaching of the mouths of South African estuaries will normally occur at water levels of between + 2,5 and + 3,0 m MSL. However, in many places estuary mouths have been breached at too low water levels for long periods, and this has caused severe sedimentation in several estuaries.

2. The mouth of an estuary should be breached as late in winter and/or spring as possible.

An estuary fulfils a primary ecological function as a nursery for marine fish. Migration of juvenile fish into estuaries on the South African coast occurs mainly during spring and summer and this migration can normally only take place when the mouth is open. The management

policy should therefore be aimed at creating an open mouth condition during this period.

A further reason for this timing is that high waves occur more often in winter than in summer along the coast of South Africa. Wave activity is the main reason for mouth closure. High waves, causing turbulence, also contribute to the influx of considerable amounts of marine sediments into the estuary. It is therefore beneficial to keep the mouth closed, if possible, during autumn and winter and to have it open in spring and summer. The third reason is that water quality problems are more likely to develop when the mouth is closed during spring and summer, when the temperatures are higher and during the holidays when the loading of pollutants is increased. Additionally, people generally prefer an open mouth during the summer holiday season.

3. The mouth of an estuary should ideally be breached three or four days before springtide.

This ensures good additional flushing during the following springtide. This recommendation is important for small estuaries such as the Great Brak, where the mouth sometimes closes at the following neap tide, and less relevant for larger systems such as the Klein Estuary, where the mouth normally stays open for several months after the breaching.

4. The position where the mouth should be breached depends on local conditions.

Controversy often exists about the location where the mouth of an estuary should be breached, but the best position depends on local conditions and expert advice should be obtained. Much time is often spent on debating this issue in meetings, but it should always be remembered that recommendations (1) and (2) above are normally far more important.

5. If possible, a deeper and wider channel should be excavated before breaching, rather than a small trench.

A considerable amount of water is generally used to flush a small and narrow trench open to a medium sized trench. A larger initial channel will cause higher immediate flow velocities, causing more sediments to be flushed out to the sea. This guideline is also more relevant at a small estuary such as the Great Brak, where a limited volume of water is available for flushing, than at a larger estuary such as the Klein.

6. The actual moment of breaching during the tidal cycle is at high tide or as close after high tide as possible, waves permitting. If it is unlikely that waves will interfere at high tide, then breaching can even be undertaken up to two hours earlier.

The high outflow causing the scouring after breaching lasts over several hours and sometimes more than a tidal cycle. The maximum outflow normally occurs approximately 4 to 8 hours after a breaching and the flow velocities will be increased at a maximum difference in water levels between the estuary and the sea. High waves can sometimes interfere with the breaching process at high tide and shortly after high tide. It is therefore important to watch the effects of the waves in front of the mouth position. The mouth can be breached as soon as it is considered that the waves will not interfere significantly with the process. Under extraordinary wave conditions that are likely to interfere with the breaching it may be better to postpone the breaching by a day, if possible.

3.5 MONITORING

A common handicap in the assessment of sedimentation problems in estuaries is the almost total lack of reliable information. This makes it uncertain to confirm whether changes have taken place in an estuary and to quantify these changes. Implementation of an effective monitoring program is therefore one of the most useful tasks that should be included in any management programme of estuaries. The requirements for monitoring of sedimentation in estuaries are listed and briefly described.

It is important to recognise that monitoring is important in any management programme, since it identifies the state of an estuary and any changes occurring; management can therefore be pro-active in remedying problems in their initial stages. As such, the responsible authorities should also accept their obligations as lead agent(s) to initialise and/or to undertake the monitoring.

3.5.1 Monitoring of Ongoing General Sedimentation

A monitoring programme for ongoing sedimentation should include:

- (a) Bathymetric surveys of cross-sections.
- (b) Water level recordings.
- (c) Aerial and fixed point photographs.

Each of these are discussed further in the following sections.

3.5.1.1 Bathymetric Surveys of Cross-sections

Bathymetric surveys of cross-sections 100 to 500 metres apart along the whole estuary should be undertaken at intervals of three to five years and extra surveys should be undertaken immediately after major floods.

Data from these surveys are essential to quantify the rate of sedimentation in estuaries and the flushing effects of major floods. The CSIR until recently undertook a monitoring program, including surveys of cross sections in several estuaries for the Department of Environment Affairs and Tourism (DEAT). This program was unfortunately terminated during 2000 because of changed priorities within DEAT. Results of this monitoring program were instructive during several investigations, and this important work should be resumed soon.

The authorities that should play a major role here are the DEAT and DWAF. Ideally, this work needs to be undertaken according to professional standards and with a high level of accuracy, as part of a comprehensive country-wide monitoring program. It is therefore considered that DEAT and DWAF should be the lead authorities.

3.5.1.2 Water Level Recordings

Water level recordings collected at the mouth and upstream in estuaries also provide useful information on sedimentation. Increased water levels at low tides are a strong indication that general sedimentation

has taken place, resulting in constriction of the estuary mouth. Water level recorders should therefore be installed near the mouth and, if possible, also upstream in estuaries.

The authority that should play a major role here is the DWAF, and the Department has already set up some water flow and water level recorders as part of an overall policy programme. This work needs to be undertaken according to professional standards, and the results will be essential for future Reserve Determinations for estuaries.

3.5.1.3 Aerial and Fixed Point Photographs

Changes in sedimentation patterns in estuaries can often be identified by comparing photographs taken at different times. The best comparisons can be made on good aerial photographs, but this is often expensive. Fixed point photographs, especially those taken from high points, can also be very effective in showing changes.

However, it is sometimes difficult to determine from such photographs whether general sediment accumulation is taking place. Nonetheless, general sedimentation often causes a shifting of channels and shoals within an estuary and this can be used to infer sediment movement on these photographs.

It is important to note at what state of the tide photographs are taken.

The responsible authority here is the DEAT. The results will be essential for the monitoring of the state of the environment of South Africa's estuaries. Fixed point photographs of the same areas at regular intervals can be taken by local authorities or private volunteers: this will provide documentation of changes over time.

3.5.2 Monitoring of Sedimentation and Erosion in Trouble Spots

Detailed surveys at regular intervals, as well as aerial and/or fixed point photographs, can assist considerably in the assessment of sedimentation and erosion in trouble spots. Here local authorities will probably benefit most and they should therefore accept the responsibility for this type of monitoring.

3.5.3 Monitoring of Estuary Mouths

Monitoring assists in establishing an optimum breaching policy for a particular estuary mouth. This should include:

1. Daily observations of the condition of the mouth of an estuary, i.e. whether it is open or closed. This is particularly useful if water-level recordings are not available. These observations should be undertaken at low tide.
2. Making direct observations and taking photographs during and after a breaching.
3. Recording of water levels before, during and after a breaching, but ideally, a permanent recorder should be installed.

4. An important factor affecting the dynamics of an estuary is the total volume of sediments present in the mouth area. Detailed bathymetric surveys are important for quantifying changes in the amounts of sediments present in the inlets of estuaries.

The undertaking of regular surveys of the inlets of selected estuaries was also part of the monitoring program until recently undertaken by the CSIR for the DEAT (§3.5.1.1).

6. Reduced base-flow from the catchment could cause a mouth to shift from being open for long periods to a state of being almost permanently closed. Any information on present and past runoff will assist considerably in improving the understanding of the dynamics of an estuary.

3.5.4 Storage of Monitoring Data

It is essential that the results from monitoring programmes are properly stored in an archive or database. They should be stored locally for a particular estuary, but ideally also in a national database for estuaries, in which the data are stored in a standard way. Such a database for estuaries was developed by *WAMtechnology* and the CSIR and at present includes, amongst others, the results from the monitoring program undertaken by the CSIR for the DEAT. This database has been developed in such a way that *different datasets can easily be added. It is planned to make this database accessible via the Internet.*

4 **OPTIONS AND TECHNIQUES TO MOVE MARINE SEDIMENTS**

4.1 INTRODUCTION

Techniques presented for the management of marine sediments in South African estuaries will be subdivided into existing proven techniques, used both locally and elsewhere in the world, and unproven potential techniques, which are considered to warrant further investigation. Essentially, the management involves the movement of the sediments away from unwanted positions to a disposal site.

Since this stage of the project is a desktop study, the information presented must be considered a review of existing information. The purpose is to serve as a basis for a decision on the appropriate methods of sediment removal from estuaries and a platform from where further studies/programmes can be undertaken.

The causes and effects of sediment accretion and sediment dynamics in estuaries are not addressed in this chapter since this is dealt with in Chapter 2. The issues of concern here are therefore the management of sediment (*exclusively marine sediments penetrating estuaries via estuary mouths from the sea*) in estuaries and aspects relating to the disposal of the removed sediment.

The focus will be on management techniques of marine sediments in estuaries with open mouths and more especially those in the Eastern Cape. Examples of Eastern Cape estuaries are discussed elsewhere in this report. The Kowie Estuary represents one end of the spectrum where the mouth has been trained by structures, while other estuaries (e.g. the nearby Kariega and the Kromme) represent the other end of the spectrum, where the mouths are untrained with varying tidal prism sizes, catchments and degrees of human impact on them (e.g. causeways/bridges, dams etc.).

The focus will also be on the management techniques of marine sediments entering from the sea and/or beaches, although most of the techniques presented could also be applied to sediments originating from the catchments of the rivers flowing into the estuaries.

Section 4.2 presents existing techniques to prevent / limit the ingress of marine sediments into estuaries.

Existing dredging and dredging disposal practices are dealt with in Section 4.3. Other proven sediment management techniques are discussed in Section 4.4. A potential, yet unproven technique which warrants further investigation (the tidal flooding concept) is presented in Section 4.5. The conclusions are briefly given in Section 4.6.

Note that before any sediment removal activities in SA estuaries can be undertaken the necessary approvals (permits) will be required as prescribed by legislation. These legal and environmental requirements are treated in detail in Chapter 5 of this report.

4.2 EXISTING TECHNIQUES TO CONTROL MARINE SEDIMENTS

The dynamics of estuary mouths are treated in detail in Chapter 2 of this report. From this chapter it is clear that natural estuary mouths on sandy coastlines, which are not confined to a fixed location by natural non-erodable features such as natural rock formations, are dynamic. The dynamic estuary mouth is continuously changing its location and configuration due to influencing factors such as longshore sand transport, *normal and flood flows from the river catchment feeding into the estuary*, tidal flood and ebb flow through the mouth, the size of the estuaries tidal prism and wind-blown sand.

Two methods are described below to fix the location of an estuary mouth and to prevent / limit the ingress of marine sediment into the estuary.

4.2.1 Double training walls

To prevent / limit marine sand penetrating into the estuary, training walls such as at the Kowie Estuary mouth can be constructed. The training walls stabilize the mouth's location and interrupt the longshore sediment movement on the coastline. If there is a net longshore transport in one direction (§2.4.2), sediment will accrete on the updrift side of the trained mouth and the downdrift beaches will tend to erode. After a period dependent on the length of the training walls, the accretion on the updrift side will reach a stage when sand will start by-passing the updrift training wall causing a shallow sand bar to form across the mouth which is potentially dangerous to navigation. Depending on the size of the offshore sediment bar some sediment will penetrate into the estuary entrained by the flood tide and some will bypass the mouth to the eroding downdrift beaches.

One approach to prevent the penetration of sediment into the estuary as well as to prevent erosion of the downdrift beaches is to artificially bypass the accreted sand on the updrift side to the downdrift side. This could be accomplished by means of floating dredgers (e.g. Durban and Richard's Bay harbour mouths) or by means of a fixed bypassing scheme such as at the Nerang Estuary mouth (Australia). At the Nerang Estuary mouth a series of jet-pumps permanently installed on a jetty bypasses the net longshore drift (Figure 4.1). Such artificial bypassing prevents updrift sediment accretion against the training wall and so also prevents tidal influx of sand into the estuary.

4.2.2 Single training wall

A single training wall in an estuary mouth does not necessarily prevent or limit marine sediment ingress, but has been applied to stabilize the mouth location and to improve navigation conditions.

Kieslich (1981) did a case history study on estuary mouths with single training walls to establish the response of an estuary mouth to the construction of a single training wall. Kieslich's study indicated that a single training wall may be on either the updrift or downdrift side of the mouth. An updrift training wall acts as a barrier to the littoral drift moving in the net transport direction. A training wall on the downdrift side of the mouth permits the sand on the updrift side to encroach upon the mouth. These effects are illustrated in Figure 4.2.

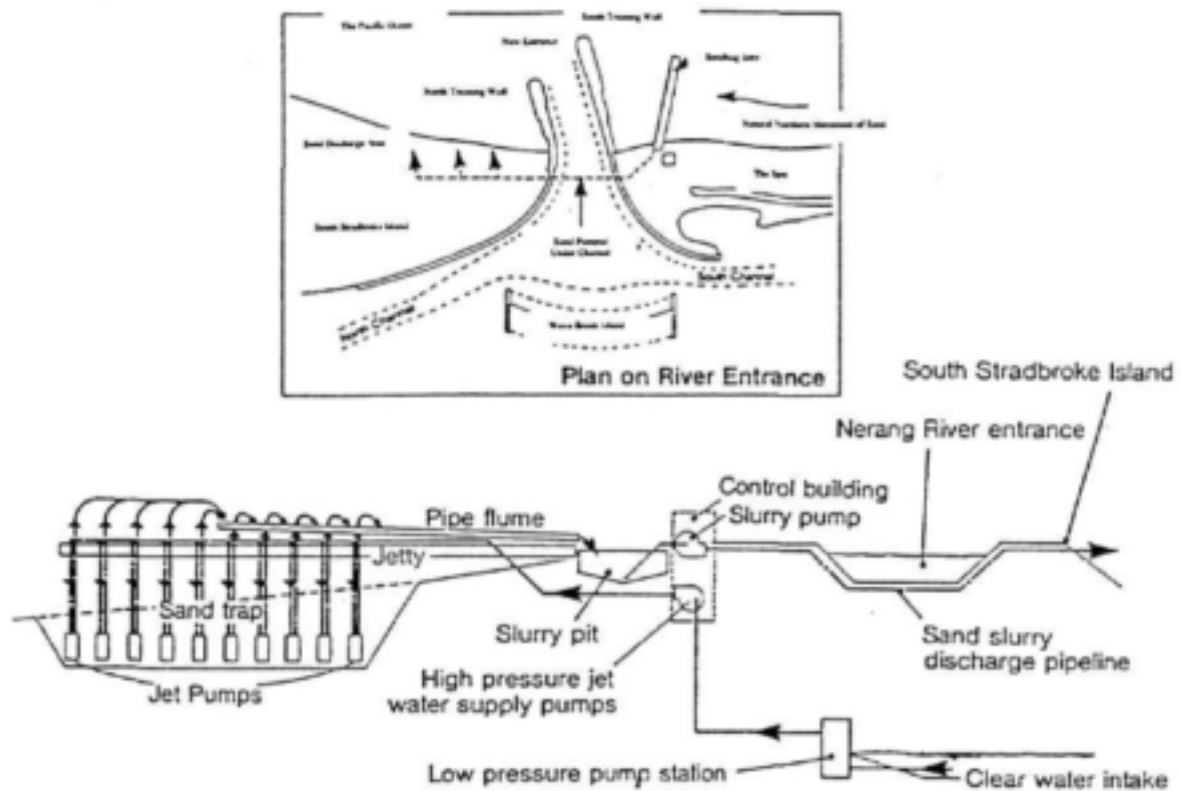


Figure 4.1 Schematic diagram of Nerang fixed sand bypassing system (Wakefield 1994). Jet Pumps mounted on a jetty at the updrift side of the main training wall pump sand via a pipeline underneath the entrance and discharge is done on the downdrift side.

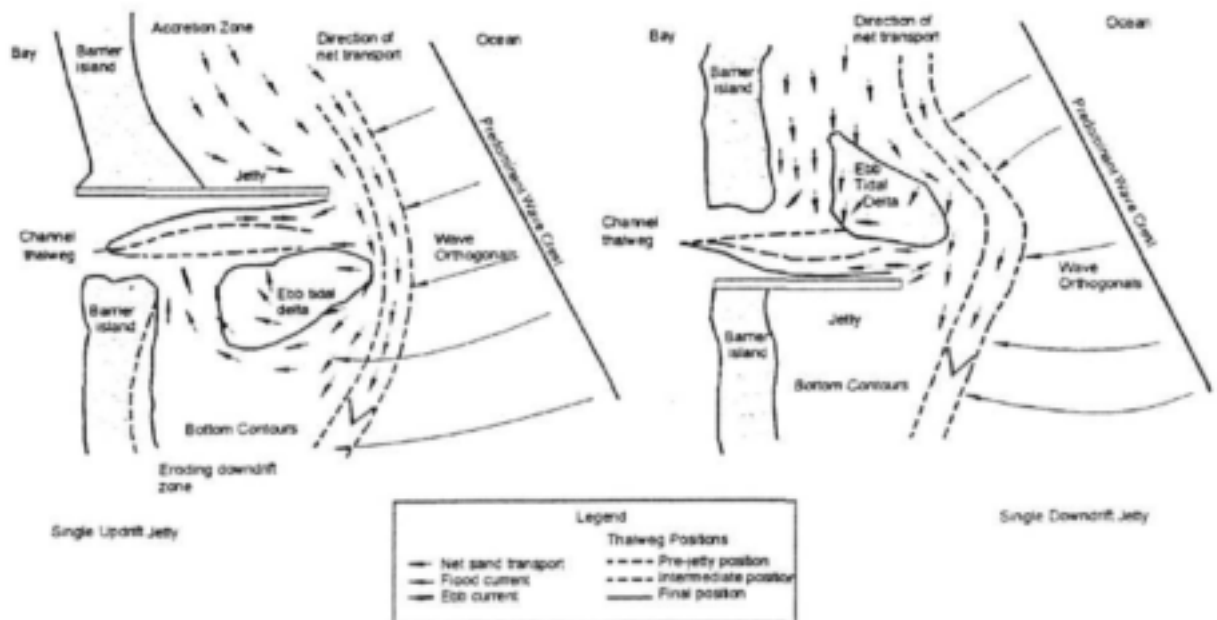


Figure 4.2 Effect of a single training wall (jetty) on an estuary mouth (tidal inlet) after Kieslich (1981). The channel in the mouth tends to form adjacent to the training wall.

Kieslich concluded that :

- (a) The construction of either an updrift or a downdrift training wall generally results in the tidal channel (estuary mouth) migrating towards the training wall.
- (b) Generally it is necessary to build a second jetty at a later date to further stabilize the channel in the mouth.

4.2.3 Potential for application of training walls in South African estuaries

Since the cost of effective training walls are very high (tens to hundred of millions of rands) it is considered unjustified to construct training walls only for the purpose of controlling marine sediments in estuaries. The construction of training walls is probably only justified in cases where improvement of navigability through the mouth is required and where associated developments that benefit from the improved navigation can carry the cost of mouth training.

Examples of South African trained estuary mouths, excluding the major harbour mouths of Durban, Richard's Bay and East London are Kowie River (Port Alfred), Berg River (Laaiplek fishing harbour and Port Owen Marina) and Mgeni River (the latter is trained with a single training wall).

4.3 EXISTING DREDGING AND DREDGING DISPOSAL PRACTICES

4.3.1 General

Since estuaries are valuable national environmental assets it is essential that they be managed with great care. If dredging is considered to remove sediment from an estuary, the dredging activities (including type of dredger, locations of dredging, disposal of dredge spoil) should be carefully planned and executed to minimize environmental impact while maximizing the beneficial uses of dredged material where possible.

To ensure that dredging operations in an estuary are carried out in an efficient, economical and environmentally compatible manner, the following are pertinent factors. (EM, 1983) :

- (a) Analysis of dredging locations and quantities including hydrographic surveys.
- (b) Dredging environment; i.e. depths, currents, waves and distance to potential disposal sites.
- (c) Evaluation of physical, chemical and biological characteristics of sediments to be dredged.
- (d) Control of dredging operation to ensure environmental protection.
- (e) Determination of levels of suspended solids from disposal areas and dredging operations.
- (f) Selection of appropriate dredger type.
- (g) Disposal site and containment of dredged material.

The US Army Waterways Experiment Station (WES) has in recent years placed more emphasis on the beneficial use of dredged material besides engineering purposes (such as building or filling material).

The more recent beneficial uses of dredged material applied by WES include wetland restoration, creation of wild-life habitats and improvement of ecological functioning of fishing habitats.

If the concentration of solids in suspension caused by a dredging operation exceeds minimum environmental standards there are effective devices on the market to contain the turbid water in the direct vicinity of the dredging operation such as the full water depth filter curtain marketed by *Gunderboom* (Alaska).

4.3.2 Dredger types

Different types of dredgers on the market provide for different applications of sediment removal. Dredgers can be divided into two main categories i.e. dredgers that pump the dredge spoil directly to disposal sites via a pipeline, and dredgers which **accumulate** the dredge spoil on board in hoppers or on an adjacent moored hopper barge. When the hoppers are full of settled sediment the hopper dredger or hopper barge sails to a suitable dumping site where the sediment is discharged.

Table 4.1 presents an overview of the main types of dredgers in use locally and elsewhere in the world.

Since this study is focusing on the removal of marine sediment from South African estuaries, and more specifically the Eastern Cape estuaries, only the dredger types considered appropriate for these circumstances and which are readily available in South Africa will further be discussed. These are the cutter-suction-type dredger and the suction-type dredgers. Both these dredger types are normally obtained from overseas suppliers. However, smaller sizes of these can be manufactured by the local industry.

4.3.2.1 Cutter section dredgers

The hydraulic pipeline cutter head suction type dredger is the most commonly used dredging vessel and is generally the most efficient and versatile (shown in Table 4.1). The cutter suction dredger can handle material ranging from mud to soft rock. The soil in front of the suction pipe is loosened by the rotating cutter head and pumped away by means of a centrifugal pump on the dredger. The dredger moves into new material by swinging back and forth about one of the two anchoring spuds using the port and starboard forward winches and anchors. The dredger moves forward by changing the position of one spud while the dredge is held in place by the others as shown in Figure 4.3. The cutter suction type dredger is capable of being accurately controlled. A depth accuracy of ± 0.25 m can be achieved and specified side slopes can be cut.

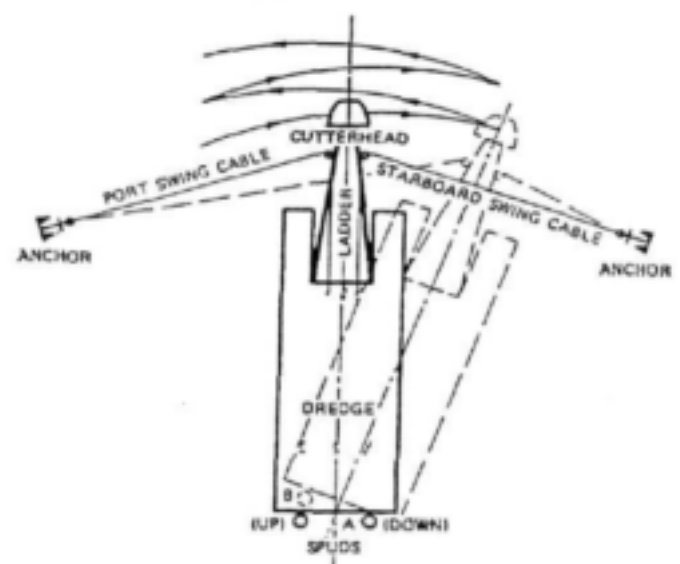


Figure 4.3 Plan view of cutter suction dredging operation

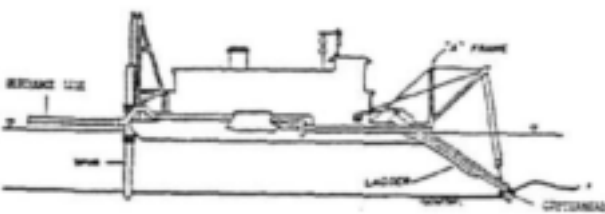
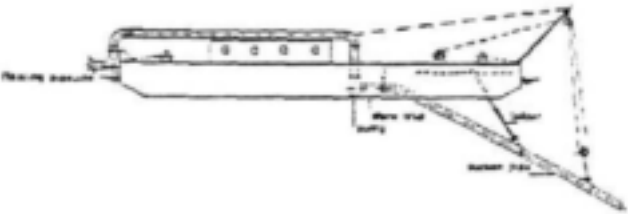
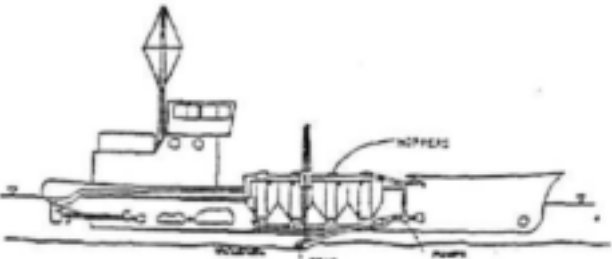
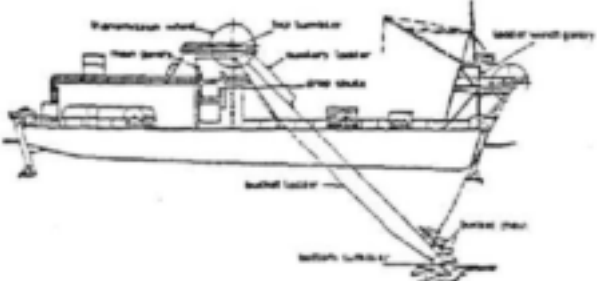
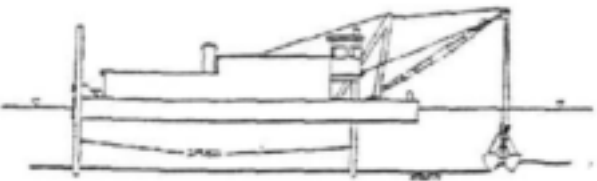
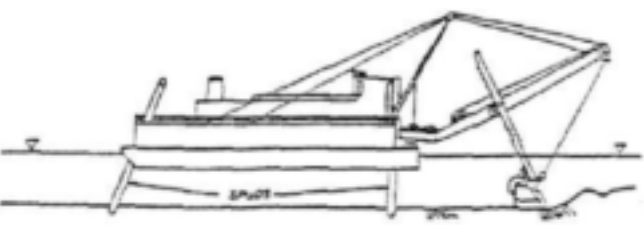
Type	Main Features	Schematic Diagram
Cutter suction dredger	<ul style="list-style-type: none"> i. Most widely used type ii. Can dredge most types of material iii. Mechanical loosening of material iv. Centrifugal pump suction of material v. Can discharge material via long pipe line vi. For use in protected waters; small waves vii. 68% of USA dredging by cutter suction and suction dredgers viii. Accurate dredging profiles are possible 	
Suction dredger	<ul style="list-style-type: none"> i. Same as cutter suction but without cutter ii. Pump could be : <ul style="list-style-type: none"> - Centrifugal pump on board - Submersible on suction pipe end - Jet-pump at suction pipe end iii. Sand disintegration could be by water jets iv. Uneven bed surface dredging ('pot-hole' formation). 	
Self-propelled seagoing hopper dredger (Trailer suction type)	<ul style="list-style-type: none"> i. Self-propelled and seagoing. ii. Accumulates sand on board in hoppers iii. Only type suitable for wave exposed areas iv. Sail to disposal site for bottom dump v. Suction by centrifugal pumps via drag end vi. Drag at speed of about 3 knots vii. Overflow from hoppers requires control to minimize turbidity in ambient water viii. 26 % of USA dredging by hopper dredge ix. Used for harbour approach channel maintenance. 	
Bucket Dredger	<ul style="list-style-type: none"> i. Mechanical removal of sediment ii. Sediment dumped on hopper barges moored alongside dredger iii. Limited to quiet water areas (small waves) 	
Grab dredger	<ul style="list-style-type: none"> i. Mechanical removal of sediment ii. Sediment dumped on hopper barges moored alongside dredger iii. Limited to quiet water areas (small waves) iv. Grab could be by : <ul style="list-style-type: none"> - Clamshell - Orangepeel - Dragline vi. Used for dredging of contaminated material with special bucket which is watertight 	
Dipper dredger	<ul style="list-style-type: none"> i. Mechanical removal of sediment ii. Sediment dumped on hopper barges moored adjacent to dredger iii. Limited to quiet water areas (small waves) 	

TABLE 4.1. Overview of main types of dredgers

South Africa has few dredging contractors. Three dredging contractors were approached to obtain an indication of local dredging capacities and costs. Responses from all three were obtained. Two of the three contractors (*Hydromar* and *Southern Oceanering*) operate mainly with cutter suction type dredgers. They operate four existing cutter suction dredgers (of the Dutch "IHC Beaver" dredger or similar). Relevant particulars of these dredgers are presented in Table 4.2 below.

Name of Dredger	<i>AL RUAN</i>	<i>PICCOLO</i>	<i>CAREY J</i>	<i>KIKI</i>
Length with ladder raised (m)	14.0	15.8	17.0	20.2
Breadth (m)	3.6	4.0	4.8	5.7
Mean draught (m)	1.0	0.9	0.8	1.1
Max. dredge depth (m)	6.0	6.0	7.0	8.0
Suction and discharge pipe diameter (mm)	250	260	250	400
Pump shaft power (kW)	175	175	300	390
Approx. production rate pumping 200 micron sand over distance of 1600 m (m^3 solids/hour)	100	100	150	300

Table 4.2 Particulars of existing cutter suction dredgers of two South African dredging contractors approached.

The listed dredgers are normally diesel driven but can be modified to be electrically driven. Present day (2000) order of magnitude costs for a dredging contract are about R150 000 for mobilizing plus demobilizing of dredging plant. The additional cost for removal of sand is about R12 per cubic metre of sand removed (measured in situ). The R12 / m^3 rate includes the costs for dredge disposal management if the dredged material is used to form bund walls for the containment / settling ponds. Savings could be effected on discharge operations if sand could be discharged directly on to beaches.

4.3.2.2 Suction dredgers

The suction type dredger shown schematically in Table 4.1 is the most common type of dredger used in the Netherlands. The dredger is similar to the cutter-suction-type but without a mechanical cutter head. Discharge is also via a floating pipeline to a dredge disposal site. The types of pumps that could be used on these dredgers include :

- (a) Centrifugal pump on board the dredger (Table 4.1).
- (b) Submersible pump at the suction end of the suction pipe. (Available submersible dredger pumps on the market include *Flygt*, *Warman* and *Toyo*).
- (c) Jet-pump (available jet-pump dredgers on the local market is that of *Genflo*)

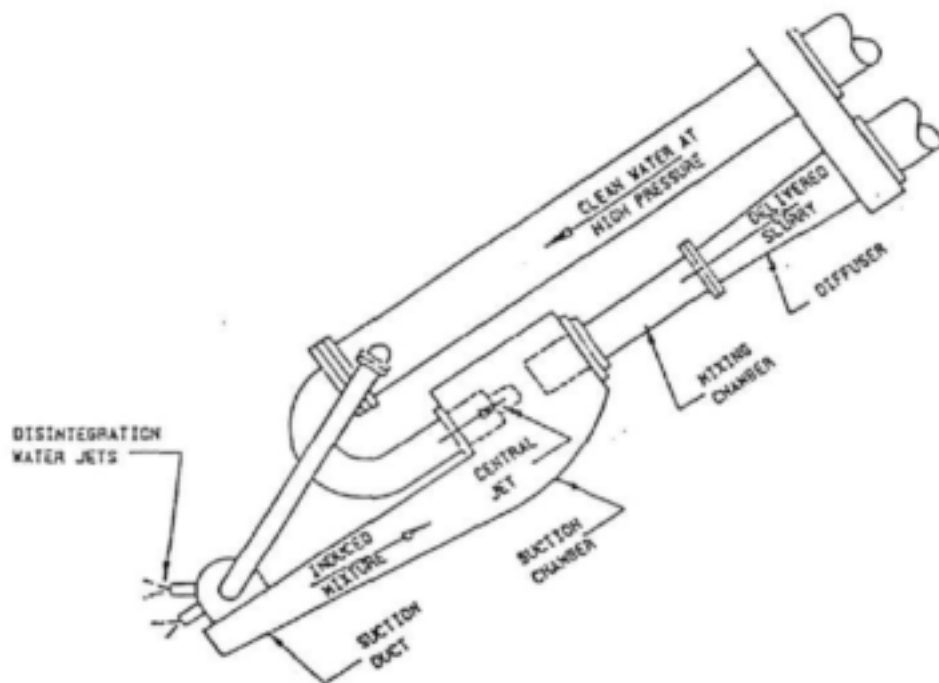


Figure 4.4 *Jet-pump components (Prestedge and Bosman, 1994). Clean water at high pressure is supplied to the control and disintegration nozzles. Sediment is entrained into mixer and velocity head and is converted to static head in the diffuser to carry slurry farther to discharge point.*

Since the jet-pump is considered the more environmentally-friendly type it will be discussed in more detail here. The principle of jet pump operation is shown in Figure 4.4.

The jet pump is different from other pumps in that it contains no moving parts and is powered by a jet of clear water. The clear water is supplied by a separate pump (usually a centrifugal pump). The basic principle behind the operation of the jet pump is the exchange of momentum within the pump. Clear water, normally supplied by a centrifugal pump, enters the jet pump through a nozzle as turbulent mixing occurs between the water jet and a sand-water mixture drawn into the suction tube.

The advantages of a jet pump dredger versus a centrifugal pump dredger are mainly :

- The suction end of the pump operates at its best efficiency when it is buried in the sand whereas a centrifugal pump suction end will tend to clog the dredging pipe under these conditions.
- With the jet pump suction end well buried in the sand, turbidity (which could impact negatively on the environment) is limited.
- The jet pump pipe system does not tend to clog. This simplifies the operation of a jet pump dredger.

There is presently one jet pump dredger contractor in South Africa (*Genflo (Pty) Ltd*) with the capability of local manufacture of jet pump dredgers. *Genflo* presently has two operational dredgers.

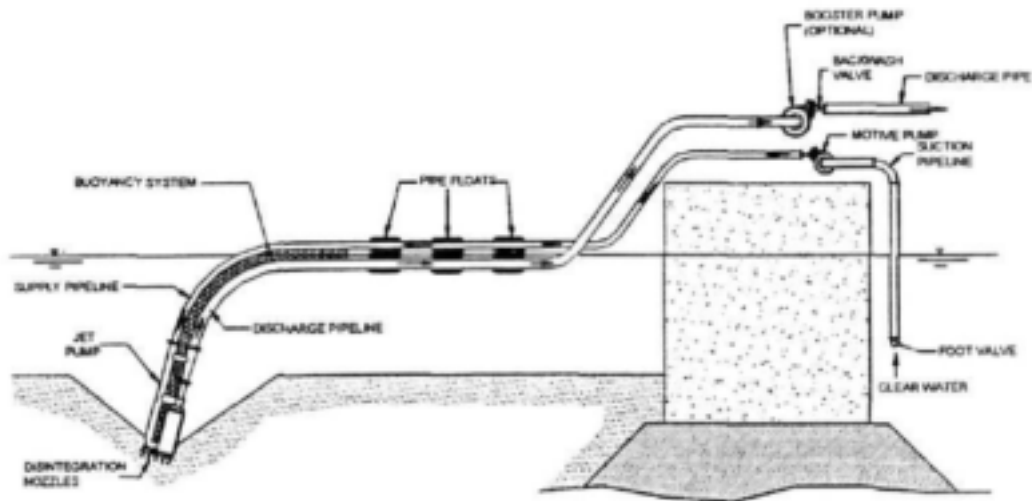


Figure 4.5 Schematic presentation of Mobile Dive Dredger (Prestedge and Bosman 1994)

The jet pump dredger can be manufactured from a very small capacity e.g. a size that can be handled by one man/diver to very large capacity. The more common size used (of which *Genflo* presently has two in operation) has a capacity of approximately 100 m³ of solids per hour for a discharge distance of about 100 m without booster (longer discharge distances are possible by the addition of a booster pump in the system).

The order of magnitude cost for mobilization plus demobilization and unit dredging cost is similar to that indicated in § 3.2.1 for the cutter suction dredger types in South Africa.

One of the smaller jet pump types in use in South Africa is the Mobile Dive Dredge (MDD) the operation of which is presented schematically in Figure 4.5.

The centrifugal motive and booster pumps are mounted on a trailer and the motive and discharge pipes are floating. The jet pump is supplied with a variable buoyancy system. The buoyancy of this system is increased when it is required to bring the jet pump to the surface (for locating it in a new position) and decreased when it is required to dive down into the sediment bed to operate. Dredging of a shallow area is done by means of a series of craters.

Presently one MDD is in operation at the Club Mykonos small craft harbour in Saldanha Bay and one is used by the Fishing Harbours Branch of the Department of Environmental Affairs and Tourism.

The above MDDs have the following main features:

- Capacity : Approximately 40 m³ solids (bulk volume) per hour
- Operating radius from one location : Normal 72 m; maximum 200 m
- Discharge distance : 300 m
- Pipe diameters : 100 mm motive; 150 mm discharge
- Motor power : 45 kW motive; 30 kW booster.
- The order of magnitude present day (2001) capital cost of an MDD system with the above capacity is about R200 000.

4.3.3 Management of Dredged Material Disposal

4.3.3.1 General

The major considerations in selecting disposal alternatives of dredged material are the environmental impact and the economics of the disposal operation.

There are commonly three main disposal alternatives available (EM, 1983) :

- (a) Open water disposal (in case of SA estuaries this would be slurry disposal on the open coastline or beach).
- (b) Confined disposal (dredged material is settled out in a settling pond with an appropriately designed overflow).
- (c) Habitat development e.g. marsh restoration.

The properties of the dredged sediment, method of disposal of the dredged sediment and character of the environment where the sediment is disposed determines the degree of environmental impact of the disposed sediment.

All physical and chemical characteristics (including contaminants) of the sediment and interstitial water must be quantified to enable evaluation of potential negative environmental impacts at the disposal site (as well as dredging site where sediment is placed in suspension). Methods to establish potential biological impact include tests where indicator biological organisms are exposed to the dredged material and their response determined.

4.3.3.2 Open water disposal

In this study of sediment removal from SA estuaries only disposal of slurry (from cutter- suction and suction-type dredgers) on a suitable open coastal beach will be considered.

The slurry of sediment and water is discharged in the active zone of the beach below the high water line in a continuous stream. The discharged sediment will be dispersed by wave action in the breaker zone, and the silt and clay fractions will be placed in suspension due to the relatively high turbulence in the breaker zone.

The beach location for discharge should be selected with care. The discharge location should be on the downdrift side of the estuary mouth outside the influence of tidal currents which could return the discharge sediment into the estuary or into the offshore ebb delta seaward of the estuary mouth.

Discharge close to rocky outcrops should be avoided to prevent smothering of marine life (such as shell fish) attached to the exposed rock. (Oysters tolerate being buried by sand, within limits of less than about 0.5 m. They feed and grow under sand, since wave pumping moves the interstitial water and maintains oxygen supplies.)

Dispersion (spreading) of discharged sediment on a beach can be assisted by conducting the disposal operation in a manner that will maximize the spread of dredged material, producing the thinnest

possible cover. The thinner the cover the easier it is for mobile beach organisms to survive burial by vertical migration through the dredged material.

Due to ongoing change in beach profiles caused by varying wave conditions, beach ecology is very robust and not easily affected by dredge spoil.

4.3.3.3 Containment area disposal

Dyked containment areas are used to retain dredged material solids while allowing the carrier water to be released from the containment area. The two objectives of a containment area are:

- (a) To provide adequate storage capacity to meet dredging requirements.
- (b) To attain the highest possible efficiency in retaining solids during the dredging operation to meet suspended sediment requirements of the effluent from the containment areas.

The major components of a dredged material containment area are shown schematically in Figure 4.6.

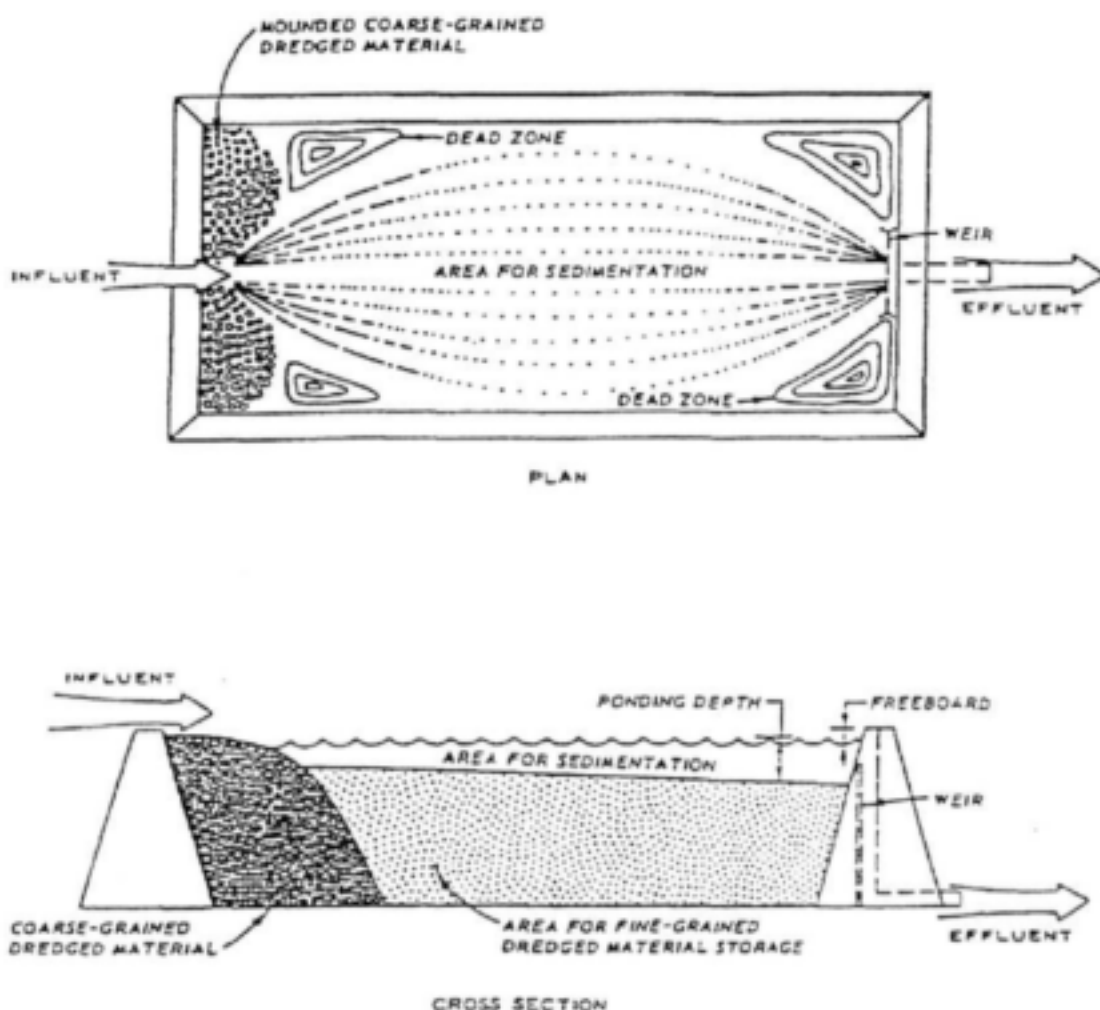


Figure 4.6 Schematic diagram of dredged material containment area (EM, 1983). Coarser sediment settles out relatively quickly while finer sediment settles over a longer period. The effluent from the containment area flows over an appropriately designed weir.

The most economical method of forming the bund walls (dykes) of a containment area of small scale dredging projects is to use the coarse (sand) fraction of the dredged material to form the dykes. The coarse material rapidly falls out of suspension and forms a mound near the dredge inlet pipe. The fine-grained material (silt and clay) continues to flow through the containment area where most of the solids settle out of suspension and thereby occupy a given storage volume. Marine sediment is likely to contain a comparatively small fraction of silt material.

The clarified water is discharged over a weir. The suspended solids concentration of this effluent which usually flows back into the estuary must comply with the limits as defined in the applicable quality criteria (usually between 10 and 18 mg/litre.)

The design of the pond size, overflow weir crest elevation and overflow freeboard must make provision for adequate storage of the dredged solids while satisfying the water quality norms with respect to suspended solids concentration. (According to Government Gazette No.9225 of 18 May 1984 the maximum allowable suspended solids concentration for the effluent into an estuary is 10 milligrams per litre).

Dredging in the marine environment has the advantage that silt and clay fractions of the dredged sediment settle more quickly in seawater as it acts as a natural coagulant (particles agglomerate during the settling process causing them to settle faster).

If the dredged sediment discharged into settling ponds contains contaminants due care should be taken regarding the fate of the contaminants. There are four possible mechanisms for transport of contaminants from settling ponds.

- (a) Release of contaminants in the overflow effluent from the settling ponds.
- (b) Leaching into the ground water.
- (c) Surface run-off of contaminants in either dissolved or suspended form.
- (d) Plant uptake directly from sediments followed by indirect animal uptake from feeding on vegetation.

In many of South African estuaries the leaching of salt water into the groundwater (item (b) above) will be a problem since freshwater aquifers (which are used as fresh water sources in many cases) will be contaminated. In such cases containment disposal of dredge spoil will not be appropriate unless special measures are taken to prevent leaching of salt water into the fresh water aquifer.

The settled finer sediment fraction (silt and clay) may take a considerable time to compact due to excessive interstitial water between grains in the early stages when it acts as a fluid.

The settled coarser fraction (sand and gravel) of the dredged sediment can be removed by mechanical plant from the settling pond even in a wet (saturated) state, however, the silt and clay fraction requires to be dewatered before it can be mechanically removed.

Figure 4.7 schematically illustrates a method of dewatering of settled sediment.

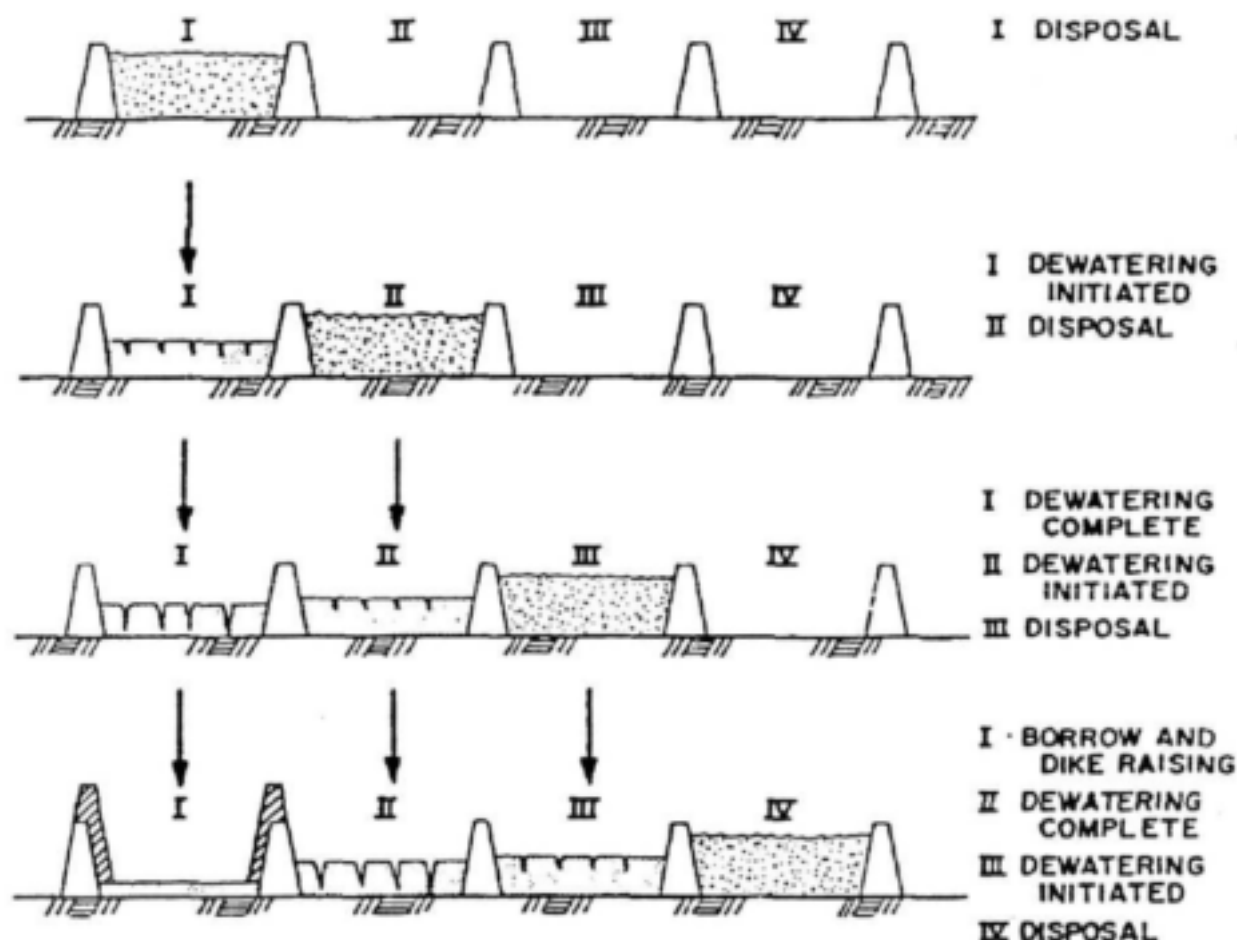


Figure 4.7 Conceptual illustration of sequential dewatering operations (EM, 1983).

The material from the settling ponds could be applied to productive uses including :

- (a) Landfill and construction material (the sand fraction is particularly ideal for landfill or base coarse for road construction e.g. Knysna Quays development).
- (b) Quarry rehabilitation (both sand and silt / clay (the latter for top soil) is ideal for rehabilitation e.g. Knysna Quays Development which successfully rehabilitated the Salt River quarry with dredged material). At Knysna an appropriate grass, which can tolerate the salinity in the sediment, was sown to stabilize the surface of the sediment. Leaching out of the salt in the sediment by rainfall occurred relatively quickly.
- (c) Top soil cover over refuse sites.

Over recent years there has been a strong movement in the United States of America (USA) to promote beneficial uses of dredged material (EPA, 2000). The USA Environmental Protection Agency (EPA) facilitates 28 National Estuary Programs (NEPs) in the USA with their motto "Bringing our Estuaries New Life". One of the NEP's objectives is to promote the beneficial use of dredge spoil and more specifically the upgrading of the environmental quality of the estuaries. Of these there exist an extensive number of successful examples in the USA, including :

- (a) Creation of wild life habitats (e.g. creation of island for birds in large water bodies).

- (b) Fisheries improvement (e.g. bottom relief created by mounding of dredged material providing refuge habitat for fish).
- (c) Aquaculture (e.g. long term maintenance settling ponds could be used as aquaculture ponds).

4.3.4 Potential of dredging for removal of sediment in South African Estuaries

Removal of sediment by cutter suction and suction types of dredgers is an appropriate method for use in South African estuaries. However, the cost of dredging is relatively high (Box 4.1). In addition to the dredging cost the impact of the dredging operation on the environment will be an additional indirect cost which will have to be accounted for. In particular, dredgers are known to be unsightly and noisy in operation.

It should be emphasized that dredging of an estuary should not necessarily mean the removal of all accumulated sediment. To minimise cost 'selective dredging' should be done, i.e. in only the areas necessary to be dredged (e.g. for navigation purposes or to ensure the ecological health of the estuary). The depth to which dredging is taken must also be carefully considered in terms of the accumulated marine sediment. It is therefore evident that a good physical and ecological understanding of the estuarine system is a prerequisite to enable a good decision to be made on where, how much and when to dredge.

To limit the distance of marine sediment penetration into an estuary, a sand trap could be dredged in the estuary (near the mouth and in the path of the penetrating marine sediment). The sand trap will have to be maintained to remain effective. Since such a trap will be located near the mouth, dredge spoil from such a trap could be discharged on the adjacent beach downdrift of the estuary mouth.

Where sediment is required to be removed from an estuary this will be an on-going process for it to be effective. This implies intermittent maintenance dredging with its associated expenditure on a long term

Box 4.1 **Approximate Dredging Costs**

Mobilisation and demobilisation of dredger: ~ R150 000.

Sand removal costs: ~ R12/m³

These costs include dredge disposal management if the dredged material is used to form bund walls for the containment. Savings can be effected if sand can be discharged directly onto beaches.

Examples

Nahoon Estuary: The flood described in §A.2 removed 410 000 m³ of sediment. To dredge this volume will cost approximately R5 000 000. The annual ingress of sediment is about 21 000 m³, which would cost about R400 000 to remove.

Kowie Estuary: The accumulated sediment in the Kowie Estuary has been estimated at between 120 000 and 200 000 m³ (§A.3). This will cost between 1 600 000 and R2 400 000 to dredge.

Careful, selective dredging will dramatically reduce these costs.

basis. To establish if dredging of an estuary is warranted, a comprehensive long term cost-budget analyses is essential.

4.4 OTHER PROVEN SEDIMENT MANAGEMENT TECHNIQUES

4.4.1 Agitation dredging (EM, 1983)

4.4.1.1 General

Agitation dredging is the process of removing bottom material from a selected area by using equipment to raise it in the water column and allowing currents (usually natural currents) to carry it from the area of concern. If the material is suspended but redeposits shortly in the same area only, agitation (not agitation dredging) has been accomplished. The method will only be useful if undesirable shallow areas are required to be deepened. In such cases deeper zones adjacent to the shallow areas must be present to enable sufficiently strong currents to carry the agitated sediment into the deeper areas. If the ebb tide current is sufficiently strong sediment could be removed out of the estuary. However, it is considered that this method could only be applicable in the close vicinity of the estuary mouth during strong ebb currents.

The decision to use agitation dredging should be based primarily on the following factors :

- (a) The equipment to generate the required level of agitation must be available.
- (b) The currents that must carry the sediment out of the area of concern must be sufficiently strong.
- (c) Agitation dredging should not cause unacceptable environmental impacts.

Techniques that are considered relevant are prop-wash and rake or beam agitation which are discussed below.

4.4.1.2 Prop-Wash Agitation (EM, 1983)

Prop-wash agitation dredging is performed by vessels specially designed or modified to direct propeller-generated currents into the bottom shoal material. The agitated material is suspended in the water column and carried away by a combination of natural currents and prop-wash currents. Unintentional prop-wash agitation commonly occurs as vessels move through waterways. This type of sediment resuspension is uncontrolled and is considered undesirable in most places.

The prop-wash vessel performs best when work begins at the upstream end of the shoal and proceeds downstream with the prop-wash-generated current directed downstream. The vessel is anchored in position and prop-wash-generated currents are directed into the shoal material for several minutes. The vessel is then repositioned and the process repeated.

Prop-wash agitation has been successfully used in coastal harbours, river mouths, river channels and estuaries. It is a method intended for use in loose sands. Cementation, cohesion, or compaction of bottom sediments can make prop-wash agitation dredging less effective. Waves may cause anchoring

problems for agitation vessels. Optimum water depths for prop-wash agitation dredging in sand is between two and three times the agitation vessel's draft, but only works well in strong current flows.

Depending on the strength of natural currents prop-wash agitation can be significantly less expensive than conventional dredging.

Limitations on prop-wash agitation dredging include :

- (a) Prop-wash agitation seems most suited for areas with little or no wave action.
- (b) Prop-wash agitation should be applied in water depths less than four times the agitation vessel's draft.
- (c) The sediments must be loose sands, silt or clay. (This project only considers loose marine sediment, mainly sand.)
- (d) The natural current (ebb current in case of estuaries) must be sufficiently strong during the agitation process to transport the sediment over sufficient distances.

4.4.1.3 Rakes and Drag Beams (EM, 1983)

Rakes, drag beams, and similar devices work by being pulled over the bottom (usually by a vessel), mechanically loosening the bottom material, and raising it into the water column to be carried away by natural currents. Since rakes and drag beams do not produce currents of their own and since they do not resuspend material as much as loosen it, these devices must be used in conjunction with currents strong enough to transport the loosened material away from the shoaling site; in addition, the vessel towing one of these devices may provide some resuspension and transport by its prop-wash. A wide range of dredging rates have been reported for agitation dredging by rakes and beams. Little value would be obtained by reporting these rates because they are highly dependent upon local conditions, however, it has been reported that the cost of agitation dredging by rakes and beams can be less than 10 per cent of the cost for conventional dredging but not as predictable or efficient as conventional dredging. Data show a definite correlation between dragging speed and dredging rate. The advantages and limitations for rake and drag beams are similar to those reported for other agitation techniques.

4.4.1.4 Potential for application of agitation dredging in South African estuaries

As indicated, agitation dredging has the potential to remove sediment from locally selected areas under suitable conditions. It is not considered suitable for the removal of sediment over large areas. For relatively small scale sediment removal in a shallow estuary, the size of boat required for agitation dredging (including Prop-Wash and Rakes and Drag Beams) will depend on the available navigable depth. However, an example of a suitable size of boat for this purpose would be a sea going fishing boat of about 15m length. For smaller-scale operations the utilisation of a large ski boat could also be considered (in the appropriate depth and with the selection of the appropriate size rake or drag beam).

A good local example is the recent successful uncovering of an existing 600mm effluent outfall pipeline in the surf zone in Camps Bay. The removal of a sand layer about 2m thick was done by directing a fishing boat's propeller downwards by means of a pipe-bend arrangement around the propeller while

the boat was anchored. More detailed information can be obtained from the contractor who carried out the operation, *Civil & Coastal Construction (Pty) Ltd*.

4.4.2 Fluidization

Two fluidization techniques are presented here i.e. Water Injection Dredging (WID) and Fluidization System to create a sand trap.

4.4.2.1 Water Injection Dredging (WES, 1993).

Water injection dredging (WID) is a technique which liquefies shoal sediments, causing it to flow to deeper areas where it does not affect navigation.

WID is based on a very simple concept : vessel mounted pumps inject water directly into the sediment voids through low-pressure jets mounted on a long horizontal pipe. The horizontal pipe with the jets, is dragged over the bottom while jetting downward. This liquefies the upper layers of the sediment creating a gravity driven density current that can flow down very mild slopes. The density current transports shoal material to deeper water, where it can settle without impeding navigation, or be carried further away by strong natural currents. The principle of WID is illustrated in Figure 4.8.

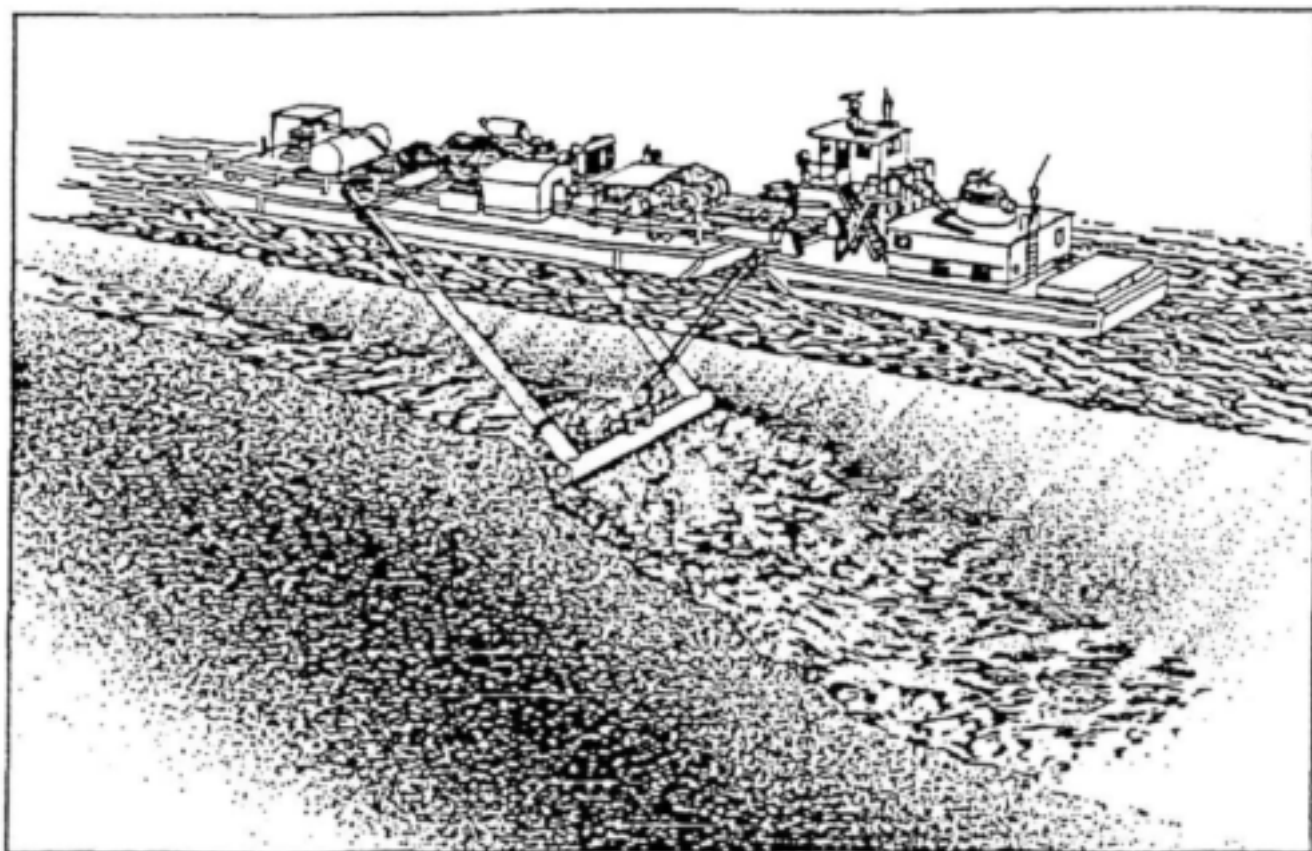


Figure 4.8 Sediment liquefaction and transport by water injection dredging (WES, 1993). By means of a series of downward jets mounted on a bar sediment is liquefied which creates a gravity driven density current that can flow down mild slopes.

Because the dredging equipment is simple to operate with minimal crew or other support and because there is no need to actively transport the dredged material to a disposal site, WID offers a potentially low-cost alternative to traditional dredging for appropriate locations. The method was successfully tested at two sites in the Mississippi river dredging section of navigation waterways in the river.

The tests concluded that WID appears to have potential at other sites. Application in sand greater than 0.2 mm diameter will be very site specific, requiring nearby deeper water and smooth down slope gradients. WID is not generally suitable if sand greater than 0.2 mm diameter has to be moved more than about 100 m.

The applicability of WID in SA Estuaries are considered limited since sufficiently deep areas in SA Estuaries are limited or non existent.

4.4.2.2 Fluidization system for channel maintenance and sand bypassing (WES, 1992)

Fluidization is a process in which fluid is injected into a granular medium (typically sand) causing the grains to lift and separate. Recent research on fluidization of sand at tidal inlets and harbour mouths has been undertaken for maintenance of navigation waterways and for use in sand bypassing. An example of the application of fluidization in a sand bypassing system is presented schematically in Figure 4.9. The fluidization is used in conjunction with a fixed slurry pump.

An example of the application of fluidization for the maintenance of a navigation channel is presented schematically in Figure 4.10.

The design objectives for a fluidization system are primarily to create a trench of a given cross section and length. To obtain a trench, complete fluidization must be achieved. The two basic parts of the design are the hydraulic aspect to obtain full fluidization and a geometric element to obtain a desired trench geometry. Recent basic research has helped to define these two aspects.

For both the applications of fluidization shown in Figures 4.9 and 4.10 the water is pumped into a perforated pipe buried beneath the sand surface. Water is pumped into the fluidizer pipe from which it exits from the perforations. The flow must be sufficient to create full fluidization of the whole region above the pipe. Once the region above the fluidizer pipe is completely fluidized the sand acts as a fluid, and will flow as a density current towards the crater formed by a slurry pump such as a jet-pump.

Full design guidelines for a fluidizing system are described in a design report of the US Army Engineers' Waterways Experiment Station (WES, 1992).

4.4.2.3 Potential for application of fluidization in South African estuaries

Fluidization (as in the case of agitation dredging) has the potential to remove sediment from local selected areas under suitable conditions. It is considered not suitable for the removal of sediment over large areas.

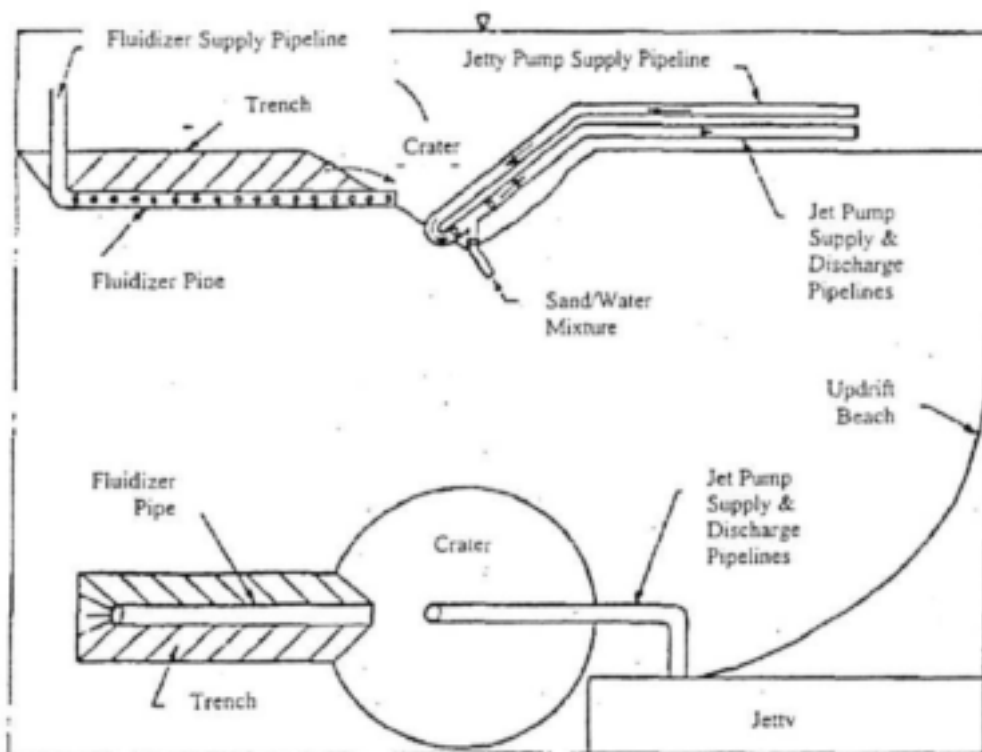


Figure 4.9 Schematic plan view of a fluidized trench creation used in conjunction with a slurry pump (WES, 1992). Sediment is fluidized by means of a fluidizer pipe to feed a stationary slurry pump located on the updrift side of a training jetty.

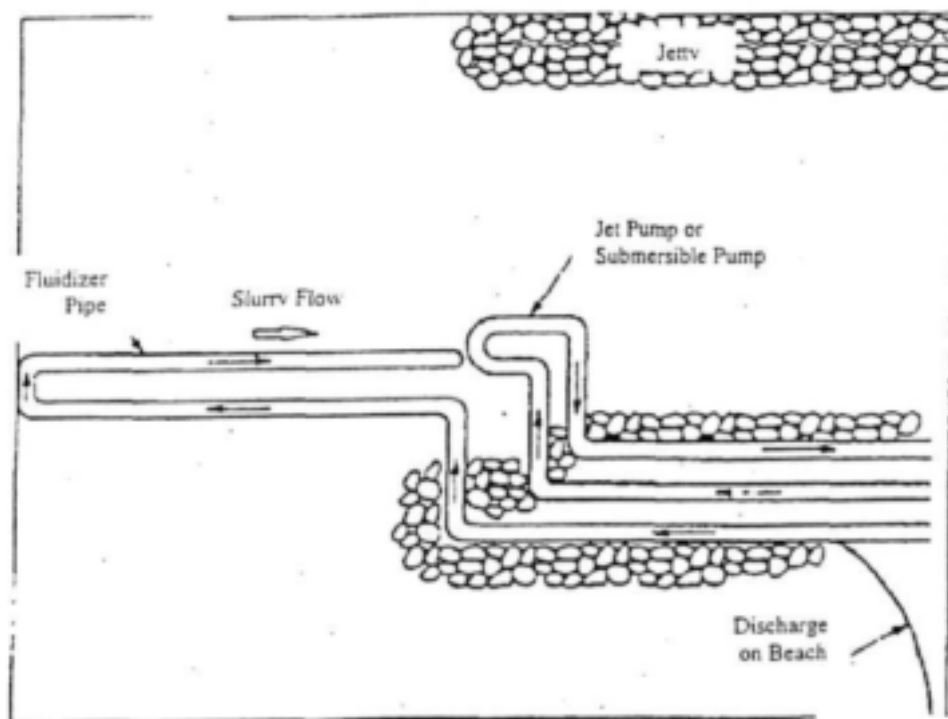


Figure 4.10 Schematic plan view of the components of a fluidizer system in a tidal inlet in conjunction with a jet or slurry pump (WES, 1992). This is similar to Figure 4.9 but located between training jetties.

4.4.3 Partial flow restriction of tidal ebb or flood flow

The partial restriction of tidal ebb flow (only allowing tidal flood flow) in a portion of an estuary where local sedimentation is required to be removed has been successfully applied in the Knysna Estuary.

Major sedimentation had occurred in the Green Hole between Leisure Island and the causeway to The Heads and the southern access channel had become blocked completely.

The CSIR supported a suggestion from the local community to attach tidal flaps to the culverts underneath the causeway to Leisure Island in the Knysna Estuary to allow only tidal flood flow through the culverts. A narrow channel was also excavated to allow initial flushing. This induced one-directional tidal flow was sufficient to remove undesirable accumulated sediment from this area and also improved water replenishment and consequently water quality in this part of the estuary (CSIR, 1989).

The potential of such a technique is again to remove sediments from locally selected areas and it can only be utilized under special conditions, in particular that more than one channel can be utilised by the ebb and flood flows. Such a situation also occurs in the Kowie Estuary, and Schumann *et al.* (2001) have proposed a variable boom to increase the ebb flows in a section of the estuary, thus scouring out accumulated sediment. The technique is specific to selected areas, and it is unlikely to be suitable for the removal of sediments over large areas.

4.5 POTENTIAL SEDIMENT REMOVAL BY TIDAL FLOODING

The concept of tidal flooding entails the temporary damming (by means of a temporary or permanent collapsible dam structure) of the ebb flow at strategic locations in the estuary. By means of controlled release of the dammed part of the tidal prism by collapsing the temporary dam, a degree of sediment flushing downstream of the temporary dam could be expected.

Laubscher (2000) proposed that this method be applied in the Bushmans or Kariega Estuaries by means of a series of temporary collapsible dams. The concept is also proposed in a report by Misselhorn (1998) and Dr Davidson (pers comm) has experimented with a small scale boom in the Kowie Estuary.

All these techniques essentially strive to increase ebb flow velocities to scour excess marine sediments from an estuary i.e. what a flood would normally do. It is also important that the region where this is done is near to the estuary mouth, so that the scoured sediment reaches the sea, and does not accumulate at another area within the estuary. Furthermore, the sea conditions at the time of the operation should also be considered, since this will determine whether the flushed sediment will be removed from the estuary mouth by the prevailing longshore drift.

It is considered that the concept of tidal flooding, utilized for the removal of sediments in an estuarine environment, warrants further investigation. Consequently the following strategy for the evaluation of the tidal flooding concept is proposed in a selected estuary:

- (a) A hydrographic survey must be carried out to establish flood and ebb flow channel configurations, sand bank elevations and sediment budgets in the estuary. At the same time the

tidal water level variations must be determined, combined with sediment characteristics. This is required for the proper planning of dam locations, and for the assessment of the effectiveness of the technique.

- (b) Where appropriate, an evaluation of the effectiveness of tidal flooding for the particular estuary should be made using suitable modelling techniques, e.g. a numerical model (hydrodynamic/sediment transport type model). The reason for the utilisation of a numerical model is to evaluate the scour efficiency of the method over a number of tidal cycles, since it is expected that if the method is feasible it will require operation over a relatively long period to have the desired effect. The scouring effect of the flooding must be established locally and farther downstream (up to the estuary mouth) for proper evaluation purposes.
- (c) In parallel with (b) above, an evaluation must be made of the technique using proven collapsible types of dams on the market (e.g. *Duradam*, which can be mounted on a suitable sand bed). The sand bed will have to be protected both on its upstream and downstream sides. Protection on the upstream side of such a dam is necessary to prevent undermining as a result of piping when the head on the upstream side is higher than on the downstream side. Bed protection on the downstream side is also necessary to prevent underscour of the structure when the dam starts to overflow. Permanent collapsible dam products are also on the market, such as that manufactured by *Bridgestone*. This type of dam is mounted/attached on a concrete foundation. Whichever method is selected, it will most probably require adaptation for the particular application. It is considered advisable that the selected method (with possible adaptations) be laboratory tested on a relatively large scale (a two dimensional flume test might be appropriate) to enable the adaptation of the method to suit the specific conditions and requirements.
- (d) If indications are that tidal flooding will be effective and economically feasible, the envisaged method and equipment should be tested on a limited scale in the field. However, before this can be done, the potential impact on the environment of such testing must be assessed; this is a legal requirement as discussed in chapter 5.
- (e) Should field testing in turn indicate that full-scale implementation is warranted, authorisation in terms of the applicable environmental legislation will likewise be required.
- (f) If the indications are that tidal flooding will be effective and economically feasible, the method can be evaluated in the field on the specified estuary (after the necessary permits have been obtained).

The concept of tidal flooding has merits in principle. The aim of the above proposed strategy is to evaluate it and to establish if it is technically practical and cost-effective compared to conventional dredging methods.

4.6 CONCLUDING REMARKS

Existing techniques for the prevention / limitation of the ingress of marine sediments have been described, and an overview of commercial dredging techniques in use locally and overseas has been presented. Those techniques considered relevant to this study have been described in more detail.

Other methods consisting mainly of techniques to manipulate sediment inside an estuary, specifically the removal of shoals, were also addressed. Finally, the concept of tidal flooding for the removal of sediment was discussed: at this stage its efficiency and feasibility has not been proved locally. Further work will be necessary to enable a comparison between conventional dredging and tidal flooding as a means to remove marine sediment from South African estuaries.

The most widely applied method used to remove sediment is by means of conventional dredging. It is considered that the most appropriate dredger type for removal of sediment from South African estuaries is the suction type dredger (with or without a cutter head). Dredging by means of this type of dredger can be done by local dredge contractors.

To minimise cost, 'selective dredging' should be done i.e. only the areas necessary to be dredged (e.g. for navigation purposes or to ensure the ecological health of the estuary). To enable a good decision to be made on where, when, and how much to dredge it is necessary to have a good understanding of the physical and ecological character of the estuary system.

Disposal practices of dredged material follow on from this, and include proven beneficial uses of dredged material. The most appropriate location of dredge spoil discharge is considered to be on the downdrift side of the estuary mouth. In some cases the dredging of a sand trap near the estuary mouth might be appropriate to limit the distance of marine sediment penetration into an estuary.

The actual removal of sediment from an estuary using any of the means discussed here forms the end-point of a process which is discussed further in Chapter 6. It involves the comprehensive definition of all relevant physical and environmental factors of the estuary, the definition of the corresponding human needs (e.g. recreational and commercial activities), and complying with all legal and permit requirements.

5

LEGAL FRAMEWORKS

5.1 INTRODUCTION

As could be anticipated, the manipulation of an estuary's morphology may invoke legal processes. In effect, specified activities associated with sediment management may not take place unless they have been permitted by the appropriate environmental authority.

This chapter provides an overview of legislative requirements which are or may be applicable to estuarine sediment management. It concludes with a summary to guide proponents of sediment management projects in the identification of, and compliance with, those statutory provisions which may be relevant to a particular initiative.

An appreciation of statutory requirements is crucial because provision needs to be made during project planning for possible costs and time involved in meeting them. Projects of this nature invariably attract keen public interest, and often controversy, and any failure to comply fully with stipulated frameworks will in all likelihood lead to adverse publicity and a compromising of the credibility of both the project and its proponent(s). Moreover, illegal activities may elicit punitive measures.

The applicable permitting processes specify opportunities for public involvement. The purpose of this involvement is to ensure that, by the time a project reaches the implementation stage, any debates and /or controversies should have been resolved.

Placing the onus on project proponents to obtain prior authorization for sediment management initiatives enables the state to evaluate project proposals in accordance with sound environmental practice. The state will also interact with proponents to a point where such proposals are officially endorsed, modified or rejected.

Notwithstanding all of the above, it is important to note that at the time of compilation of this report (mid-2001), South African legislation pertaining to estuarine management has not been finalised. This is in part attributable to the law reform exercise underway at present. At the same time, while the drafting of a coastal management bill to complement the *White Paper for Sustainable Coastal Development in South Africa* in 2000 has been initiated, its implications for existing legal parameters applicable to the coastal zone are unclear.

Under the circumstances, if this particular document is utilised in the planning of a sediment management project, it will be important for the user to ascertain the implications for the project of any changes which may have been effected to the legal frameworks outlined here.

5.2 RELEVANT LEGISLATION

The Bill of Rights in the Constitution of the Republic of South Africa declares that everyone has the right to have the environment protected for the benefit of present and future generations. This is done through reasonable legislative measures that promote conservation and secure ecologically sustainable development and use of natural resources, while promoting justifiable economic and social development.¹

Statutes which may be applicable to sediment management initiatives in South African estuaries include:

- The National Environment Management Act (Act 108 of 1998), or NEMA;
- The Environment Conservation Act (Act 73 of 1989), or ECA;
- The Sea-Shore Act 21 of 1935, or SSA, and
- The National Water Act (Act 23 of 1998), or NWA.

Depending on the exact nature of any particular sediment management initiative, provisions of other legislation such as the Minerals Act (Act 50 of 1991) and the various provincial planning ordinances may also apply. Furthermore, the Marine Living Resources Act (Act 18 of 1998) places specific constraints on activities which may be carried out within a marine protected area as provided for in the Act. These activities expressly include dredging and the extraction of sand or gravel, as well as the erection of structures.²

Specific implications of this review exercise for estuarine sediment management are included in the outline of legislation which follows.

5.2.1 National Environmental Management Act (NEMA)

In addition to giving effect to the Constitutional provision referred to in §5.2, NEMA seeks to establish principles for decision-making on matters affecting the environment. In particular, the principles set out in Chapter 1 of NEMA “*serve as guidelines by reference to which any organ of state must exercise any function when taking any decision in terms of this Act or any statutory provision concerning the protection of the environment.*”³

One of these principles is that “sensitive, vulnerable, highly dynamic or stressed ecosystems, such as coastal shores, estuaries, wetlands or similar systems require specific attention in management and planning procedures, especially where they are subject to significant human resource usage and development pressure.”⁴

A further principle is that “environmental management must be integrated, acknowledging that all elements of the environment are linked and interrelated, and it must take into account the effects of

¹ Section 24 of Act 108 of 1996

² Section 43

³ Section 2 (1) (c)

⁴ Section 2 (4) (r)

decisions on all aspects of the environment and all people in the environment by pursuing the selection of the best practicable environmental option.”⁵

Chapter 5 of NEMA purports “to promote the application of appropriate environmental management tools in order to ensure the integrated environmental management of activities.”⁶ As such, the chapter contains the provision that “the Minister⁷ may with the concurrence of the MEC⁸, and every MEC may with the concurrence of the Minister, in the prescribed manner identify activities which may not be commenced without prior authorization from the Minister or MEC.”⁹ Likewise, the Minister and every MEC “may make regulations.....in respect of such authorizations.”¹⁰

One task being addressed in the law reform exercise mentioned above is the promulgation under Chapter 5 of NEMA of a suite of environmental impact assessment (EIA) regulations. It must be stressed that **a suite of regulations of this nature was promulgated under the Environment Conservation Act in 1997, and has been an effective framework to date for containing environmental impacts associated with specified activities.** This framework is dealt with in §5.2.2.1.

Notwithstanding this, numerous sections of the ECA were repealed by virtue of the promulgation of NEMA,¹¹ while NEMA furthermore indicates that the EIA regulations will be repealed upon or after the promulgation of alternative provisions under Section 24 (of NEMA).¹²

Of particular relevance is that a component of the law review exercise involves evaluation of the existing (ECA) regulations, with a view to the promulgation of a refined suite under NEMA. Therefore, while details pertaining to the former suite will be presented below, it must be borne in mind that an equivalent suite will in future reside under NEMA, that the NEMA suite may differ substantially from the ECA one, and that such differences could be directly relevant to estuarine sediment management.

Before dealing with the ECA regulations (§5.2.2) mention must be made of Chapter 7 of NEMA, which deals with the issues of compliance, enforcement and protection. The Act states that “every person who causes, has caused or may cause significant pollution or degradation of the environment must take reasonable measures to prevent such pollution or degradation from occurring, continuing or recurring, or, in so far as such harm to the environment is authorized by law or cannot reasonably be avoided or stopped, to minimize and rectify such pollution or degradation of the environment.”¹³

⁵ Section 2 (4) (b)

⁶ Section 23 (1)

⁷ The *Minister of Environmental Affairs and Tourism* (Section 1 (xx))

⁸ “The member of the Executive Council to whom the Premier has assigned the performance in the province of the functions entrusted to a MEC by or under such a provision” (Section 1 (xix))

⁹ Section 24 (2) (a)

¹⁰ Section 24 (2) (c)

¹¹ Section 50 (1)

¹² Section 50 (2)

¹³ Section 28 (1)

The persons on whom the Act places these obligations “include an owner of land or premises, a person in control of land or premises or a person who has a right to use the land or premises on which or in which

- (a) any activity or process is or was performed or undertaken, or
- (b) any other situation exists, which causes, has caused or is likely to cause significant pollution or degradation of the environment.”¹⁴

Among the measures which may be required of such persons are measures to “investigate, assess and evaluate the impact on the environment”¹⁵ of a given activity or process.

By way of enforcement of these provisions, it is specified that the Director-General of the Department of Environment Affairs and Tourism, or alternatively the head of a provincial department responsible for environmental affairs, may direct any person who fails to take such measures “to-

- (a) investigate, evaluate and assess the impact of specific activities and report thereon;
- (b) commence taking specific reasonable measures before a given date;
- (c) diligently continue with those measures, and
- (d) complete them before a specified reasonable date.”¹⁶

The Act furthermore makes provision for the Director-General or provincial head of department to “take reasonable measures to remedy the situation,”¹⁷ should a person fail to comply, or inadequately comply, with a directive issued as described above. It also establishes a basis¹⁸ for the recovery of costs incurred as a result of acting under this provision.

The majority of estuarine sedimentation management initiatives would in fact be unlikely to attract action under NEMA in its present form. The reason for this is that the frameworks created by the ECA and the Sea-Shore Act (SSA) will encompass most initiatives of this nature.

However, it is possible that situations will arise where neither of the latter are applicable. In such instances, their non-applicability does not imply that no legal constraints are applicable to such initiatives. Given both the principle quoted above in terms of which estuaries require specific attention in management and planning procedures, and the extensive and over-arching provisions of NEMA, it can be inferred that authorities may be inclined to invoke NEMA to ensure that those initiatives falling outside the scope of these two Acts (ECA and SSA) will nonetheless be controlled using integrated environmental management perspectives.

In summary, the purpose of this coverage of NEMA has been to:

- (a) provide insight into some of the precepts encompassed by the country’s primary

¹⁴ Section 28 (2)

¹⁵ Section 28 (3) (a)

¹⁶ Section 28 (4)

¹⁷ Section 28 (7)

¹⁸ Section 28 (8)

environmental statute;

- (b) provide notice of the impending incorporation into NEMA of a suite of environmental impact assessment regulations, *in lieu* of the regulations currently residing under the ECA, and
- (c) point out the applicability of NEMA to estuarine sediment management in situations where other statutes are not applicable.

5.2.2 Environment Conservation Act (ECA)

The ECA aimed “to provide for the effective protection and controlled utilization of the environment and for matters incidental thereto”¹⁹, and predated NEMA as the country’s primary environmental statute.

As indicated, much of the ECA was repealed with the promulgation of NEMA (§5.2.1), while those sections which provide a foundation for the environmental impact assessment regulations will in turn be repealed when equivalent regulations under NEMA are adopted. Broadly, this foundation consists of Parts V and VI of the ECA, which relate to the “control of activities which may have detrimental effect on the environment”, and provide a basis for the promulgation of regulations.

With regard to estuarine sediment management, these parts of the Act have further bearing because they also provide a foundation for what are known as the Sensitive Coastal Area Regulations. Both of these sets of regulations will be dealt with here, as will other pertinent aspects of the Act.

5.2.2.1 The Environmental Impact Assessment (EIA) Regulations

In terms of the Act the Minister of Environmental Affairs and Tourism “may by notice in the *Gazette* identify those activities which in his opinion may have a substantial detrimental effect on the environment, whether in general or in respect of certain areas.”²⁰ Accordingly, Schedule 1 to Government Notice No. R. 1182 of 5 September 1997 (Government Gazette No. 18261) lists activities which the Minister identified in general as activities of this nature. Schedule 2 specified dates on which the notice would come into effect in respect of the various activities, the latest of which was 1 April 1998.

The following listed activities are or may be of relevance to estuarine sediment management:

- (a) the construction or upgrading of marinas, harbours and all structures below the high water mark of the sea;²¹
- (b) the construction or upgrading of canals and channels, including diversions of the normal flow of water in a river bed²²

¹⁹ Preamble

²⁰ Section 21 (1)

²¹ Activity 1 (e) of Schedule 1 to GN No. R. 1182 of 1997.

²² Activity 1 (i) of Schedule 1 to GN No. R. 1182 of 1997

- (c) the construction or upgrading of dams, levees or weirs affecting the flow of a river,²³ and
- (d) the reclamation of land below the high water mark of the sea and in inland water including wetlands.²⁴

While neither the Act nor the EIA regulations qualify the terms “high-water mark” and “sea”, for practical purposes guidance can be drawn from the Sea-Shore Act (§5.2.3) in implementing the regulations relative to activities (a) and (d) above.

Accordingly these activities are subject to the regulations if they are contemplated in an estuarine context, since the Sea-Shore Act is quite explicit in its inclusion of “tidal lagoons” and “tidal rivers” within its ambit. (A precedent exists for cross-reference from the ECA to the Sea-Shore Act, in the sense that Sea-Shore Act definitions have been adopted for the purposes of the Sensitive Coastal Area regulations, which were also promulgated under the ECA (§5.2.2.2)).

Having made provision for the identification of activities which may have a detrimental effect on the environment, the ECA stipulates that no person shall undertake an identified activity “or cause such an activity to be undertaken except by virtue of a written authorization” issued by the Minister or a competent authority as defined in terms of the Act.²⁵ A competent authority is effectively the provincial authority to whom administration of the Act has been assigned.²⁶

It further stipulates that such authorization “shall only be issued after consideration of reports concerning the impact of the proposed activity and of alternative proposed activities on the environment, which shall be compiled and submitted in such manner as prescribed.”²⁷ The Minister or competent authority “may at his or its discretion refuse or grant the authorization on such conditions as he or it may deem necessary.”²⁸ Provision is made for withdrawal of the authorization in the event of specified conditions not being complied with.²⁹

Finally, the Act creates the facility for the Minister to make regulations with regard to identified activities, concerning *inter alia* the scope and content of environmental impact reports, and the evaluation of such reports and of the effect of a proposed activity and alternative activities on the environment.³⁰

Arising from this facility, the Schedule of listed activities in Government Notice No. R. 1182 of 1997 is complemented by the environmental impact assessment regulations published as Notice No. R. 1183 of 1997 in the same gazette. The regulations specify the responsibilities of both applicant and competent authority in relation to the applications for authorization to undertake activities, as well as associated procedures, including the lodging of appeals against the outcome of applications. An

²³ Activity 1 (j) of Schedule 1 to GN No. R. 1182 of 1997

²⁴ Activity 7 of Schedule 1 to GN No. R. 1182 of 1997

²⁵ Section 22 (1)

²⁶ Proclamation No. R. 43, 1996

²⁷ Section 22 (2)

²⁸ Section 22 (3)

²⁹ Section 22 (4)

³⁰ Section 26

applicant must appoint an independent consultant to comply with the regulations on his / her behalf, and emphasis is placed on public participation in the specified process.

The application process involves numerous iterations, and makes provision for ongoing liaison between the applicant's consultant and the authorizing agency. It also grants the latter discretion to determine whether certain of the iterations can be combined or truncated. In general, it could be said that the length and complexity of the impact assessment process is a function of the scale of the envisaged activity, the characteristics and sensitivity of the receiving environment, and the extent to which the project proposal engenders stakeholder reaction.

A fundamental variation in processes conducted in terms of the regulations revolves around whether an authority is able to issue a decision on an application based on the information contained in a scoping report, or whether such information needs to be supplemented by an environmental impact assessment proper. In brief, key components of a scoping report include descriptions of how the environment may be affected by a proposed activity, environmental issues identified, all alternatives identified, and the public participation process followed.³¹

Upon receipt of a scoping report, and after the effecting of any amendments to the report required by the authority, the authority may issue an authorization with or without conditions, or reject the application.³²

Alternatively, the authority may require an environmental impact assessment which focuses on the identified alternatives and environmental issues identified in the scoping report.³³ Following the submission of an environmental impact assessment which complies with the requirements specified in the regulations,³⁴ the authority may, as above, authorize the application with or without conditions, or reject it.

In conclusion, the outcome of an application in terms of the EIA regulations is detailed in a "record of decision," which must be issued on request to any interested party.³⁵ Provision is made for the lodging of appeals against such decisions.³⁶

Compliance enforcement in respect of the EIA regulations is dealt with in §5.2.2.2 (the Sensitive Coastal Area Regulations), since the same penalty provisions under the ECA are applicable to both sets of regulations.

5.2.2.2 The Sensitive Coastal Area (SCA) Regulations

Utilising the same facilities under the Act as those used for the identification and regulation of activities under the EIA legislation, the Minister has identified activities which may have a substantial detrimental

³¹ Regulation 6 (1) of GN No. R. 1183 of 1997

³² Regulations 6 (3) and 9 of GN No. R. 1183 of 1997

³³ Regulation 6 (3) (b) of GN No. R. 1183 of 1997

³⁴ Regulation 8 of GN No. R. 1183 of 1997

³⁵ Regulation 10 (1) of GN. No. R. 1183 of 1997

³⁶ Regulation 11 of GN. No. R. 1183 of 1997

effect on the environment in demarcated coastal localities, and published regulations pertaining to the permitting of these activities.

One class of activities identified in this manner is covered under the term "dredging," which is qualified as "dredging, excavation, removal or moving of soil, sand or rock from a river, tidal lagoon, tidal river, floodplain or wetland."³⁷ For the purposes of these provisions, "tidal lagoon" and "tidal river" respectively mean a tidal lagoon and tidal river as defined in the Sea-Shore Act (§5.2.3).

The so-called test case for these regulations pertained to the area between Tergniet and the Kaaimans River on the Garden Route, or the Outeniqua Sensitive Coastal Area.³⁸ Subsequently the demarcated area was extended eastwards to the Bloukrans River,³⁹ while regulations were promulgated proclaiming sensitive coastal areas at Pennington and Umtamvuna on the KwaZulu-Natal south coast.⁴⁰

In complexio these regulations are similar to the EIA regulations, in that proponents of listed activities within the demarcated areas are required to apply for permits prior to engaging in such activities, and environmental impact reports must be submitted in support of applications. A significant difference is that these reports do not necessarily have to be prepared by consultants, but may be prepared by the applicants themselves. Moreover, local authorities are mandated in the regulations to issue authorizations for listed activities. However, the regulations are not applicable to activities which are subject to approval in terms of the environmental impact assessment regulations, or the Sea-Shore Act.

In practical terms, these regulations are clearly only relevant in the various demarcated areas. On the other hand, they are currently under scrutiny as part of the law reform exercise. Among the options being investigated as regards their future are their continued existence under a coastal management act or under a coastal chapter in NEMA, or alternatively their amalgamation with the EIA regulations.⁴¹ In all of this, amendment of existing provisions, or even the adoption of elements thereof for general (as opposed to locality-specific) applications, has to be regarded as a possibility. **Those parties with an interest in estuarine sediment management need to stay abreast of the changing scenario as regards these regulations.**

The Act specifies⁴² severe penalties for those found guilty of contravening both the EIA and SCA regulations. At the present time (July, 2001) any person who contravenes a provision of the section of the acts in terms of which they were promulgated, or fails to comply with a condition of a permit, permission, authorization or direction issued or granted under the said provision, "shall be guilty of an offence and liable on conviction to a fine not exceeding R100 000 or to imprisonment for a period not exceeding 10 years or to both such fine and such imprisonment, and to a fine not exceeding three times the commercial value of any thing in respect of which the offence was committed." Additionally, provision is made for the imposition of a fine not exceeding R250, and imprisonment for a period not

³⁷ Schedule 1 to GN's No.'s R. 879 of 1996, 1526 of 1998 & 1529 of 1998 respectively

³⁸ GN's No.'s. R. 879-881 of 31 May 1996

³⁹ GN's No.'s. R. 1526-1528 of 27 November 1998

⁴⁰ GN's. No.'s. R. 1529 -1531 of 27 November 1998

⁴¹ *Pers. Comm., S MacDonald, DEAT*

⁴² Section 29 (4)

exceeding 20 days, or both, for every day of persistence of an offence for which a person has been convicted under the Act.⁴³

In the event of a conviction under the Act, a court may order that environmental damage associated with the offence for which a person has been convicted be repaired to the satisfaction of the Minister or competent authority.⁴⁴ If such damage is not repaired within a specified period, the Minister or competent authority may take steps to effect the necessary repairs, and recover costs incurred in the process.⁴⁵

Provision is also made for the granting, with or without conditions, of exemption from the requirements of regulations promulgated under the Act, subject to the Minister or competent authority being satisfied that adequate motivation has been attached to an application submitted in the prescribed manner.⁴⁶

5.2.3 The Sea-Shore Act

This Act declares the State President to be the owner of the sea-shore and the sea within the territorial waters of South Africa, and provides *inter alia* for the granting of rights in respect of the sea-shore and the sea.⁴⁷ The sea-shore and the sea “shall not be capable of being alienated or let except as provided by this Act or by any other law, and shall not be capable of being acquired by prescription.”⁴⁸

However, **any portion of the sea-shore and the sea which was alienated before the commencement of the Act (1935) “shall be deemed to have been lawfully alienated.”**⁴⁹ This is of particular relevance to estuaries in as much as the common boundary of riparian properties to either side of a particular estuary, at the (pre-commencement of the Act) time of alienation, may have been demarcated as the centre of the estuary itself. It follows that the provisions of the Act are not applicable to this category of property.

In terms of the Act, “sea” is defined as “the water and the bed of the sea below the low-water mark and within the territorial waters of the Republic, including the water and the bed of any tidal river and of any tidal lagoon,” whereas “sea-shore” means “the water and the land between the low-water mark and the high-water mark.”

A “tidal river” is defined as “that part of any river in which a rise and fall of the water-level takes place as a result of the action of the tides,” while a “tidal lagoon means any lagoon in which a rise and fall of the water-level takes place as a result of the action of the tides.” Furthermore, “High water mark” is “the highest line reached by the water of the sea during ordinary storms occurring during the most

⁴³ Section 29 (6)

⁴⁴ Section 29 (7)

⁴⁵ Section 29 (8)

⁴⁶ Section 28A

⁴⁷ Preamble

⁴⁸ Section 1 (3)

⁴⁹ Section 2 (2)

stormy period of the year, excluding exceptional or abnormal floods.”⁵⁰

The Act stipulates that “the Minister may, on such conditions as he may deem expedient, let any portion of the sea-shore and the sea”⁵¹ for a variety of listed purposes. The Minister, in so far as a provision of the Act is applied in or with reference to a particular province, means the competent authority to whom the Act has been assigned in that province, with an exception being where portions of the sea and sea-shore fall within ports or harbours.⁵² Assignment is generally to the provincial department charged with environmental management.

Among the purposes for which portions of the sea and sea-shore may be let, the following are of particular relevance to estuarine sediment management:

- “the construction or improvement of wharves, piers, jetties and landing stages;”⁵³
- “the construction of breakwaters, sea walls, promenades, embankments, esplanades, buildings or other structures,”⁵⁴ and
- the carrying out of any work which in the opinion of the Minister serves a necessary or useful purpose.”⁵⁵

The Minister may furthermore permit “the removal of any material (other than precious stones, natural oil, precious metals, base minerals, aquatic plant, shell or salt, all as qualified under the Act) from the sea-shore and the sea.”⁵⁶

Before any lease is entered into, or permit granted, for the above purposes, the Minister must, in terms of the Act, “cause a notice to be published in the Provincial Gazette and in not less than one newspaper” in the area of the envisaged activity.⁵⁷ Any objection submitted in response to such advertisement must be considered by the Minister prior to entering into a lease or issuing a permit.⁵⁸

In respect of offences and penalties, any person who

- uses, for the purposes mentioned in the Act, any portion of the sea-shore or sea of which the State President is the owner, without having obtained the requisite lease;
- removes any material as contemplated above from the same zone, or
- contravenes or fails to comply with a lease condition,

“shall be guilty of an offence and liable on conviction to fine or to imprisonment for a period not exceeding two years.”⁵⁹

⁵⁰ See Section 1 for definitions

⁵¹ Section 3 (1)

⁵² Section 1

⁵³ Section 3 (f)

⁵⁴ Section 3 (g)

⁵⁵ Section 3 (o)

⁵⁶ Section 3 (2)

⁵⁷ Section 3 (5)

⁵⁸ Section 3 (6)

⁵⁹ Section 12A (1)

In the event of conviction for the erection of an illegal structure, the court may order the person convicted “to remove the structure at his own cost and within such time as the court may determine.”⁶⁰ The court may further order the person convicted “to repair any damage caused to the sea-shore by the act constituting the offence to the satisfaction of the Minister.”⁶¹

The relevance of this Act to estuarine sediment management is obvious. In conclusion it is pertinent to point out that although the Act was not overtly promulgated to protect the environment, its assignment to environmental agencies has resulted in it being used as such, given the prerogative of the competent authority to attach conditions to the letting of property in terms of the Act, and the points of departure to be expected in agencies of this nature.

5.2.4 The National Water Act

A stated purpose of this Act is “protecting aquatic and associated ecosystems and their biological diversity.”⁶² Chapter 4 lays the basis for regulating water use. For the purposes of the Act, water use includes “impeding or diverting the flow of water in a watercourse”⁶³ and “altering the bed, banks, course or characteristics of a watercourse.”⁶⁴ In turn, “watercourse” is defined *inter alia* as a river, a natural channel in which water flows regularly or intermittently, or a wetland into which or from which water flows.⁶⁵

In general, a water use must be licensed. In issuing a license a responsible authority must take account of all relevant factors, including but not limited to the likely effect of the proposed use on the water resource, and on other water users.⁶⁶ In considering an application for a license for water use, the authority may require the applicant to undertake various actions with a view to supporting the application with pertinent information, assessing the likely effect of the proposed use on the environment, and facilitating public participation in the application process.⁶⁷

Although the Act was published in 1998, it only came into effect during 2000. As such, the extent to which its custodian, the Department of Water Affairs and Forestry, will give effect to the above provisions by becoming actively involved in estuarine sediment management, is unclear at present, in particular given the current mandates of the provincial departments charged with environmental protection. Proponents of sediment management initiatives should therefore be familiar with any developments in this regard.

⁶⁰ Section 12A (2)

⁶¹ Section 12A (3)

⁶² Section 2 (g)

⁶³ Section 21 (c)

⁶⁴ Section 21 (i)

⁶⁵ Section 1 (xxiv)

⁶⁶ Section 27 (1)

⁶⁷ Section 41

5.3 LEGAL CHECKLIST FOR SEDIMENT MANAGEMENT INITIATIVES

In broad terms, sediment management is likely to be accomplished with or without the use of structures erected or constructed within an estuary. To a significant extent, this will determine the legal framework within which such management must occur.

In the first instance, the construction or upgrading of any structures below the high water mark renders an initiative subject to the EIA regulations, which will then form the basis for the state to evaluate and take a position on the initiative. Compliance will not exempt the proponent from the requirement to obtain a lease under the Sea-Shore Act for the portion of the estuary below the high-water mark where the structure will be placed. It is however reasonable to anticipate that such a lease will be granted should authorization be issued under the regulations. In turn this assumes that the portion of the estuary involved is in fact subject to the provisions of the Sea-Shore Act.

The scenario described above is not applicable solely to the establishment of structures below the high water mark. It must be remembered that the construction or upgrading of canals and channels, as well as of dams, levees or weirs which affect the flow of a river, and diversions of the normal flow of water in a river bed, also require authorization under the EIA regulations. This is similarly the case should an initiative entail the reclamation of land below the high water mark. In the event of an initiative falling within this category of activities, the situation as regards the Sea-Shore Act likewise has to be ascertained.

On the other hand, sediment removal through the use of techniques such as dredging, which techniques do not involve the establishment of structures, may currently not be covered by the EIA regulations, depending on the exact nature of the operation. In such instances, the state will therefore rely on the Sea-Shore Act for evaluation and permitting purposes, with proponents needing to apply to lease the portion of the estuary where dredging is planned. Of course, this is on the basis that the Sea-Shore Act is applicable at the target locality. This must be determined in accordance with the limitation associated with the Act as alluded to in §5.2.3.

Thus far it has been shown that sediment management initiatives are likely to be covered by the EIA regulations, the Sea-Shore Act, or both of these. However, it is also evident that situations may arise where neither of these have reference. In such cases it is stressed that the duty of care provisions under NEMA will in any event be applicable, and hence proponents should be able to demonstrate that their initiatives have benefitted from deliberations akin to those which would have been required had these Acts applied.

Practically, this implies that proponents should collaborate with environmental authorities even when the EIA regulations and the Sea-Shore Act are not applicable, in order to familiarise themselves with the authorities' points of departure, ascertain their requirements, and minimize the probability of NEMA action being leveled against them.

In situations where the Sea-Shore Act does not apply to a portion of an estuary, it will in all likelihood nevertheless apply to the sea-shore and sea at the mouth of the estuary. Hence initiatives such as the breaching of an estuary mouth to facilitate sediment scour, will hinge on fulfillment of the requirements

under this Act for manipulation of the mouth area, and should not commence without this taking place.

Finally, it has been assumed that the Sensitive Coastal Areas regulations are not applicable at the locality where a sediment management project is envisaged. This is because of their limited application at present (§5.2.2.2), and the fact that their application at these localities, and the implications thereof for sediment management, are likely to be well-known there. Their applicability would add a further dimension to efforts to comply with all relevant legislative provisions, in the course of implementing a sediment management project.

At present, the exact requirements under the National Water Act as regards sediment management are unclear, but project proponents should stay informed about associated emerging frameworks. Consultation with the Department of Water Affairs and Forestry in the project planning stage is recommended. Disposal of dredge spoil for financial gain will involve the Minerals Act, while special provisions apply in marine reserves as provided for in the Marine Living Resources Act.

Within the context of estuarine sediment management initiatives, numerous situations may arise where multiple permitting is necessary. Where this is the case, these processes may be conducted in parallel. **In all instances, however, early consultation with appropriate authorities is vital, since apart from establishing a foundation for the requisite technical assessments, this approach will clarify which legal parameters are applicable to a particular initiative.**

In conclusion, therefore, since legal endorsement is likely to be at the epicenter of all estuarine management projects, the sooner contact is initiated with the decision-making authority, the better for project proponents and stakeholders.

An overview of the legislation which has been discussed in this chapter, together with an indication of which state authority should be contacted in any endeavor to comply with such legislation, is presented in tabular form in Section 6.2.4.

5.3.1 The Estuarine Reserve

Although not strictly relevant in terms of applicable legislation for initiatives involved with sediment movement, the determination of the so-called *Estuarine Reserve* impinges on sediment accumulation in estuaries. Chapter 3 of the National Water Act deals with the *Reserve*, which is the minimum fresh water flow which has to be maintained to comply with specified needs. The Reserve consists of two parts, namely the basic human needs reserve and the ecological reserve.

Of interest here is the ecological reserve, since this protects the resilience of water resources in order to sustain ecological functions and processes, which also include the mouth condition and potential to scour sediment. River floods play a major role in flushing sediments from an estuary (§2.6, §3.2.2.1, §A.2), and a reduction in the magnitude and occurrence of such floods because of dam developments in the catchments can therefore result in a disturbance of the long-term sediment balance in an estuary, and result in ongoing sedimentation. The reserve of freshwater required for the estuary, in terms of the Water Act, should therefore include the condition that the occurrences and magnitudes of such floods in future should be adequate to ensure that sufficient scouring of sediments will still occur.

However, before a reserve can be set, the class for an estuary must be determined. For this determination, its reference condition must be ascertained, i.e. how did it look in the past, its condition at present, and how it should look in the future. Thus each estuary has to be put into the most appropriate *ecological management class*. In order to do this, the Act makes provision for the inclusion and participation of local communities via the Catchment Management Agencies.

Once the class of an estuary is known, then the volume and quality of water needed to give it the level of protection specified can be determined. In this way the *resource quality objectives* can be implemented.

Editor's Note

As far as marine sedimentation in estuaries is concerned, in the context of the NWA the necessity of "regular" floods to scour out accumulated sediment must be considered as part of the ecological reserve. In other words, the use of water in catchment areas (through the building of dams, etc.) should be strictly managed and controlled if it inhibits the scouring effects of floods, depending on the allocated class of each estuary considered.

Determination of an ecological reserve is not a trivial matter, and is subject to uncertainties and interpretations of available data. In fact the lack of relevant data over long periods is one of the main shortcomings of such determinations, and reinforces the importance of monitoring as discussed in chapter 3; this includes storage in a central data bank. Protocols for undertaking reserve determinations in estuaries include the assessment of the extent to which the scouring effect of major floods has been inhibited. If such floods are reduced, then detailed investigations are required to predict effects on the long-term sediment equilibrium in estuaries.

However, the extent and manner of DWAF's intended application of the NWA to estuarine management, and the relationship of the envisaged application to existing government roles and responsibilities under other statutes, has not been clarified. In particular, clarification is still required whether estuarine reserve determinations are necessary before any of the specified steps can be taken to alleviate problems caused by the unwanted accumulation of marine sediments. The consequences of such determinations are also unclear. Very few estuarine reserve determinations have been completed in South Africa as a whole, while those in the Eastern Cape have had a low confidence because of a lack of data. Moreover, this state of affairs is likely to continue because of limited resources being made available for the implementation of legislative provisions.

These changing conditions emphasize the necessity of communities to work with local and national government structures in any attempt to move accumulated sediment or alter estuary channels; this should enable them to stay abreast of the latest legislative regulations. Nonetheless, it is strongly recommended that the practicality of government (DWAF, DEAT etc) and provincial department approaches are evaluated at a strategic level, and within the context of cooperative governance and involvement of local organisations; this has been recognised, and a committee for environmental co-ordination has been established between different government departments. There are complex issues involved, and the rules should be clarified.

6 SYNTHESIS OF MANAGEMENT OPTIONS

6.1 INTRODUCTION

The first five chapters of this report dealt in some detail with the natural causes and processes involved in marine sedimentation of estuaries, as well as management aspects, engineering techniques that can be used to move sediment, and the appropriate legislation. This chapter serves to present some guidelines for the approaches to be taken in solving problems that may arise in practice.

At the outset it must be recognised that perceived sedimentation problems can be due to the natural dynamics inherent in estuarine configurations; this has been discussed in Chapter 2. On the other hand, the problems could be due to man-made structures and other developments, and here the limitation of freshwater flow from catchment areas of parent rivers must be seen as a prime reason for greater sedimentation in estuaries. It may be that it is not possible to rectify the fundamental causes, e.g. by removing offending dams or changing a long-term natural progression of an estuary mouth. Whatever the case, a management decision could be made to use one, or some of the techniques described in Chapter 4 to move unwanted sediment.

Such a decision needs to be taken with a good knowledge of the fundamental processes involved, and a detailed comprehension of all the possible consequences. Moreover, it is important to appreciate that estuarine management involves a long-term programme, and that there are no 'quick-fix' solutions. Consequently, decisions must be made with long-term objectives in mind.

At the same time, management involves people and social responsibilities. Apart from the legal requirements detailed in Chapter 5, estuarine management needs to be firmly established within the local government structures, so that it is seen as a long-term investment by the community. This may be self-evident, since in most situations the estuaries themselves are the basic reason why communities were first established there. However, it is also true that many people seem to think that estuaries function independently of their activities, and therefore require no formal intervention.

Solutions of sedimentation problems will require funding, and some indication of the costs of moving sediment are given in Chapter 4. In sections of the Eastern Cape there are many relatively small estuaries in close proximity to each other, and to minimise costs, cooperation should be encouraged between local authorities to share resources and experience.

Guidelines for the approaches to be taken are detailed in the next section. Quite obviously these will vary from estuary to estuary, and adaptations need to be made as required: no standard solution exists that applies in all cases. The following section lists a number of 'don'ts', that must be observed in any estuary management plan, while a short conclusion ends the report. The Appendix details some unsuccessful remedies, then covers the effects of a flood in the Nahoon Estuary, and ends by discussing the sedimentation problems in the Kowie Estuary.

6.2 PROCEDURAL GUIDELINES

The management of an estuary should involve a number of stages before any decisions are made to remove unwanted sediment. At the start the basic management structures should be set up, and a definite commitment made for a long-term programme with definite objectives. Before any direct actions can be taken, a monitoring system must be established, and all the legal requirements must be satisfied.

It is important to recognise that sedimentation is only one part of the management of an estuary, but is quite obviously also impacted by other developments, particularly those involving constructions within its environs and the catchments of its parent rivers. Furthermore, this report deals only with problems due to marine sediment within the estuary.

6.2.1 The Management Structures

The South African policy on Sustainable Coastal Development approved in November 1999 “outlines a vision for the coast, and principles, goals and objectives for coastal management, together with a plan of action for implementing the policy”. In addition, “The policy introduces a *new facilitatory style of management* that involves cooperation and shared responsibility” (Glavovic, 2000). The policy, therefore, makes provision for participation of local stakeholders in the management of estuaries.

Estuaries, and the goods and services they provide, are clearly defined in space. This helps to define the group of people who have a direct interest in the state of the estuary. In essence these are the custodians of the estuary, and they need to organise themselves so that their voice can be heard and so that they can act as partners in estuary management.

In a healthy state, estuaries provide a wide range of goods and services. Since individuals value these differently, management must continuously seek to reconcile differences and strive to achieve equitable, efficient and sustainable use. Participation of interested and affected parties is essential. Before any physical intervention is possible in an estuary, there must therefore be basic agreement by the local community and the local authorities that there are specific problems. Objectives must be set for the future of the estuary and the community, and the means to reach these objectives identified; on an overall basis, such programmes should continue indefinitely into the future.

Since recreational and economic activities are not always compatible with each other, users of estuaries can be in conflict as each group strives to achieve their own objectives. Whilst conflict is commonly destructive, it is a source of energy and opportunity for collaboration to solve shared problems.

A critical first step in aligning individual energies, emotions and aspirations surrounding the problem is to reach consensus that it is a shared problem, and as such, it requires a shared solution. In many instances personal views are held so strongly that external, neutral, facilitation and establishment of formal processes and structures is required. Even then it may not be successful because dissenters can continuously disrupt the process. It takes leadership and robust processes and structures to weather these destructive influences successfully. Building trust is essential. Once stakeholders, at least the large

majority of those engaging the process, accept that they are partners in solving the problem, and begin to trust one another, behaviour becomes constructive and there is a willingness to work together.

Communication is an important foundation for progress. It is fraught with difficulty because stakeholders vary so much in their expectations, experiences, preferences, knowledge and understanding, and because individuals may hold particular views so strongly that they try to impose them on others. A structured process that continuously holds focus on the problem and the solution, rather than on individuals is essential. Barriers to communication can be broken down by starting discourse at a general rather than specific level. This allows individuals to move comfortably away from the particular issues that they feel very strongly about, and it reduces their ability to impose a view on others. Stakeholders generally aspire to protect the estuary as it contributes to their wellbeing. It is relatively easy, therefore, to arrive at a shared vision for the desired state of the estuary. This vision reinforces commitment to being a part of a collaborative endeavour, and helps rally stakeholders to action. Once stakeholders have a shared vision they are able to focus on the logical sequence of steps necessary to arrive at the actions they have to engage to promote attainment of their vision for the estuary. They can also decide on monitoring and auditing progress. In essence they can establish a management process that is strategic in that it enables them to anticipate problems, and adaptive in that it promotes continuous learning and corrective action.

It is impossible to implement actions without resources. The reality is that national and provincial government has neither the resources nor the intention of engaging management of estuaries, other than by providing policy direction and a degree of policing. Government has made provision for stakeholder participation in management of the coast and of estuaries and the fresh water required to sustain them. The opportunity exists therefore for stakeholder forums to gain the recognition necessary for contributing constructively to management of estuaries. The expectation is that stakeholders will mobilise their own resources in support of management to achieve the desired state of their estuary. This can be difficult and disheartening because it so dependent on volunteers. Leadership and alliances founded on trust and commitment are necessary for success.

The process of establishing co-management to promote sustainable use of estuaries is not for the fainthearted. Those who engage it will face many challenges. These are, however, minor compared with the challenge of living with continuous dissent and failure to solve problems. Further insights into estuary management are discussed in Breen and McKenzie (2001).

Figure 6.1 Conceptual interaction of management and monitoring actions for an estuary (from Breen and McKenzie, 2001).



6.2.2 The Physical Setting

For effective management the physical setting of the identified estuary must be described, since this will determine the kinds of management options available. The information listed below covers aspects necessary for this description, and should be readily available to a greater or lesser extent from published documentation. It must be recognised that the list is comprehensive, and that the details actually required will depend on the estuary itself and the reasons why the information is required. Thus there is no sense in obtaining information which is not pertinent for effective management, though reasons should then be given why specific information is not necessary.

Information required describing the physical setting of the estuary:

- The estuary type must be established in terms of the geology of the area. Thus the maturity of the estuary should be established in terms of the sediment level and the erosion base (§2.2.2), with other aspects being the slope of the coastal geomorphology and nearshore bathymetry, whether it is a rocky valley, the extent of the coastal plain, and the valley slope and shape.
- The estuary structure must be determined, in particular the extent and location of marine and fluvial sediments, the extent and nature of flood and ebb deltas and existing estuary channels. If not known, the freshwater inflow should be estimated, while the length of estuary and tidal prism can be calculated approximately from water level maxima and minima and aerial photographs. The characteristics of the estuary mouth, i.e. whether it is permanently or temporarily open must be documented in relation to seasonal changes.
- The coastal environment must be described. This should include the position of the estuary mouth in relation to local features such as headlands, bays, pocket beaches, dune fields and subaerial sandy barriers or bedrock barriers. The direction of the prevailing longshore drift and sediment transport should be apparent, and estimates of sediment volume transport should be obtained. The exposure to wave activity is important, and local tidal and longer period sea level variations should be described.
- Weather and climate. This should cover rainfall, the prevalence of floods, air temperatures and evaporation. The dominant seasonal winds should be described. In addition, an estimate should be made of the capacity and effect of dams in the catchment areas of parent rivers.
- Historical background information should be gleaned from all available sources. In particular, photographs are very valuable in defining the variability of the estuary mouth, flood and ebb channels, delta structures and the propensity for mouth closure. Anecdotal evidence can also be very revealing.

This information will allow assessments to be made of the nature of flow in the estuary during floods, and the possible frequency and size of such floods. The effects of scouring, channel structure, and possible positions and movement of the estuary mouth can then also be judged. Deposition of any sediment moved from reaches in the estuary must also be considered, and here the nature of the nearshore environment will give an indication of whether the sediment could be added successfully to the prevailing longshore drift.

6.2.3 Monitoring

The descriptions in Chapter 2 have emphasized that estuaries are never static: they change continuously in response to a variety of forces that vary from global (e.g. climatic change and sea level rise) to local (e.g. construction of jetties). Consequently management must continuously seek to envisage the likely direction of change and prepare for it. Monitoring is used to measure change and to inform management, and as such it is a requirement for good governance. Because monitoring never stops it is a recurrent expense, which can be costly. Every monitoring action should have a clear purpose and defined target. Unless the information gathered is used in management decision making it will not secure commitment and allocation of the required resources. Monitoring is discussed further in §3.5.

The longer routine measurements are available, the better the state of an estuary can be judged, and therefore basic measurements by local communities should be encouraged in all estuaries. Such monitoring can involve a range of complexity and costs. It is not suggested that all the monitoring must be done, but the data all help in assessing changes occurring in an estuary, and where remedies must be applied. Some data will be required for determining the estuarine reserve (§5.2.4), which means that funding may also be available from the DWAF.

The following observations and measurements can be done at reasonable cost:

- Documented observations and photographs (either aerial or fixed point) can provide a time series of the condition of the estuary, the positions of channels and deltas and the movement and state of the estuary mouth. The occurrence and nature of freshwater inflow should also be estimated during dry periods and during floods; actual flow measurements are more sophisticated and probably require additional expertise and funding.
- Cross-sectional measurements at various fixed positions along the estuary can be made using a Dumpy level and a staff held onto the estuary bed, preferably with respect to chart datum. These measurements are best made at slack tide, otherwise currents can make it difficult to hold the staff in place. Errors can come in from bedforms and positional accuracy, but regular measurements will give a good indication of changes occurring over time. Accurate echosounders used in conjunction with position-fixing systems (e.g. GPS), will expedite cross-sectional measurements, though this must then be correlated with simultaneous water level measurements.
- The results depicted in Figure 2.13 demonstrate the value of water level measurements in an estuary. They show the effects of constrictions of the estuary mouth, and over time can identify changes occurring in water exchanges and flows in an estuary. Such tide gauges involve relatively simple equipment, but need a level of expertise and commitment for accurate results; the tide gauges need regular servicing (Figure 6.2).
- Of further value is the determination of sediment types along the length of an estuary. Such relatively simple analyses will indicate where fluvial and marine sediment sources meet, and over time changes can be depicted.

Figure 6.1 The tide gauge on the Bushmans Estuary. The vertical pipe contains the float and counter-weight, while the digital recording system is housed in the box on top. Note that the system must be firmly anchored to avoid any movement, and should preferably be surveyed into datum level. (Photo: E H Schumann)



6.2.4 Possible Technical Solutions

Once the management structures have been set in place and the estuary and nearshore characteristics described, the objectives of the sediment management process can be defined. In this context, areas where there has been unwanted excess sedimentation can then be identified, and the consequences of different technical solutions can be postulated.

6.2.4.1 Mouth Closure Condition

In those situations where sedimentation has caused the closure of an estuary mouth, breaching of the berm can remedy the problems: this can flush sediment out to sea and provide an ecologically important connection between estuary and sea. However, the procedure must be conducted within well-defined protocols (§3.4.3), namely:

- The water level in the estuary should be as high as possible and if possible breaching should occur naturally, so that as much sediment as possible will be flushed from the estuary
- The mouth of an estuary should be breached as late in winter and/or spring as possible. This is aimed at creating an open mouth condition when juvenile fish migrate into estuaries on the South African coast. Moreover, high wave conditions occur more often in winter than in

summer, and are therefore more likely to close the mouth again in winter. People also generally prefer an open mouth during the summer holiday season when pollutant loading is increased.

- The mouth of an estuary should ideally be breached three or four days before springtide, since this ensures good additional flushing during the following higher tides.
- The position where the mouth should be breached depends on local conditions. This can vary, and expert advice should be sought.
- If possible, a deeper and wider channel should be excavated before breaching, rather than a small trench. A larger initial channel will cause higher immediate flow velocities, causing more sediments to be flushed out to the sea.
- The actual moment of breaching during the tidal cycle should be at high tide or as close after high tide as possible, waves permitting. The maximum outflow normally occurs approximately 4 to 8 hours after a breaching and the flow velocities will be increased at a maximum difference in water levels between the estuary and the sea.

6.2.4.2 Sediment Removal

A number of factors need to be considered and steps taken to ensure that, before sediment is removed from an estuary, it is the appropriate action for that particular estuary. Such an estuary is an asset to the community and the aim should always be to nurture the estuary and enhance its ecological quality, and therefore increase its asset value. The estuary should be maintained in an environmentally healthy condition to ensure the environmental and financial well being of the local community. Therefore, when the removal of sediment from an estuary is considered, these principles should be integrated into all the decisions and actions in the process/procedure to establish if sediment removal is appropriate and if so, what method of removal should be used.

If sediment removal is proven to be environmentally and economically appropriate, the different techniques described in chapter 4 can be assessed for the purpose.

The most widely applied method used locally and abroad is that of conventional dredging. It is considered that the most appropriate dredger type for removal of sediment from South African estuaries is the suction type dredger (with or without a cutter head). There are presently at least three local dredging contractors in South Africa who are capable of doing this type of dredging in estuaries. The commissioning of a dredging contract to a contractor will require strict contract specification and close supervision to minimize negative impact on the environment during the dredging operation.

The present day (August, 2001) order of magnitude costs for an estuary where say 10 000 m³ of sediment is required to be removed is approximately R150 000 (mobilization and demobilization) plus R12 per m³ that is dredged. For 10 000 m³ this comes to a total of R270 000 (see Box 4.1).

The most appropriate location of dredge spoil discharge is on the down-drift side of the estuary mouth if the negative impact on the coastal environment is within acceptable limits. If there is a need for fill material or rehabilitation of e.g. a worked out quarry, the dredged material could be used beneficially in such cases on condition that the operation could be performed in an environmentally acceptable

manner.

In cases where marine sediment ingress into the estuary is the main contributing mechanism of excessive estuarine sedimentation, the dredging of a sand trap near the landside of the estuary mouth could be considered.

Other proven sediment removal methods described in §4.4 could be applied where they are appropriate to the conditions. These methods are mainly for removing sediments in localized (confined) areas and most of them act to displace shoals in an estuary to deeper water in the estuary.

Where unproven methods (such as the tidal flooding methods addressed in §4.5) are considered to remove sediment from an estuary, a systematic procedure should be followed before its application in the field. This procedure should evaluate the practicality, efficiency and financial feasibility and environmental impact of these unproven methods; generally such an evaluation should use sound engineering techniques, including, where appropriate, numerical and physical modelling techniques. At the same time the feasibility costs should be established. Only after the method has been shown to be practical, efficient and financially feasible as well as environmentally acceptable, can implementation in the field (with the necessary permits) continue.

It must be emphasized that selective dredging can reduce costs considerably, while still reaching desired results in an estuary. However, such selective dredging can only be considered if the functioning of the estuary is properly understood, and the sediment bodies have been mapped.

6.2.5 Legal Requirements

The relevant legislation has been presented in Chapter 5, and Table 6.1 summarises the applicable sections.

The required environmental impact assessment (EIA) will

- identify the environmental constraints imposed on the activity
- identify potential negative impacts e.g. increase in turbidity, release of contaminants into the water column, and potential positive impacts, e.g. environmental enhancement.
- identify mitigatory measures for the negative impacts.

The public participation process will ensure full involvement of all interested and affected parties. After all these procedures have been satisfactorily completed, and if sediment removal is proven to be environmentally and economically feasible, the relevant environmental authority will be able to make an informed decision on whether to give approval for the sediment removal.

LEGISLATION	APPLICABLE PORTION(S)	RELEVANT AUTHORITY	NOTES
National Environmental Management Act 108 of 1998	Section 28 (1)	Provincial Environmental Authority	Projects must conform with <i>duty of care</i> provisions in the Act.
National Water Act 23 of 1998	Chapters 3 and 4	Department of Water Affairs and Forestry	Applicable to altering the bed, banks, course or characteristics of a water course.
Environmental Impact Assessment Regulations published in terms of Environment Conservation Act 73 of 1989	Government Notices No's. R. 1182 & 1183 of 1997	Provincial Environmental Authority	Applicable to: (a) the construction or upgrading of structures below the high water mark; (b) the construction or upgrading of canals or channels, including diversions of the normal flow of water in a riverbed; (c) the construction or upgrading of dams, levees or weirs affecting the flow of a river (d) the reclamation of land below the high water mark and in wetlands.
Sensitive Coastal Area regulations published in terms of Environment Conservation Act 73 of 1989	Government Notices No's. 879 - 881 of 1996 and 1526 - 1531 of 1998	Local Authority	Applicable in Outeniqua sensitive coastal area (Tergriet to Bloukrans Rivers) and Kwa-Zulu Natal South Coast sensitive coastal area (Pennington to Umtamvuna).
Sea-Shore Act 21 of 1935	Section 3	Provincial Environmental Authority	1. Before evaluating a project in terms of this statute the status of the work area in relation to Section 2 (2) of the Act must be assessed. 2. Applicable to erection of structures and/or carrying out of work below the high water mark, as well as to removal of material from below the high water mark.

Table 6.1 Relevant legislation applicable for estuary sediment management.

6.3 DONT'S IN SEDIMENTATION PROBLEMS

The procedural guidelines have detailed the steps to be taken in solving estuarine sedimentation problems. In this section a list of 'don'ts' is given, i.e. **what not to do** in sediment management of an estuary. There is some repetition, but this serves to emphasize the procedures.

- Do not start any remedial action until as much information as possible has been obtained about the functioning and structure of the estuary. This must include geological information, mouth configuration and adjacent sea conditions, sandbanks, sediment characteristics and changes that have taken place over time, weather, rainfall and flood information, and population demographics. Any previous attempts at solving sedimentation problems must also be assessed.
- Do not build retaining walls or structures to deviate flow without an adequate knowledge of the consequences. In the vast majority of cases where this has been attempted without proper control, it has not produced the envisaged solution. In addition, the estuaries have been left littered with broken walls and unsightly debris.

- Do not start any actions in the estuary until all the required legal steps have been taken, and the relevant communities have been consulted. These steps are described in detail in chapter 5 and §6.2.4. Note that these requirements were specified in mid-2001, and adherence is required to all new relevant legislation.
- Do not start any dredging procedures before consulting other local communities at nearby estuaries. Cooperation can lead to reduction in operating and capital costs.
- Do not start any sediment removal actions until clear objectives have been identified, i.e. there should be consensus on problem spots and what the desired result of any actions should be in terms of solving those problems.
- Do not start any sediment removal until the estuary has been properly surveyed. If this is not done, then there will be no opportunity to assess the effectiveness of the removal techniques used. Moreover, a detailed knowledge of where sand has accumulated will enable selective sediment removal to be applied, which will reduce costs.
- Do not dally: start a system of obtaining as much information as possible about the estuary - see §6.2.3. This will enable an understanding to be gained of the functioning of the estuary, essential for any future management plans.
- Do not begin to remove sediment from an estuary unless a well-considered plan has been formulated of where to dispose of the spoil in a way that it does not find its way back into the estuary. It must not cause unwanted side-effects elsewhere.
- Do not begin to remove sediment unless it is known how much it will cost and who will pay for the removal.

6.4 CONCLUSIONS

Estuaries are the jewels along the South African coastline. As such, communities have settled in their vicinities, and over time the settlements and wider developments have impacted on the natural functioning of these estuaries. This report has dealt with one particular impact, namely the excessive ingress of marine sediments, and it has discussed the causes and possible remedial measures that can be taken to cope with these problems.

Guidelines have been given for the management of marine sediment in estuaries. Such management must be seen as part of the overall management of an estuary, and it must form part of a long term vision for the community and its environs. As such, it is important that the resources and inherent beauty of the estuaries remain intact for future generations to use and appreciate.

Regular monitoring must form a part of any management strategy, since this is the only way in which a careful check can be kept of the health of the estuary. In addition, it is likely that factors such as climate change will impact on South Africa in the future. In particular, the associated sea level rise will have additional implications for estuaries, and it is only by understanding the processes that adequate management strategies can be devised to cope with new problems.

CASE STUDIES

A.1 INTRODUCTION

In this Appendix two examples of estuarine marine sedimentation problems and processes in the Eastern Cape are presented. The next section A.2 covers the effects of a substantial flood in the Nahoon Estuary, where fortuitously measurements were available before and after the event. Reasons are also given why it is important to measure the processes involved in sediment accumulation, and that the Nahoon Estuary would provide a suitable measuring site.

The third section A.3 gives details of the kind of information which would be required for the solution of the sedimentation problem in the lower Kowie Estuary.

A.2 THE EFFECTS OF FLOODING IN THE NAHOON ESTUARY

The Nahoon estuary is a small system with a permanently open mouth between East London and Beacon Bay in the Buffalo City Metropole of the Eastern Cape. As part of a research programme of the then Institute for Coastal Research at the University of Port Elizabeth during the mid-1980's, a series of benchmarks were installed along the estuary banks and accurately surveyed to mean sea level.

Seven representative cross sections were measured across the 5 km-long estuary in November, 1984. Earlier, sediment samples had also been collected on a grid of stations in the estuary, and sediment characteristics were determined (Esterhuysen and Reddering, 1985, Reddering and Esterhuysen, 1985). Fortuitously, a river flood with a peak discharge of $1\,400\text{ m}^3\text{s}^{-1}$ passed through the estuary during the night of 1–2 November, 1985, causing significant erosion (Reddering and Esterhuysen, 1987). Cross sections were re-measured and sediments were sampled on the same grid as before. Two comparable data sets were established as a result, showing what areas of the estuary were most severely affected by flood erosion, and which sediment types were influenced.

These results showed that $410\,000\text{ m}^3$ of sediment were removed during the flood (Reddering and Esterhuysen, 1987). Most of this sediment was removed below the low-tide level and from the lower estuary where loose marine sand had prevailed. The sand body known as the flood-tidal delta (§2.6) was entirely removed and the erosion level at the channel floor lay at a gravel horizon. In the muddier middle and upper reaches of the estuary, where the sediment consisted either predominantly of mud or of sand bound by mud, the cross sections were either unaffected or very little affected by the flood.

Indications exist that the erosional capacity of the flood exceeded the volume of sand available for erosion. No marine sediment was left in areas previously occupied by flood-tidal deltas, and what little loose sediment was present in the estuary consisted of river sand. Brick sand, derived from brick

works in the catchment area of the river, and which was absent in the estuary a year before the flood, was distributed throughout the estuary. It was mixed with the river sand, showing that river sand was easily distributed throughout the system, and possibly onto the beaches too. This land-derived sand was probably deposited in the estuary during the waning stage of the flood when conditions changed from erosional to depositional.

The previous large flood in the Nahoon Estuary occurred in 1970, with probably comparable scouring effects. Knowing the volume of sediment scoured from the estuary, and the period that had elapsed between the two floods, allowed Reddering and Esterhuysen (1987) to calculate the net, mean annual influx of sand into the estuary. A volume of about 21 000 m³ per annum was found.

A monitoring programme was established in the Nahoon Estuary after the 1985 flood, designed to follow the growth of the flood-tidal delta, and concentrating on the lower estuary by measuring closely-spaced cross sections. Initial results showed that the influx estimate appears to be reasonable, but funding for this work was withdrawn soon afterwards and the monitoring stopped. A closely spaced system of benchmarks installed and surveyed at the time for this monitoring have all been destroyed or have corroded away.

Although useful, the Nahoon data were not properly archived and much work would be required to extract details from old field notebooks to get the data into a format suitable for inclusion into a functional database. The whole process of growth of the flood-tidal delta was missed by the aborted monitoring, but in any case it is unlikely that the project would have been funded until the next flood. However, these are the kinds of data required to establish details of the growth processes of flood-tidal deltas, information on the influx of marine sand relevant to estuarine management. At present it is not known if the annual influx of sand into the lower estuary equals the long-term mean, or whether it accelerates or decelerates as the flood-tidal delta grows over the years. In other words, is the mean value determined by Reddering and Esterhuysen (1987) actually realistic?

The sooner a monitoring programme is implemented, the better, because a fully formed flood-tidal delta now occupies the lower estuary, and measurements before the next flood will add value to the monitoring process. For example, prior to the 1985 flood only one cross section adequately covered the flood-tidal delta and calculations had to be interpolated, introducing significant uncertainty into the figures. At least five sections are required to determine adequately the details of the erosion of flood-tidal deltas by such river floods. As another example, a minor flood passed through the system in 2000, and eroded some sand from the flood-tidal delta, but the resolution of the cross sections in place in 1985 would have been inadequate to determine any impact.

A.2.1 Monitoring the Nahoon Estuary

The Nahoon Estuary is a suitable monitoring site because it has already been the subject of scientific observations (Esterhuysen and Reddering, 1985; Reddering and Esterhuysen, 1986; Reddering *et al.*, 1986), and the effects of the river flood in November 1985 on the sedimentation state of the estuary were documented by Reddering and Esterhuysen (1987). Located in a city, the estuary is accessible and has a good infrastructure with benchmarks near its banks, so an array of estuary-bank benchmarks

could be reestablished to reintroduce monitoring comparable to, or better than that stopped in the late 1980's. On the other hand, the area is prone to vandalism of scientific monitoring equipment.

Furthermore, it has a permanently open estuary mouth and is fairly typical, if such a notion exists, of Eastern Cape estuaries: it accumulates marine sediments and land-derived mud. It is also a comparatively small system, allowing intensive measurements over a short period, and has a history of short, high-discharge floods (1970, 1985), the effects of which are convenient to illustrate pre- and post-flood effects. Floods passing through the system do so quickly, allowing immediate access to affected areas after floods. Soon afterwards the tides start producing new flood tidal deltas growing at a measurable rate, and any influence of the growth of the delta on tidal circulation in the estuary would also be measurable.

Integrated, multidisciplinary research has been carried out on the system so that the results of physical behaviour can be used to infer biological response. In addition, an intermediate determination of Resource Directed Measures, as required by the NWA, has been carried out for the Nahoon Estuary (Taljaard, 2001). This provides an appropriate background and framework for monitoring in such a pioneer estuary.

A.3 THE LOWER KOWIE ESTUARY

The Kowie Estuary has been heavily impacted by developments, ever since a decision was made in the early 19th century to use it as a harbour. The settlement of Port Alfred grew primarily on the flood plain of the estuary, and at present the commercial base of the community is largely geared to the holiday trade and the daily needs of the resident population (Figure A.1). The fishing industry forms another important source of income and job creation, with the boats using the estuary as a safe refuge (Plan Associates, 1986).

In the lower flood plain the Kowie Estuary is flanked by hills underlain by hard shales and sandstone of the Witteberg Group. At this stage the flood plain is about 700 m wide, and originally there were several channels crossing this area, with extensive sandbanks exposed at low tide. Construction of the harbour in about 1840 constrained the flow in a narrow channel on the western side of the flood plain, and the banks were reinforced by stone quarried from nearby hillsides. Two piers were constructed, extending into the surf zone, and in 1941 a 65 m extension to the western breakwater was undertaken; the two breakwaters are about 75 m apart (Turpin, 1964; Plan Associates, 1986; Gray, 2001).

The Kowie River has a meandering course through the Bokkeveld shales which make up most of the catchment area, estimated to be between 576 and 769 km² (Heydorn and Grindley, 1982). Major tributaries are the Bloukranz, Brak and Torrens Rivers, with the Little Kowie River entering the estuarine section 14 km from the mouth. The total length of the Kowie River is about 70 km, flowing over a gently sloping coastal plain, with the result that the lower 21 km are tidal. There are no major dams constructed in the catchment, though a weir supplies domestic water to Port Alfred.

The Kowie River falls within the bimodal rainfall regime of the south and south-east coast of South Africa. Average rainfall over a 30-year period was 663.3 mm, which fell during an average of 74 days

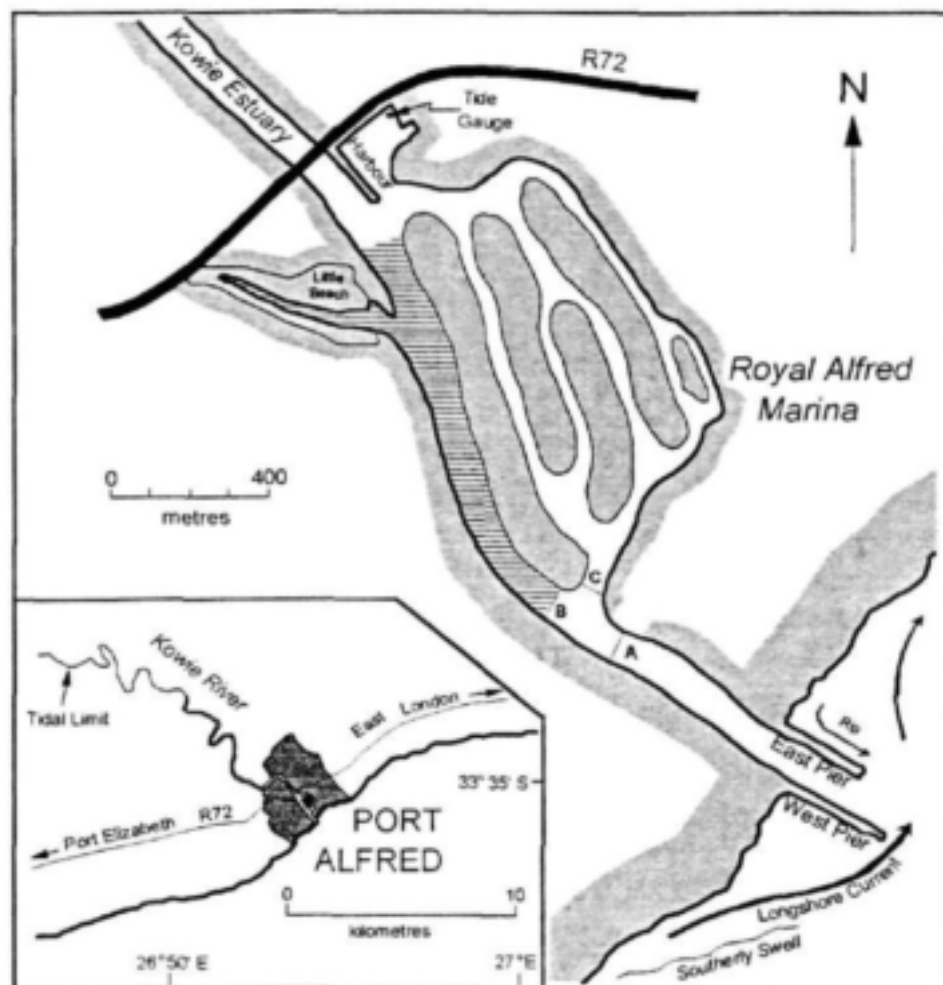


Figure A.1 Map of the lower Kowie Estuary showing the nearshore current and wave characteristics, as well as the position of the Royal Alfred Marina. The area in which sediment has accumulated is shown hatched.

of rain per year. However, rainfall is often erratic, and droughts and floods are not infrequent. The largest recorded flood occurred in December, 1970, when a flow of $1182 \text{ m}^3/\text{s}$ was measured at the Wolfscrag gauging station (Heydorn and Grindley, 1982).

Southerly swell drives a longshore drift in a northeastward direction along the coast (Figure A.1). There is evidence of a strong north-bound current at the tip of the Western breakwater, and this is reported to create an eddy behind the East Pier which at times forms a powerful rip running out to sea (Heydorn and Grindley, 1982). Currents in the area appear to preclude a buildup of sand south of the Western Breakwater, however, bars are not uncommon across the mouth of the estuary.

Canalisation of the Kowie Estuary allows for an unconstricted exchange of water over the tidal cycle, and Figure A.2 shows that there is little indication of a flood dominant tidal flow (compare Figure 2.13c). There is little diminution of the tidal amplitude at the harbour where the recordings were made, though there is a lag over the whole tidal cycle due to the time taken for the tidal signal to travel from the estuary mouth to the harbour position. The semidiurnal tides in the lower estuary can be expected to have amplitudes ranging from around 0.5 m at neap tides, to around 2 m at spring tides. The tidal prism of the estuary has been calculated to be about $2.6 \times 10^6 \text{ m}^3$ for spring tides, and

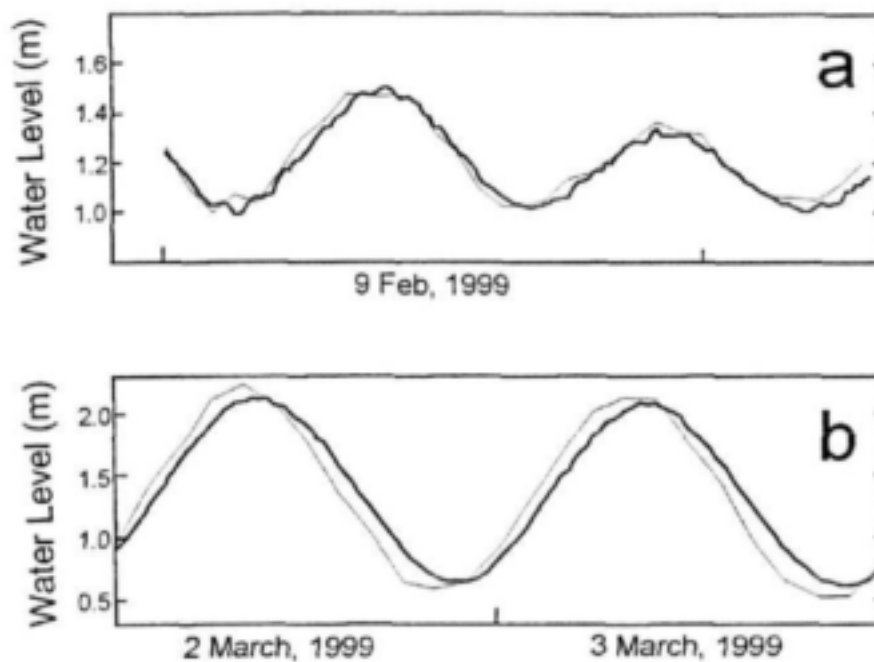


Figure A.2 Relative water level variations measured at the position in the Port Alfred harbour indicated in Figure A.1 (dark line), and measurements made in the nearby East London harbour (light line). The upper figure (a) was made at neap tide, and the lower figure (b) at spring tide.

$0.9 \times 10^6 \text{ m}^3$ for neap tides (Plan Associates, 1986). Records also show that coastal trapped waves can have a substantial effect on the overall water levels along the coast and in the estuary.

As a consequence of the lack of flood dominance, there was no evidence of any buildup of sediment in the main estuary channels in the period 1941 to 1981 (Plan Associates, 1986); however, it must be recognised that there is no data on variations within this period.

During the period 1987 to 1989 the Royal Alfred Marina was constructed (Figure A.1). While the effect on the tidal prism has been negligible (a change of less than 5%), it has altered the flow structures in the lower Kowie Estuary (Schumann and Gray, 1998; Gray, 2001). Thus on the flood tide the abrupt increase in cross-sectional area from the position A to B and C combined has meant that sediment transported as bedload or in suspension has been dropped in the region between the two marina entrances; such sediment has also been deposited in the marina channels. Similarly, the divided ebb tidal flow has not been sufficient to remove this sediment again. Note that the construction of the marina canals parallel to the estuary itself has meant that substantial flood and ebb tidal flow can be expected in the canals.

Because no regular monitoring was in force, the accumulation of sediment in the region between the marina entrances was not noticed until it began to affect boat traffic. To assess the changes, the Port Alfred Municipality began occasional cross-sectional measurements in 1996, with the last measurements made in 1999. These indicate a continued shoaling of the estuary, and some scouring of the main marina channels.

An investigation was made of current and sediment structures in the lower Kowie Estuary (Schumann

and Gray, 1998; Schumann *et al.*, 2001; Gray, 2001). These confirmed the subdivision of the flood flow at the lower marina entrance, with apparently increasing volumes flowing through the marina and scouring deeper channels.

Because of the canalisation and consequent lack of flood dominance, the Kowie is not really a typical Eastern Cape estuary. Nonetheless, it is clear that the technical solutions described in chapter 4 and §6.2.3 can be used to solve the sedimentation problems. It has been established that the unwanted sediment consists essentially of unconsolidated marine sand, and for this purpose a suction-type dredger would be suitable. Disposal of the dredged material could then also be onto the local beaches, preferably north of the mouth to take advantage of the prevailing longshore drift; this will require the deployment of suitable piping and pumping equipment.

The total volume of sediment to be moved has been estimated to be between 120 000 and 200 000 m³ (Schumann *et al.*, 2001). On the basis of charges outlined in §4.3.2.1, this would cost in excess of R1 600 000 to remove, and would need to be repeated over periods of less than 10 years (based on the build-up of sediment since completion of the marina). Since this is a relatively small system, it may be preferable to invest in a mobile dive dredger (§4.3.2.2). Nonetheless, selective dredging will also reduce these costs.

Other potential, though untried, solutions are those of tidal flooding (§4.5) and partial restriction of the ebb flow (§4.4.3); the latter is possible because of alternative flow routes through the estuary or marina. On that basis, Schumann *et al.* (2001) suggested that the flood tide could be allowed to flow normally, but that a suitable barrage could then force the ebb flow to flow out only through the estuary channel. Over a large number of tidal cycles this ebb flow would then scour out the channel to the situation existing prior to the construction of the marina.

Sedimentation problems may ensue in the marina channels as a result of the limitation of the ebb tide. However, this must be seen as an overall sediment management problem, involving careful monitoring of the conditions in the estuary and the marina. To remove sediment in the marina, the ebb flow could be diverted through to the relevant positions and agitation dredging techniques applied (§4.4.1). Note that a dredger has been used to remove sediment from the marina channels, but with limited success.

In 1998 the Port Alfred Municipality embarked on a EIA procedure to obtain permission to proceed with removal of excess sediment in the estuary channel by use of ebb-tidal flow; the procedure was carried out by the University of Port Elizabeth's Institute for Coastal Resource Management (Wooldridge *et al.*, 1998). No serious environmental constraints were found, though it was recognised that scouring of the estuary banks may be a problem. In February, 1999, permission was therefore given for a well-monitored research project to investigate the effectiveness of restricting the ebb flow primarily in the estuary itself. However, this project had to be carried out within twelve months, and since nothing further ensued the authorisation subsequently lapsed.

The Institute of Natural Resources at the University of Natal launched the Eastern Cape Estuaries Management Plan in 1998. As part of this programme an Estuary Management Plan was formulated for the Kowie Estuary (INR, 1999). This plan requires the removal of excess marine sediment in the estuary, and still needs to be put into operation.

GLOSSARY OF TERMS

- base flow** - freshwater seepage from banks into a river or estuary
- bathymetric survey** - survey of depths in a water body (sea, estuary, river, lake)
- berm of an estuary mouth** - the (often natural) sand dyke between an estuary and the sea
- bedforms** - regular geometric surface shapes in loose sediment formed by flowing water or air at the bed surface, and includes features such as dunes, ripples and flat beds, and erosional features such as scour marks
- catchment** - the natural drainage area which catches the rainfall feeding the flow of water in a river
- deforestation** - the clearing of an area of forests or trees
- delta** - a sediment body produced by sediment accumulation at the edge of a relatively deep water body formed by deposition of sediment derived from an adjacent shallow-water source. A **tidal delta** originates from tidal sedimentation
- dune stabilization** - the protection of dunes against erosion by coverage of material (e.g. branches) or vegetation
- dyke** - in dredging terminology, a wall constructed from material such as sand to contain disposed dredged material
- embayment** - an indentation in a shoreline forming an open bay
- environmental flow requirements** - the (river) flow required to maintain desirable environmental conditions
- environmental reserve** - the environmental flow requirements of a water body such as a river or estuary. Terminology used in the Water Act (No 36 of 1998).
- ephemeral stream** - stream with intermittent river flow
- erosion base** - a theoretical sediment level in an estuary above which erosion takes place, and below which deposition occurs
- evapo-transpiration** - the loss of water from rainfall because of evaporation and transpiration (from leaves) of plants or trees
- extensional faulting** - takes place when two parts of the crust pull apart, creating a fracture system in the earth's crust composed of ridges and valleys
- facies** - (sedimentological sense) a suite of related sedimentary deposits set apart from another sedimentary suite by distinctive depositional features.
- flood dominant** - an asymmetric tidal variation in an estuary, where the flood flow is stronger, but lasts for a shorter time, than the ebb flow
- fluvial** - produced by originating in a river
- Geological time periods**
- Mesozoic - an era of geologic time extending from 247–65 million years ago, and encompassing the Triassic, Jurassic and Cretaceous Periods
 - Cretaceous - a period of geologic time extending from 144–65 million years ago
 - Miocene - a period of geologic time extending from 28–5 million years ago

Pleistocene - a period of geologic time extending from 1,8 million – 10 000 years ago

geomorphology - the description of, and the study of the origins of landscape features

Gondwana - a large supercontinent originally composed of Africa, South America, Antarctica, Australia and India, which broke up into the constituent continents that separated by continental drift during the Mesozoic

grain size - the measure of size of sedimentary particles indicated by the mean particle diameter. Accepted definitions for different grains sizes are given below:

< 0.05 mm: silt and clay

0.06 to 0.13 mm: very fine sand

0.13 to 0.25 mm: fine sand

0.25 to 0.50 mm: medium sand

0.50 to 1.00 mm: coarse sand

1.00 to 2.00 mm: very coarse sand

> 2.00 mm: gravel to boulders

groyne - a low wall of concrete, stone or timber used to guide the flow in a river or to protect a river bank or beach against erosion

headland - any projection of the land into the sea

hydrodynamic (investigations) - investigations of movements of water, i.e. flow, water levels, waves, currents

inundation - the flooding of normally dry areas, for example flood plains

jetty - a structure built from a shore out into a water body. It could be either solid (such as a training wall at an estuary mouth) or it could be a piled-type structure (vertical column supports) with a horizontal deck. A *floating jetty* is built on pontoons and moves up and down with the tide

littoral drift - see *longshore drift*

littoral zone - this term has different meanings for different disciplines: biologists consider it to be only the intertidal region, while geologists take it to extend from the shore to a depth of 10 or 20 m offshore. Engineers equate it approximately with the nearshore zone as defined here

longshore drift - the sedimentary material moved predominantly in the nearshore zone under the primary influence of surface gravity waves and their associated currents

marine sediments (in estuaries) - the sediments, mainly consisting of sand from adjacent beaches, transported upstream from the inlet by tidal flows and wave action

meandering (of rivers and estuaries) - the mainly sideways movements of channels of rivers or estuaries because of hydro- and sediment dynamic processes

monitoring - regular environmental measurements made over a long period of time, and continuing indefinitely into the future

mouth breaching (of an estuary) - the natural or artificial opening of the inlet of an estuary

mouth closure (of an estuary) - the natural or artificial closure of the inlet of an estuary

nearshore zone - the zone extending seaward from the shoreline to just beyond the region where waves break, i.e. to just beyond the *surf zone*

non-cohesive sediment - loose sediment composed of particles not bound to one another by cement or stiff clay or any physico-chemical interactions. Each grain is free to move independently.

palaeovalleys - ancient valleys

prop-wash currents - currents generated by a ship's propeller

reclamation - the making of land fit for cultivation, for example on flood plains of estuaries

reserve - the ecological reserve of an estuary is the water quality and quantity required to sustain ecological functions and processes

ria - an estuary occupying an incised river valley drowned by a rise in relative sea level

sand shoal or sand bank - shallow areas in rivers or estuaries

semidiurnal - occurring twice per day. Thus the semidiurnal tide has two high tides and two low tides per day.

shoaling - the shallowing of channels in rivers and estuaries because of sedimentation

slurry - in dredging terminology, a mixture of water and sediment which could be transported in a pipeline by means of pumping.

suspended load (solids) - material moving in suspension in a fluid, being kept up by the upward components of turbulent currents or by colloidal suspension.

swash - on a beach face, this is the thin layer of water from a wave which sweeps up the face, and then moves back down under the influence of gravity.

tidal flap - a mechanism that allows flow in a conduit or channel in one direction only.

tidal prism - The volume of water exchanged with the sea through an estuary mouth over a tidal cycle, i.e. the volume of water flowing in on the flood tide, and out again on the ebb tide. Freshwater flow is excluded in this calculation.

topsoil - the often fertile top layer of soil upstream in the catchment, which at times is lost by erosion

translational faulting - takes place when two parts of the crust move past each other generally producing linear, steeply-sloping crustal margins when the blocks separate.

wave refraction - In shallow water near the coast, wave speed is proportional to the square root of the water depth. This means that waves in deeper water travel faster, and leads to the phenomenon that wave crests tend to line up parallel to the local coastline. It also means that waves can refract around headlands, etc.

weir - a wall-type structure built across a channel to raise the water level, divert the water or control the water flow rate.

GLOSSARY OF PLACE NAMES

Note the following conventions regarding capitalization of regional names:

'*Western Cape*' (capitalized) refers to the provincial name, whereas compound place references such as '*western, southern and eastern Cape*' (lower case) refer to particular regions within the former Cape Province.

Formal terms such as '*West Africa*' take the capital, whereas terms such as such '*west and south coast*' refer to geographic regions and take the lower case.

Ciskei - The region colloquially known as the Ciskei is now part of the Eastern Cape Province, and stretches along the coast from the great Fish River to south of East London.

Eastern Cape (EC) - formerly the eastern part of the erstwhile Cape Province. This province now includes the former Ciskei and Transkei.

KwaZulu-Natal (KZN) - formerly the province of Natal, which included Zululand

Northern Cape (NC) - formerly the north-western part of the Cape Province

Western Cape (WC) - formerly the south-western part of the Cape Province

Maputaland - Coastal plain in the north eastern region of KwaZulu-Natal and southern Mozambique, bounded by the Lebombo Mountains in the west and the Indian Ocean in the east

southern Cape - The southern coastal strip from Cape Agulhas in the west to Cape St Francis in the east

Transkei - The region colloquially known as the Transkei is now part of the Eastern Cape Province, stretching from the Kei River to Port Edward on the KwaZulu-Natal border

Wild Coast - a colloquial name given to the coast of the Transkei.

Zululand - in KwaZulu-Natal, the eastern coastal belt and adjacent interior from the Tugela River to the Mozambique border

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