Chapter 10
Impacts of Ocean Dynamics, Climate Change and Human Pressure on the East African Coast: The Case of Maputo

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Abstract Coastal erosion and loss of coastal environments are worldwide phenomena. These typical processes occur on different spatial and temporal scales, from river basins to coastlines, and from the ocean-atmosphere system to the global climate scale. All climate change scenarios foresee an increase in the global mean sea level in the next century, from a few tens of centimeters to over a meter. However, these scenarios are not sufficient to explain the accelerating erosion that already occurs today. In coastal areas, such change appears to be linked not only to sea level rise as a direct cause, but also to changing climatic conditions (changes in the rain distribution, winds, sea waves, etc.) and to increased human pressure on land (excessive use of weirs and dams along watercourses, loss of coastal dunes and areas of protective vegetation such as mangroves, etc.). The case of Maputo is quite informative, as none of the known effects of climate change is the main cause of the significant erosion processes that occur there today. Rather, this erosion is attributable to an altered balance between the contributions of sediment from neighboring river basins and to certain effects of coastal dynamics.

Keywords Sea level rise · Coastal erosion · Coastal flooding · Sediment balance · Maputo

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10.1 Introduction

Sea Level Rise (SLR) has been discussed extensively in recent decades. As early as the 1960s, the effects of SLR had already been noted by Bruun (1962) as a possible cause of the loss of coastline in many areas, especially along low shores. Over subsequent decades, increased attention was paid to SLR as a phenomenon closely linked to global warming. Many studies have aimed to determine its causes, and predict its future evolution (Jevrejeva et al. 2010; Rahmstorf 2007; Vermeer and Rahmstorf 2009).

Projected SLR scenarios are expected to have significant impacts on the economies of entire coastal regions, and may even affect the very survival of many settlements and major coastal cities. Such long-term scenarios require the design of new rules that will facilitate human adaptation to these changes and attenuate the level of risk, particularly since storm surges and floods in coastal areas will have greater impacts as SLR increases. To date, SLR has been widely recorded to be in the order of a few mm/year (2–4), although this rate seems to have increased in recent years. Looking at actual data, there is still no evidence of the sharp increase that is predicted by numerical models for the coming decades. However, this does not exclude the realization of forecasted scenarios, since SLR is far from being linear. Other processes acting to modify land-sea level changes include tectonics and eustasy, which should be carefully considered in a long-term perspective (Bruun 1988). Whatever the real SLR will be, it cannot be characterized simply as a greater elevation of sea level that will submerge coasts, but rather as a long-term process that will certainly have some degree of interaction with short-term processes. Today, in many parts of the world, we are already witnessing the loss of coastal environments due to processes that are globally referred to as *coastal erosion*.

One preliminary question arises directly from a rereading of Bruun's article: what is the actual role of the SLR observed in recent decades in terms of the loss of coastal areas (mostly sandy littorals) and more generally in what we call *coastal erosion*? The immediate answer is that, in some areas where spectacular coastal erosion phenomena are present, they have little to do with SLR, rather they are due to the alteration of an existing morphodynamic equilibrium. A coastline in morphodynamic equilibrium (i.e. not in erosion or in growth) is one where the sediment input and output are balanced. Such erosion is usually a local phenomenon, where reduced sediment input, and the continuation of causes that determine sediment transport (e.g. waves and coastal currents) act together. The input of sediments to a stretch of coast is due to sediment transport from an adjacent coast, or to the contribution of sediments derived from a watercourse. In the latter case, it is well known that many interventions made in the catchment area to inhibit the transport of river sediments have a negative impact on sandy shores. Along the African coast, this effect is particularly important because sediment transport depends on the river flow, and such flows have reduced considerably in recent years due to the documented reduction in rainfall, rising temperatures, and increased consumption of water for domestic, agricultural, and industrial use. Such increased consumption can also be considered an indirect effect of CC and the growing needs of the population. It is therefore *change*, in a broader sense, to which we refer to understand the complex phenomenon of coastal erosion.

This chapter refers to a case study of the Municipality of Maputo (Mozambique). To compare the two phenomena (coastal erosion and SLR) short- to medium-term dynamics and long-term trends are discussed. The former can be very significant and their influence on overall dynamics can cause intense, though possibly reversible, erosion. On a longer time scale, the changes indicated by SLR scenarios determine permanent and non-reversible effects. The first part of this chapter describes a model for interpreting the dynamics of Maputo Bay, based on dynamic variables (meteorological, hydrological, and oceanographic) and on their possible long-term changes.

It is subsequently argued that consideration of these phenomena must receive greater attention from planners, as knowledge of these dynamics is essential to successful planning of coastal protections and the reduction of vulnerability and risk for the population.

10.2 Description of Site

Maputo Bay is a subtropical embayment of the Indian Ocean, between 25° 50′ and 26° 20′ S, subject to large seasonal freshwater and tidal variations, and extends around 45 km from east to west and approximately the same from north to south. The bay is closed to the west by the Mozambique coast and to the east by the Machangulo peninsula and Inhaca Island. The bathymetry of Maputo Bay is shallow with an average depth of 5 m reaching $\sim$30 m at the ocean boundary. The bay opens to the shelf through an 18 km wide inlet (from the Macaneta sand dunes, the eastern boundary of the Incomati River, to *Ilha dos Portugueses* near the eastern side of the bay) (Fig. 10.1).

Maputo Bay is in itself a sort of natural harbor, well protected from wind and waves, particularly in the south, near the capital. The sea bottom is characterized by the presence of numerous sandbars and shallow areas, as well as by a large number of submarine channels. These channels in the bay's bathymetry were formed by the interaction between tides and the estuarine system, and in particular by the interaction between the Maputo River delta and the tidal inlet north of it (Mussa et al. 2003). The Machangulo peninsula and Inhaca Island form a barrier through a combined action of tides and aeolian deposition, thus protecting the river delta from the continental shelf.

Satellite images show plumes of turbidity at the main rivers' mouths, carrying in suspension mostly sandy and silty sediments. The shores in the area are either sandy beaches or mangroves at different stages of conservation.

Maputo Bay is subject to the impacts of a number of industries and several types of anthropogenic activities (heavy aluminum, salt farming, artisanal fishing,

Fig. 10 1 Maputo Bay and its main riverine contributions

mangrove cutting for firewood) some of which are in conflict with each other in terms of water use and sustainability (e.g. pollutants from domestic and industrial wastewater disposal contrast with fishing activities).

10.3 Hydrographic Characteristics of Maputo Bay

From a hydro-morphological point of view, the bay is a very complex system, whose dynamics need to be properly understood in order to predict future change.

Forcing by tidal action in Maputo Bay increases from neap (range $\sim$0.5 m) to spring tide (range $\sim$3 m) with corresponding changes in the tidal currents (from $\sim$0.1 to $\sim$1 ms^{-1}).

The region is also subject to strong seasonal rainfall: freshwater flow can be very low in the dry season, and then peak at more than 10^3 m^3s^{-1} following intense rains in the winter season. The volume of river discharge into the Indian Ocean reflects, to a certain extent, the rainfall patterns in the region, thus rivers draining high rainfall areas have relatively higher discharges. Consequently, the region is characterized by the presence of large estuarine zones and extensive mangrove forests.

Some of the most important river basins of the region conveying flow into Maputo Bay are:

- Komati (Incomati) river, which enters the bay at its northern end;
- Maputo river, which enters in the South;

- Several smaller streams originating in the Lebombo Mountains, including the Matola (from the north), the Umbuluzi (from the west), and the Tembe (from the south), which meet towards the middle of the bay in an estuary generally known as the *English River* (formerly the *Espírito Santo River*). We will refer to this estuary simply as the Umbuluzi river.

The Incomati and Maputo rivers have large catchments, while the Umbuluzi's encompasses a relatively small area. Most of the flows are concentrated in the period from October to April, and have a pulse-like character.

The Incomati River has a total basin area of about 46,800 km^2, and an average yearly flow of 3.59 $km^3\ y^{-1}$, 50 % of which is extracted mainly for agriculture. Concerning the flow regularization, the Incomati has the most significant dams, with $2060 \times 10^6\ m^3$ of storage, followed by the Maputo and the Umbuluzi. The volume of water extracted from the basin has been rising. Historical data shows that, during the wet season, the mean flow in the Incomati was 80.69 $m^3\ s^{-1}$ with a recorded maximum 6827 $m^3\ s^{-1}$ during the catastrophic floods of 2000.

In comparison with the Incomati, the Maputo River has a basin area of about 29,800 km^2, has a lower peak flow, and is smoother throughout the wet season with less marked pulse discharges.

The rivers carry large quantities of freshwater and sediments to the bay. The main flows are diverted to the left due to the effect of the Coriolis force (quite evident from satellite imagery), so the flow exiting from the Incomati River tends to leave the bay, while that from Maputo is diverted along the western edge of the bay and tends towards north, joining its contribution with the Umbuluzi, in turn diverted to the north, and so feeding the sandy coast to the east of Maputo. Inside the bay, freshwater and sediments are stirred by the action of currents, and in particular by the interaction of oscillating tidal currents at the river entrance, and wind-induced currents (the so-called Ekman drift).

The action of surface waves is very weak. In fact:

1. The bay is closed with respect to almost all directions of the incoming waves, the fetch is very small in all directions, except for the northeast, which can be significant but hits only on the south coast of the bay (the mouth of the Maputo River);
2. A small percentage of waves from the Indian Ocean can enter the bay by diffraction, being much attenuated by this effect;
3. The bay is shallow, and this significantly contributes to reducing the height of the waves in the surf zone (where sediment transport is expected to increase).

However, while the shallows do limit the impact of wind waves on the coast, these do not prevent the entry of long waves (tidal surge) that can interact significantly with the hydrodynamics of the bay.

Satellite images show the presence of underlying forms that are shaped like large ripples, typical of areas with strong tidal excursions. The sediment balance is very delicate and liable to undergo changes as a result of any of the causes that promote the growth or erosion of the seabed and of the coastline. The same ecosystem has a strong dependence on freshwater input, not only because it is vulnerable to adverse effects from pollutants, but also because the sustainability of fishing activities (mainly shrimp) and the maintenance of the mangrove ecosystem are dependent on a minimum freshwater supply to the bay.

10.4 Hydrodynamic Modeling

The use of numerical models for understanding the oceanographic dynamics near the coast is one of the main tools for monitoring coastal seas, for planning measures to be carried out on the coast, and for developing future scenarios related to CC. It is worth noting that models are derived in large part from measured data, both remotely sensed and collected in situ. In coastal areas, oceanographic information that can be derived from satellite data has many limitations (e.g. for sea level). In situ data are crucial for this study. Unfortunately, apart from some data accessible through available publications, it is difficult to access local data, particularly updated bathymetric data at a good resolution, as well as hydrographical and water level data (to process information on tides, sea levels and morphodynamic parameters).

By contrast, a considerable amount of large-scale data is available from world atmospheric/ocean atlases and global numerical models, particularly as regards broad hydrographical features (mainly temperature and salinity), medium resolution bathymetry products, and atmospheric data regarding hydrodynamic forcing and tidal components. The local data needed for the present study was therefore derived through application of downscaling models to available large-scale data.

Maputo Bay is on the margin of the monsoonal regime, with large expected variations of atmospheric pressure and high winds. The bay is subject to considerable seasonal variations in freshwater input (~ 10–10^3 m^3 s^{-1}) and pronounced variations in tidal stirring power. During the dry season, the water column is fully mixed, with a weak horizontal density gradient and residual circulation mainly due to tidal currents. By contrast, during the wet season freshwater buoyancy was observed to induce marked horizontal salinity gradients and stratification, which is pronounced around the time of neap tides. Such a coastal system may be classified, as regards the freshwater input, as a monsoon-like regime (Lencart e Silva 2007): a sudden increase in rainfall induces large river runoff and creates the conditions for a change in circulation patterns.

In this context, the main exchange controls are not only tidal shear diffusion mechanisms, but also residual currents coming from:

- interaction between tides, coast, and bathymetry;
- density gradients (created by river runoff and surface heating); and
- large-scale effects, such as slope in the mean sea level (MSL) imposed by strong winds, atmospheric pressure, and variability in the off-shore current and eddy structures, among others.

A model of Maputo Bay at 1 km of resolution has been developed. The model, which integrates the ocean hydrodynamic (primitive) equations, is forced by wind, atmospheric pressure, the astronomical tide, temperature and salinity gradients, and main riverine input (in particular the three main contributions to Maputo Bay). The model is based on the Regional Ocean Modeling System (ROMS) code, a state of the art numerical circulation model (Shchepetkin and McWilliams 2005) that has been specially designed for accurate simulations of regional ocean systems. ROMS has been applied for the regional simulation of many different regions of the world ocean (Marchesiello et al. 2003).

To characterize the scales of detail and to obviate the problem of downscaling information from the global scale to the coastal scale of interest in this study, we chose to use a chain of nested models, starting from a large-scale climatological model at 1/4° of resolution and forced by climatological atmospheric data (COADS).

As for the oceanographic context, Maputo Bay is a sub-regional complex system situated between the Agulhas Current and the eddies system of the Mozambique Channel. The large-scale model includes the high-pressure system that dominates the region, and the intensification of the westward coastal current, typical of many of the western continental margins. In a classical view of the currents, the North Madagascar Current would flow south through the channel to form the Mozambique Current and, to the south, the Agulhas Current. Today, such a view has changed and the low variability scenario has been replaced by a configuration with greater spatial and temporal variability, in the form of a train of non-permanent anticyclonic eddies.

An intermediate (1/16°) resolution model has been spun to provide the boundary conditions of the high-resolution model of the bay (1/80° is about 1 km) (Fig. 10.2).

Maputo Bay is subject to a strong semidiurnal tide with a marked spring to neaps ratio (Canhanga and Dias 2005). Following the model, currents inside the bay range from 0.1 ms^{-1} in neap tide (minimum range of excursion) to about 1 ms^{-1} in spring tide (maximum range), as it is also confirmed by in situ data (Lencart e Silva 2007). Tidal analysis of the historical surface elevation established by Canhanga and Dias (2005) shows a minimum range of 0.2 m and a maximum of 3.8 m.

The model shows that temperature has an annual warming cycle, while on the other hand salinity has a small degree of variation: this is confirmed by observed data (Lencart e Silva 2007). Also, tide-induced residual currents show the formation of a non-permanent (although recurrent) eddy, just in front of the Incomati estuary, probably determined by the mutual interaction between tidal forcing, density front, and the coastline shape.

Tidal amplitudes vary over the year between 80 cm during neap tides and about 300 cm during spring tides. This is correctly reproduced by the model, as are the frequencies of tidal oscillation (Fig. 10.3).

In the INGC report (2009), the Highest Astronomical Tide (with a return period of 1 year) is estimated at 178 cm above MSL, which is consistent with measurements and model results. Moreover, an extreme sea level of about 270 cm is

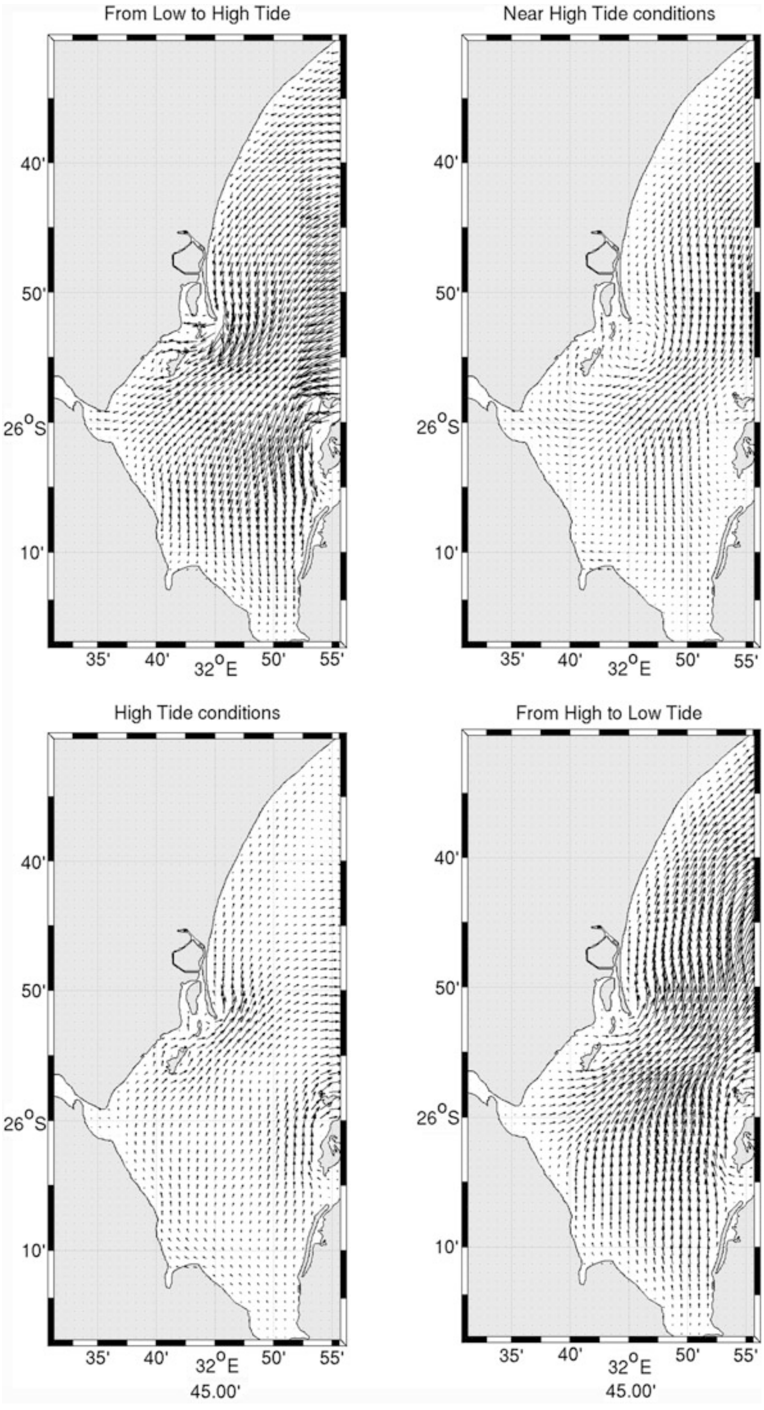

Fig. 10.2 Simulation of a Spring tide cycle in Maputo Bay, 16th November of a climatological year

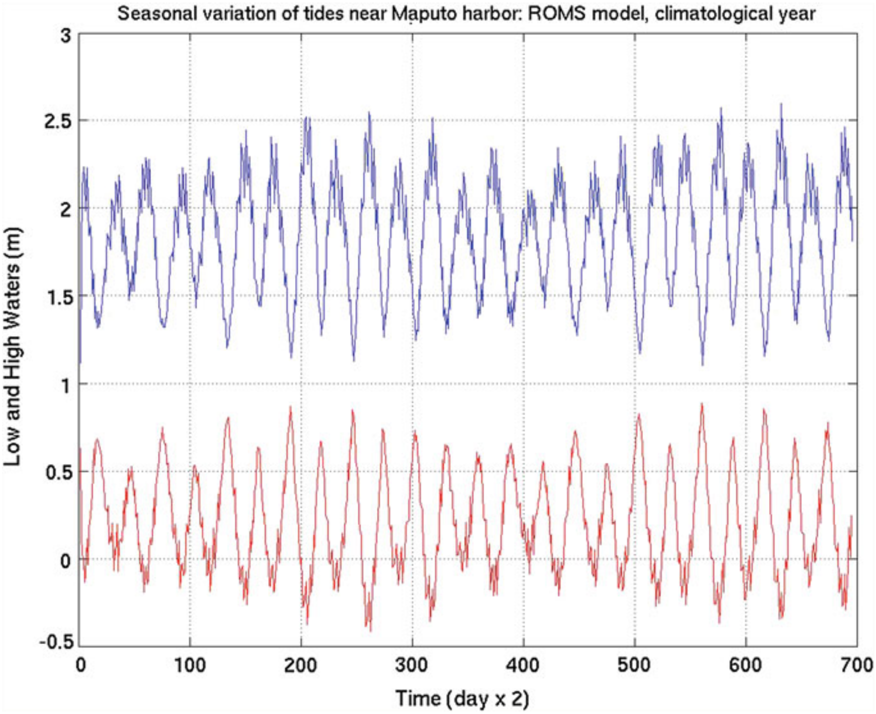

Fig. 10.3 Tidal variations calculated using the ROMS model. The reference level is global MSL

estimated for a return period of 100 years. These developments can reasonably be registered when a low-pressure system (e.g. a tropical cyclone) hits the coast and adds the effect of high tide to the inverse barometer effect, the latter due to strong winds causing a surge towards the coast.

10.5 Climate Change and Coastal Erosion

One of the biggest impacts that can be expected on the coast as a result of CC is brought on by the rising sea level. Although multiple data sources are now available to estimate the rise in average sea level, estimates of MSL based on in situ data do not support sufficiently reliable forecasts for the next century.

In particular, it is not possible to obtain data on sea level rise derived from historical hydrographical data over a long enough period to obtain valid extrapolations for the area in question. The only estimates of future SLR are from global models. Considerable efforts are being made by the scientific community to obtain more reliable estimates of future MSL. In coastal cities such as Maputo, this increase in MSL may have devastating consequences, especially if combined with other causes of rising sea level along the coast.

However, there is considerable variation among the projections being advanced at present in the international community:

(1) The IPCC estimates include an increase from 18 to 59 cm to be reached by 2100 (IPCC 2007). In comparison to the ongoing debate, these estimates are considered among the most conservative, and do not take into account a scenario of rapidly melting of ice.
(2) The melting of ice, as measured in multiple field studies, is associated with time scales in the order of several centuries and millennia. Most studies do not expect, for the next century, an increase of more than a few tens of cm to be contributed by melting ice.
(3) Many studies on sea level rise have been derived from paleoclimate studies, which have great validity, but are a poor basis for projecting scenarios of rapid changes over a few tens of years (Grinsted et al. 2009).
(4) Most of the studies that exceed the IPCC estimates of MSL rise by 2100 provide values that are usually lower or slightly higher than 1 m (Rahmstorf 2007; Rahmstorf 2010). However, some recent studies predict that sea level could rise by more than one meter this century if greenhouse gas emissions continue to escalate (Vermeer and Rahmstorf 2009).

This estimate is obviously not to be applied at the global scale, and differs from point to point along the coasts of the earth, interacting with local geological conditions such as tectonic uplift/subsidence, isostasy, or sediment compaction. Nevertheless, a maximum projected MSL rise of 1.25 m by 2100 has been deemed sufficiently conservative for the purposes of the present study, and that estimate has been applied to all subsequent determinations in this work.

Figure 10.4 depicts four scenarios, assuming an average sea level rise of 1.25 m in 2100:

1. the current situation;
2. the future scenario, in the case of an SLR of 1.25 m;
3. the current situation if the coast were be flooded by a storm surge during spring high tide conditions and with a return period of 100 years; and
4. the future scenario, in which MSL rise is compounded by a storm surge with return period of 100 years.

We can see that the majority of the city of Maputo would not be affected by the circumstances described above, with the exception of several newly urbanized areas to the east of Maputo (Costa do Sol). That area would not be particularly affected by rising sea level in itself, but it would be affected, even now, if a surge of great magnitude were to impact the coast, and that effect would be amplified in the future when combined with SLR.

The INGC report (2009) on the impact of climate change in Mozambique contemplates a much more severe scenario involving a rise in sea level equal to 5 m by 2100. It should be noted that none of the evidence presently available to the scientific community supports this hypothesis. Even more questionable statements appear in the same report to justify the need for coastal defenses against SLR.

Fig. 10.4 From *top* to *bottom*: current situation; mean sea level rise of 1.25 m in 2100; current situation with a surge return period 100 years; and future surge. Area of the port of Maputo on the *left*, Costa do Sol on the *right*

However, the only way to reduce the impact of sea level rise on human activities is through the rules of good building and good urban planning, and not through coastal defenses. The municipality should simply avoid the building of homes and neighborhoods in areas that are less than 4–5 m above MSL.

As in many other world areas, coastal erosion in the Maputo Bay is due to the combination of man-made and natural processes. Among the most significant anthropogenic activities are the damming of rivers (which causes a sediment deficit in the inputs to the coastal zone) and overexploitation of the littoral areas. Other conditions being equal (i.e. ignoring the causes attributable to human behavior), natural causes are likely to determine the main effects of CC. These natural processes include floods, storms, sea waves, and sediment transport (in both alongshore and cross-shore directions). Although the completion of this study would require more detailed data than those available, the model highlights major flows of water and sediment across the bay.

The concentration of suspended sediments within the bay was modeled using a number of Lagrangian particles released in the vicinity of the river mouths, and assuming a concentration of suspended sediments proportional to the input. The impact that a 20 % reduction of transport (freshwater and sediments) would have on the concentration of suspended sediment near the beaches was then estimated, taking as reference points the beaches near Costa do Sol. In practice, most of the sediment that nourishes the beaches to the east of Maputo seems to come from the mouth of the Umbuluzi river (10 %—i.e. half—of the total 20 % impact) and to a lesser extent from the Incomati and Maputo rivers. This highlights, once again, that the morphodynamic equilibrium within the bay is rather delicate and extremely sensitive to the reduction of sediments. In particular, the impact on sediment caused by the construction of river dams (such as the recently built *Pequenos Libombos* dam along the Umbuluzi river, close to Maputo) appears to be very high.

This low intake of fresh water flow (and sediment) at the river mouths, on the other hand, is well documented (UNEP 2009).

It should be noted that the coastal structures (groynes) put in place to protect the shoreline have been shown to be quite effective in protecting the coastal area: three such groynes, built on the eastern coast of Maputo, show an accumulation to the south (which seems to capture part of the sediments moved from the south, thus mostly coming from the Umbuluzi), while further north a slight accumulation has occurred on both sides, more pronounced on the northern side. This means that there is no clear trend in the direction of longshore sediment transport, with tidal oscillations moving comparable volumes of sediment in the two directions. The significant setback that the beaches have suffered in many places is therefore not due to alterations in the hydrodynamic regime, but rather to a reduced amount of sediments in the bay.

Coastal protection constructions (coastal walls) are effective in areas where the sea has already eroded much of the coast and the central problem is to protect existing infrastructure (e.g. along the Avenida Marginal). It should be noted that the conservation status of some natural elements along the coast, such as sand dunes and mangrove forests (often in combination) near the capital, is substandard. Recently,

Fig. 10.5 Examples of coastal erosion along the Avenida Marginal

many construction projects have been carried out in low areas occupied by mangroves. The restoration of these *natural* elements today is expensive or even impossible, However, in areas where mangroves are still intact, every effort should be made to maintain the natural elements that act as partial protection against erosion.

10.6 Conclusions

The projected long-term impact that climate change may have on the coast of Maputo, and other parts of the African coast, entails critical aspects that are insufficiently appreciated. Such aspects must, of course, be considered on a case-by-case basis. In the case of Maputo, the bay is part of a complex coastal system with a very delicate morphodynamic balance, determined by the joint action of tidal forcing and freshwater and sediment inputs from neighboring river basins (Maputo, Incomati, and Umbuluzi).

The reduction of sediment transport from hydrographical basins, caused by the intensive use of water (dams) and by the decrease in cumulative rainfall, is the most likely cause of coastal erosion, which is occurring mainly along the beaches east of Maputo. In the future, we can expect water consumption from rivers to increase, due to the economic development of this part of Mozambique and the consequences of global warming. This will undoubtedly lead to further reduction of the sediment transport, with serious consequences for the morphodynamic equilibrium of the beaches and of the bay in general.

The rise in sea level is currently a very controversial topic. Considered in isolation, the impact of this rise is not expected to be particularly serious for the city of Maputo, however important consequences are expected to occur along the beaches of the east coast (Costa do Sol), where intense urbanization is ongoing.

It is important to stress that there are no coastal defenses to counter the sea level rise. As such, a number of actions should be taken to avoid building in areas lower than 4–5 m above the actual MSL. Urban planning and urban rules are the only reliable tools with which to counter sea flooding phenomena, a risk that already exists today (e.g. in the event of a storm surge during a phase with very high tides).

Finally, it is worth noting that many elements of natural protection against coastal erosion (dunes, mangroves) in the Maputo region are now in poor condition, compromised, or destroyed (Fig. 10.5). There is therefore a need to avoid the over-exploitation and destruction of coastal sand dunes and mangrove forests, where they still exist. These environments are also important from an ecosystem standpoint as elements of outstanding environmental quality.

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