Chapter 13
Mitigating Coastal Erosion in Fort Dauphin, Madagascar

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Abstract The city of Fort Dauphin is one of the most attractive tourist spots in Madagascar. In recent years, it has become one of the development centers of the island. However, the city is facing coastal erosion related to human activity as well as natural factors. Mitigation of coastal erosion at the catchment and regional scale is extremely important for the sustainable economic and social development of this region. Spatial analysis using satellite imagery over a long period has been considered as an important tool for determining the extent of the most affected areas and for analyzing how the erosion has developed in the past and at present. Measurement and field work need to be integrated to develop appropriate strategies to mitigate the problems. Satellite imagery analysis in combination with field work and measurement consists of generating long-term information required to determine threats and pressures in time and space. It takes into consideration assessment of land use, the geology of the area, urban planning, local and regional climate, and coastal management. Madagascar faces multiple challenges in mitigating coastal erosion, but the involvement of authorities and local communities plays a key role in long-term shoreline protection.

Keywords Fort Dauphin • Mitigation of coastal erosion • Spatial analysis

13.1 Introduction

Due to its growing intensity, coastal erosion seems to be an abnormal phenomenon, but it is in fact a common occurrence. It has served as the key factor shaping coastal environments throughout history (Niesing 2005; Prasetya and Black 2003). Coastal systems play a variety of roles including assimilation of wave energy, hatching of

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flora and fauna, and groundwater protection, and they contribute significantly to recreational activities (Niesing 2005). Fort Dauphin is among the coastal zones threatened by coastal erosion. A recent rise in sea level, landslides, and coastal erosion have become serious threats to this municipality. Since 2005, coastal erosion has resulted in loss of housing facilities, four recreational beaches, and road communication links. In 2011 and 2012, widespread diminishing of beaches was observed around the city, with some areas badly damaged. Coastal erosion can be classified as a major risk for the city due to the threat it poses to economic development activities. In light of this, in 2012 the government decided to finance coastal erosion surveys through the PIC (Pole Integré de Croissance) project.

According to the Intergovernmental Panel on Climate Change (IPCC) in its Fourth Assessment Report in 2007, climate change marked by increasing temperature and a rise in sea level will place populations living in coastal areas in grave danger in 80 years' time. Moreover, Key human activities (Neuvy 1981; Schiereck 2004; Williams and Micallef 2009; Brebbia et al. 2009; Kim 2010; Slovinsky 2011) are located in coastal zones. In other words, the pressures of climate change and increase in human activity toward the coasts has turned coastal erosion into a more serious problem, not only for coastal municipalities, but for the world as a whole (Prasetya and Black 2003; Niesing 2005). Coastal erosion is usually the outcome of many factors in combination including natural and human-induced influences operating on different scales (Shore Protection Manual 1984; Ir Zamani Bin Mindu 1988; DGENV European Commission 2004; Williams and Micallef 2009; Slovinsky 2011). In undertaking this case study, therefore, it was necessary to understand the factors responsible for coastal erosion in order to develop mitigation strategies.

Fort Dauphin is an urban municipality in the southern part of Madagascar. According to the administration division, it is the capital of Anosy Region, and Amboasary district is positioned at the south eastern limit of Madagascar, in an area where winds blow from the Indian Ocean (Fig. 13.1). Geomorphologically, this study area is characterized in its eastern part by a small coastal plain dominated by the Anosyan Mountains. Morphological disposition makes the region highly exposed to winds blowing from the east (alize) and orographic lifting occurs frequently (Ratsivalaka Randriamanga 1985). The contacts with the ocean in the eastern and southern parts of the study area constitute cliffs varying between 5 and 10 m in height.

13.1.1 Climate

Under the influence of the Indian Ocean and its morphology, this region receives significant rainfall; its average annual rainfall is 1,800 mm/year (Direction de la météorologie 1980). As in the other regions in the country, December and January are the rainy months, comprising the rainy season. As it is exposed to the Indian Ocean, however, rainy and dry seasons are sometimes mixed. Temperature in this area varies between 20 and 26 °C (Direction de la météorologie 1980), where the maximum temperature corresponds to the rainy season and, conversely, the minimum temperature typifies the dry season.

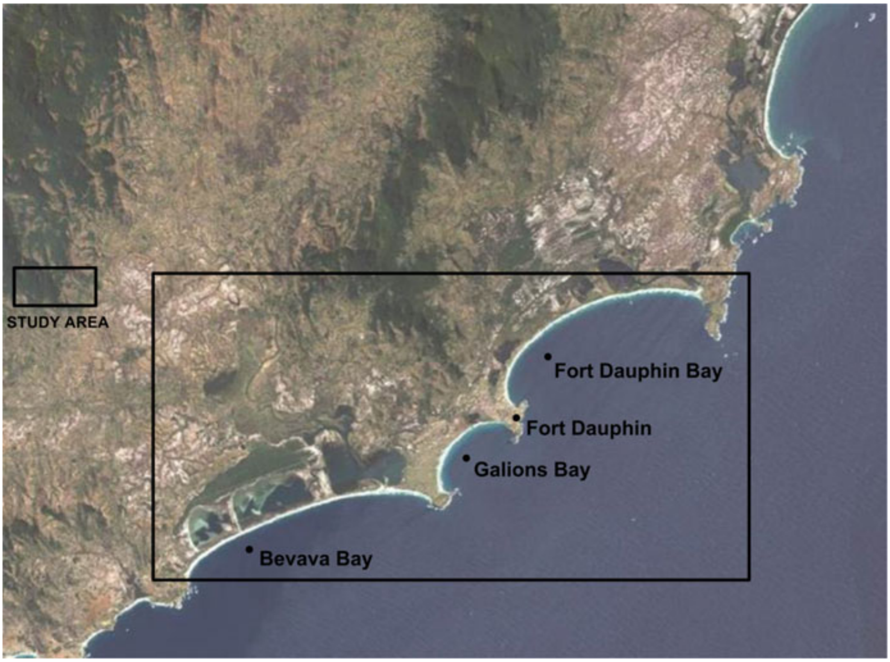


Fig. 13.1 Location of the study area

13.1.2 Geology

Fort Dauphin essentially comprises sedimentary rocks that form Pleistocene and Holocene dunes. The eastern and southern areas are characterized by cemented dunes, where limestone playing the role of cement makes relatively hard rock. Due to its hardness, it forms cliffs in some areas. Westward, this formation is topped by unconsolidated recent dune, which occupies three fourths of the area. In the north east of this locality, metamorphic rocks of the Paleoproterozoic Era (1.8 Ga) act as a climatic barrier (Fig. 13.2).

13.2 Methodology

The development of Fort Dauphin's coastal degradation was studied by comparing satellite imagery taken at different times, namely 1998, 2004, 2009, and 2011. These satellite images enabled us to measure and observe the variation of the beaches and the coastal area width (Cambers 1998; Brebbia et al. 2009; Y Wang 2010). In this survey, the most damaged areas in each of the years were analyzed, such as Bevava Beach, Galions Bay, and Fort Dauphin Bay, as well as Libanona

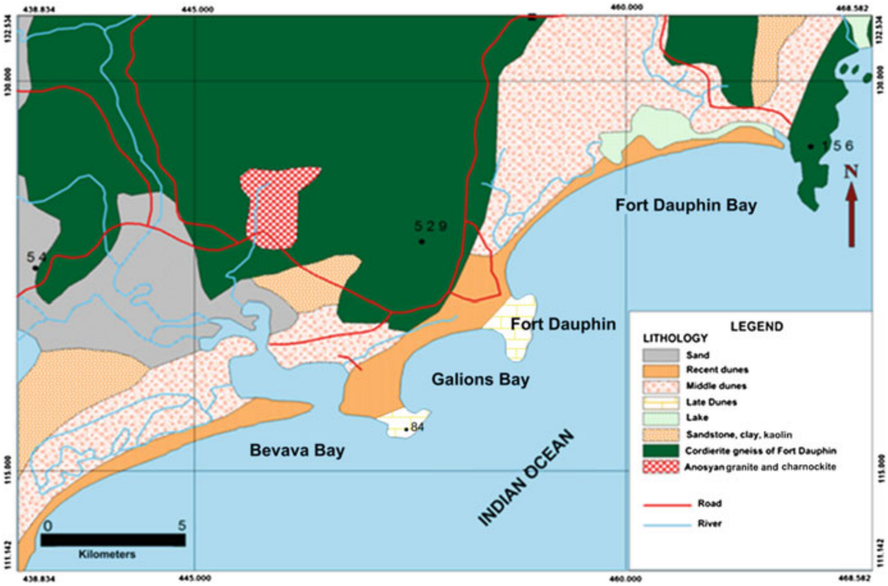


Fig. 13.2 Geology of Fort Dauphin and its surrounding areas

Beach. The dunes of Galions Bay were also studied due to the combination of coastal and aerial erosion. The analysis involved measuring a fixed 20 m portion of the bays for each of these periods; 1998 was taken as the reference point in these measurements, and the analyses incorporated some measurements of water levels, waves, and currents made by QIT Madagascar Minerals (QMM).

These cartographical analyses were coupled with field work and villagers' observations, where coastal erosion was observed for each measurement at different periods. Some photos and video were obtained from the fieldwork, facilitating the formulation of appropriate solutions to stop or mitigate the coastal erosion Phenomenon (Auckland Regional Council 2000; DGENV European Commission 2004; Brebbia et al. 2009; NSW Government 2010; Y Wang 2010).

13.2.1 Data Processing

Numerical models were also used to assess and analyze the waves in the surrounding area and around Ehoala Port. The results of these models were checked using satellite, recorded wave, and pressure data. Based on satellite imagery analyses, Orthophoto, Quickbird, and worldview respectively for 1998, 2004, 2009, and 2011 were treated with GIS assessment methods using Arc gis.

13.3 Results and Discussion

Table 13.1 summarizes the development of coastal erosion in Fort Dauphin, which manifests by reduction of beach width in the four selected portions that are most affected by coastal erosion (Fig. 13.3). In some periods, the phenomenon of accretion was also apparent, but in general, diminishing of the beach width ranged from 2.6 m (Galions bay) to 9 m (Ambinanibe). The accretion measured during the study periods was insignificant compared to the sediment loss.

Table 13.1 Development of coastal erosion in Fort Dauphin

Period	Ambinanibe Beach (630 m)	Galions Bay (400 m)	Libanona Beach (430 m)	Fort Dauphin Bay (1,000 m)
2004–2009	Accretion = 9.4 cm/year	Loss = 0.87 m/year	Accretion = 29 cm/year	Accretion =30.4 cm/year
2009–2011	Loss = 9.165 m/year	Loss = 2.64 m/year	Loss = 4.81 m/year	Loss = 5.265 m/year

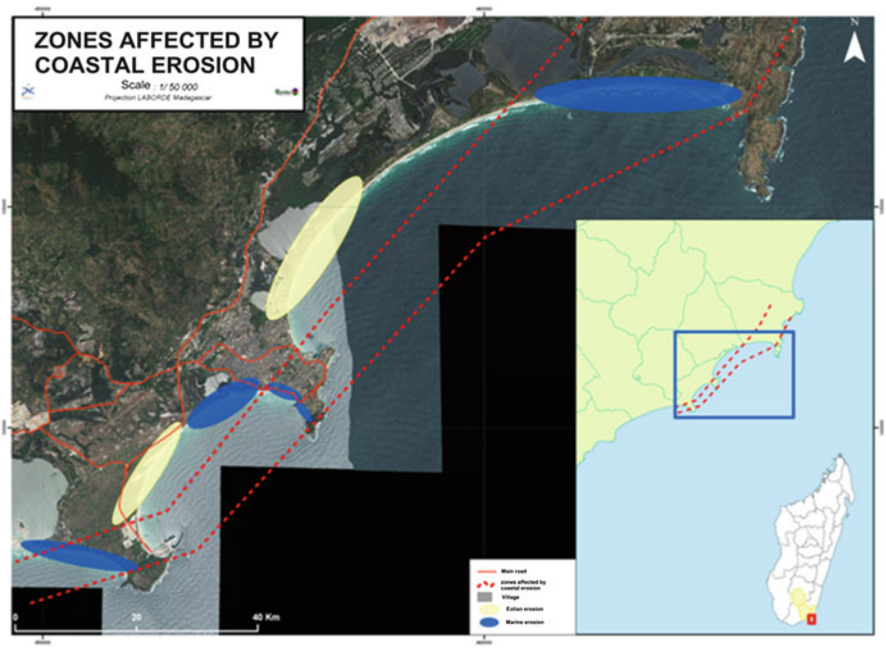


Fig. 13.3 Selected portions showing coastal erosion and wind erosion respectively in *blue* and *yellow*

13.3.1 Impacts and Causes of Coastal Erosion

The impacts of coastal erosion most frequently encountered in Fort Dauphin can be grouped into three categories: coastal flooding as a result of dune erosion, undermining of sea defenses associated with foreshore and subaerial erosion, and retreating cliffs, beaches, and dunes causing loss of land (Fig. 13.4).

Coastal erosion is derived from numerous causes but wind and current are particularly significant. These two parameters play important roles in coastal abrasion. Due to the similarity in the locations of the most affected areas, and the wind

Fig. 13.4 Impacts of coastal erosion in Fort Dauphin

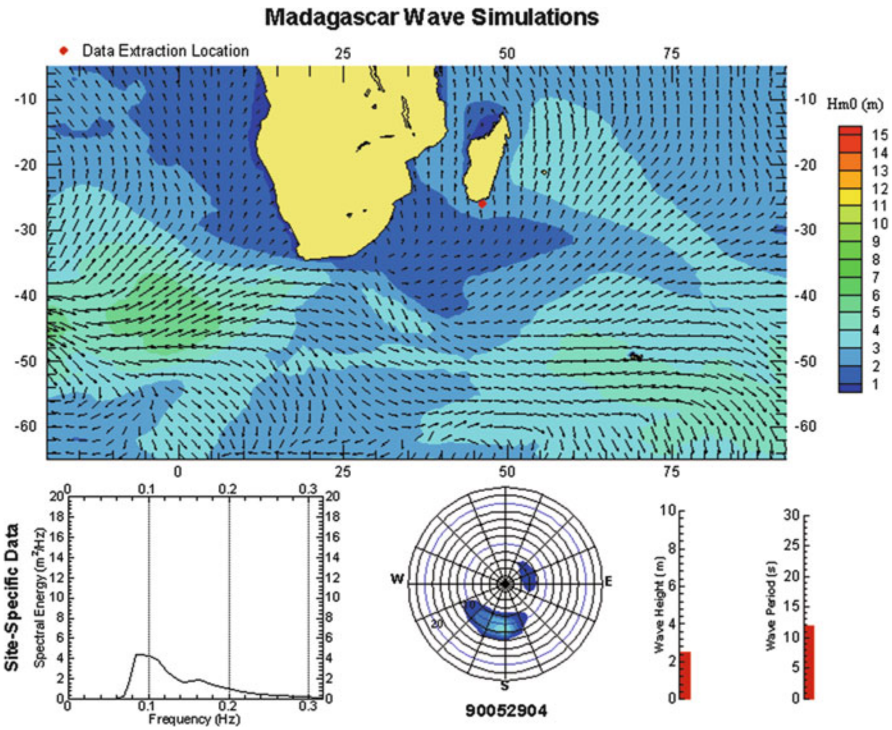


Fig. 13.5 Wave simulations in Fort Dauphin showing wave directions (Rio Tinto-QMM 2008)

and current directions, the results of numerical models of waves and current direction show that wave action and ocean currents are among the most important factors causing coastal erosion in Fort Dauphin. As shown in Figs. 13.5, 13.6, 13.7, and 13.8, the majority of the strongest waves and currents come from the southwest and east.

The manifestation and activity of these two parameters on beach and dunes could be explained by combinations of various natural forces such as the wave direction approach, as well as the dredging (digging) phenomenon in the coastal area. Before explaining the coastal erosion process in Fort Dauphin, it is interesting to remember that the surf zone is the area where waves break. It is a turbulent zone, as waves smash and dissipate their energy in this area while producing intense local currents that eventually reach the coastal shores (Hyndman 2006). During this turbulent time, water removes sediment in its path and then local currents carry it to the sea when leaving the coast. The same process occurs in the wave zone; in this zone, the depth of breaking varies depending on wave size (Hyndman 2006). This phenomenon is observed on all the beaches in Fort Dauphin, and beach and dune dredging appears in the same manner as shown in Fig. 13.9.

During the study, natural sand transport into the deep sea was observed in almost all the beaches of the city after dredging. Sand content in sea water varies depending on the area, but it seemed greater in Bevava Bay (Ambinanibe) and Galions Bay.

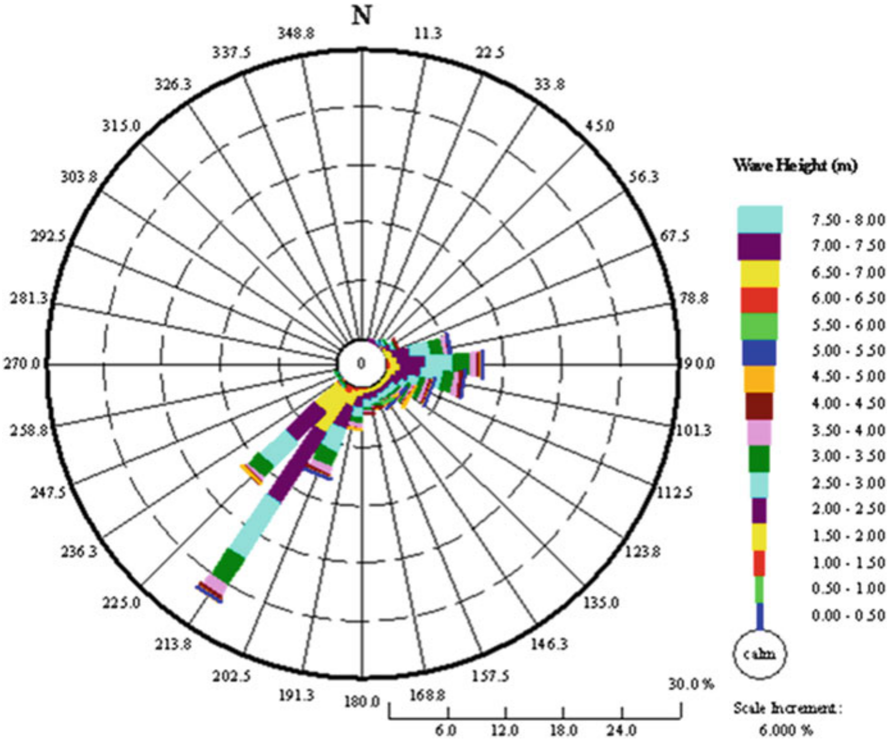


Fig. 13.6 Wave heights (offshore)

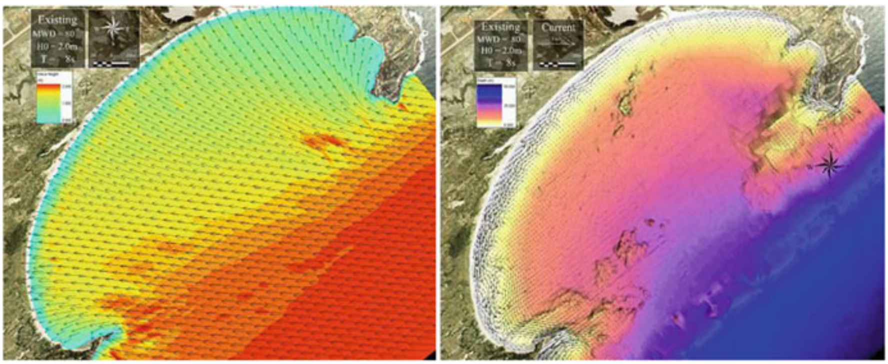


Fig. 13.7 Wave direction and current from eastern part of the study area (*Source*: QMM)

Usually, dredging activity depends on wave direction approaches. Wave direction approaches to the shore are important for coastal stability because the changes in angle lead to coastal erosion by removing beach sediment and transporting it into the sea. Normally, wave direction approaches should be perpendicular to the shore (Hyndman 2006). In that case, the energy produced by wave forces dissipates into

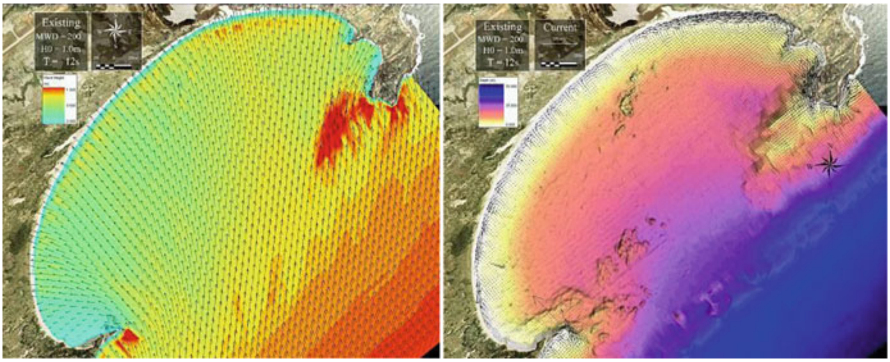


Fig. 13.8 Wave direction and current from southern part of the study area (*Source*: QMM)

Fig. 13.9 Image showing the actual state of Libanona in Galions Bay, 2012

the terrestrial zone and longshore current follows a parallel direction along the shore line. But if wave direction approaches are not perpendicular, a huge amount of energy is dissipated to the shore, leading to coastal destabilization. Hence, coastal zone is unable to resist this energy, and eventually longshore current direction at an angle along the shore line dredges sediment (Hyndman 2006). In Fort Dauphin, coastal erosion may have been caused by the irregularity of wave direction approaches because they were not perpendicular to the shoreline during the field-work in 2011 and 2012.

Dredging is always happening in coastal areas but its intensity is weak in the normal environment (Hyndman 2006). Coastal dredging, characterized by the lack of sediment supply or sand in the coastal zone, is probably due to the formation of canyons in the deep sea or atmospheric air disorders. When canyons have formed, nature tries to fill the gaps at the expense of beaches or sensitive areas whose sand can be transported. Both formation of canyons and atmospheric air disorders might have occurred in Fort Dauphin because human-induced dredging during the Ehoala port construction could be one of the causes leading to coastal erosion in this area.

The dredging of the ocean bottom on a superficies of 181,000 m^2 (QMM S.A. 2009) might also have led to coastal erosion in Galions Bay between 2004 and 2009. This might also explain the beach diminishing in this area during that period as no major change was noticed at the other beaches.

Furthermore, waves and tides act on cliffs formed of solid rock in the same way on beaches and dunes, but their action is focused at the base and on arches. Some pieces of rock at these points are washed away each time leading finally to instability, or even to rocks being torn off and thrown into the sea at the foot of the cliffs. These rocks are later pulled into the sea, accelerating the erosion. It means that the results of wind-induced erosion and current-induced erosion are the same but the processes are different.

Moreover, during this period (2004–2009) the study area was threatened many times by tropical cyclones. As a result, heavy damage to the coastline was recorded between 2009 and 2011. The damage observed on the beach portions probably resulted from heavy waves with very active currents. In addition, traces of subaerial erosion characterize some places. Coastal erosion and particularly subaerial erosion could therefore be occurring at the same time with heavy rain. Overall, a loss of ten meters from the coastal area was measured between 2009 and 2011. These facts suggest that only cyclones are capable of causing storm surges, winds, and currents at the highest levels that can destroy 10 m of coastal area in 2 years.

Looking at the weather events that have occurred recently in Madagascar, the island has experienced frequent tropical cyclone passage during the past ten years (Rakotondravony 2012) (Fig. 13.10). Generally, tropical cyclone passage is accompanied by heavy rain and violent storms. Tropical cyclones that attacked the country were strongly associated with marine movements in the immediate vicinity of Fort Dauphin. Although the path of a storm may not directly affect the coastal city of Fort Dauphin, this area sustains heavy rains, high waves, and storm surges along the coast (Donque 1974; Météorologie Nationale 1975; Direction de la météorologie 1984). Moreover, these factors have an influence on the local atmospheric circulation and the influence remains even a few years after the cyclone event. It takes approximately 4–6 years before normal conditions return (Nicholson 1997), but due to climate change that disrupts the air circulation, normal conditions may never be recovered (Rasmusson and Wallace 1983). It is also surprising that many tropical cyclones affecting Madagascar, eventually reach Fort Dauphin and dissipate there, or nearby.

During the period from 2004 to 2009 coastal accretion occurred although longshore currents did not significantly affect the beach; the waves were certainly less aggressive due to less precipitation. Nevertheless, residents along the shoreline found that the sea level increased significantly after the tsunami event in 2004. According to villagers, they noticed that the width of the beach had declined by about 80 m since 2004. One factor that can amplify the action of cyclone is a rise in sea level. This takes place extremely slowly and seems minimal, but also causes the removal of shoreline.

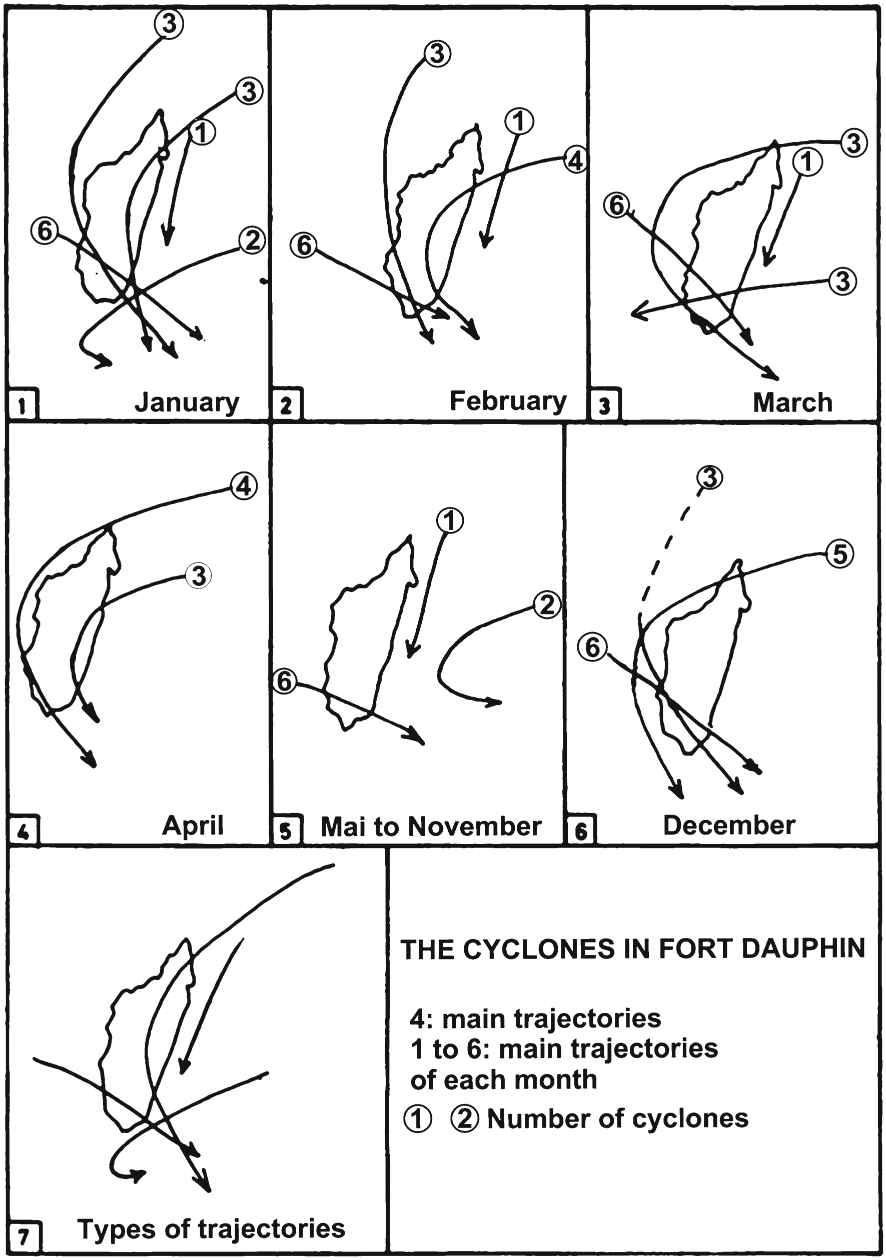


Fig. 13.10 Habitual trajectories of cyclones in Madagascar

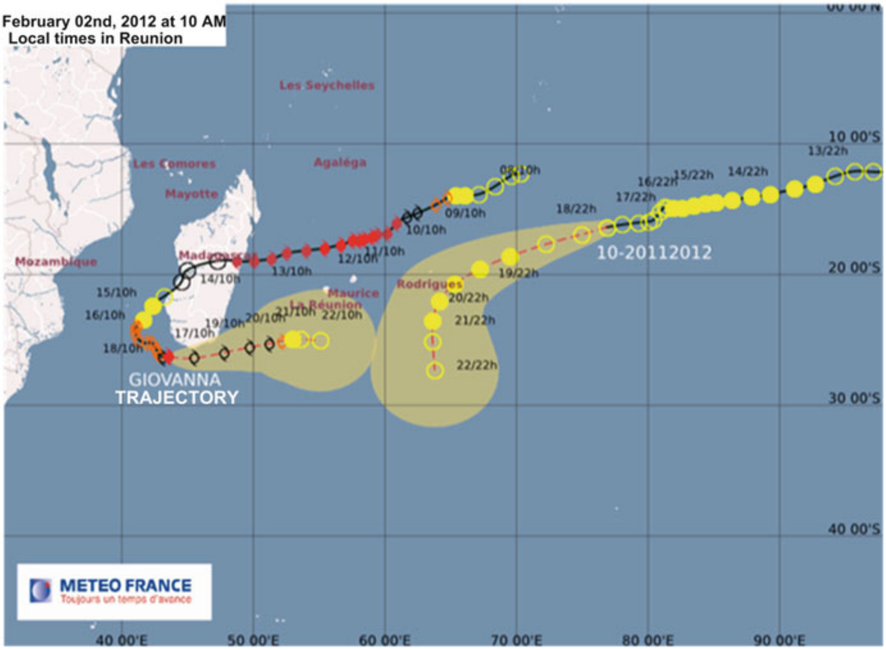


Fig. 13.10 (continued)

13.4 Solutions

To limit the damage caused by coastal erosion, residents have devised solutions using gabions or garbage. These initiatives may be collective or individual. A protective wall has been constructed facing the sea on a portion of the coast in the south through a private initiative. Groins have also been installed in the study area by QMM. However, no shoreline protection project has yet been initiated to fight against or mitigate coastal erosion in Fort Dauphin.

As explained above, marine erosion around the city of Fort Dauphin can take different forms (marine, subaerial, or wind erosion) but all are controlled directly or indirectly by the wind. It would be wise to consider several options for countermeasures depending on the type of erosion.

13.4.1 Marine Erosion

Several solutions can be adopted to fight against coastal erosion. However, these solutions must take into account the specifics of protected areas (e.g., tourist sites, areas characterized by dune formations, etc.), as well as the local availability of protective materials. Taking these considerations into account, two or three options were adopted immediately after the damage was sustained to stop or mitigate the effects of coastal erosion in Fort Dauphin. But they were mostly private or individual initiatives.

13.4.1.1 Groins

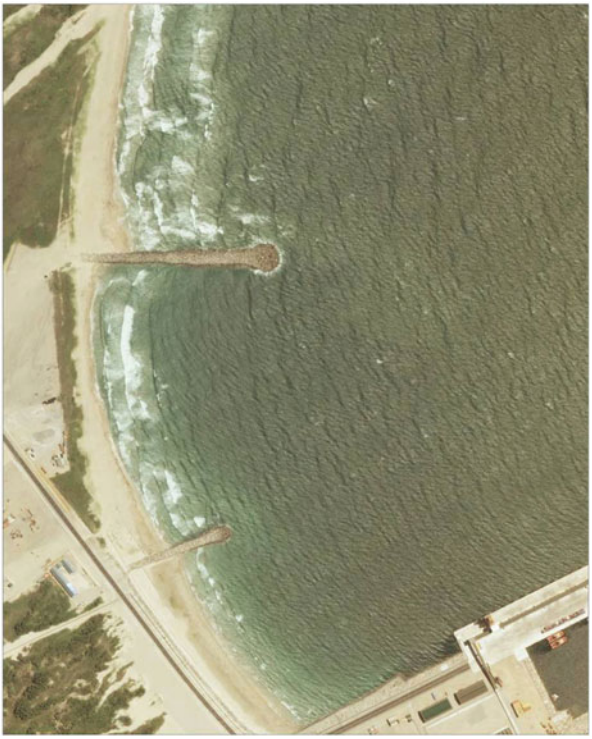
This technique is based on the construction of stone or concrete walls perpendicular to the shore and extending into the water. They are primarily intended to promote the accumulation of sand on the beach by trapping the sand, or slowing its movement along the shore. They can also be constructed of either wood or steel. The groins can be built separately or in groups along the beach (Fig. 13.11).

These coastal groins will therefore be used to reduce the transport of coastal sand and/or sediment to maintain the current speed away from the shore at high tide. In this case, the wave attack is first concentrated on the end of the groins. Groins operate more efficiently on coasts where the directions of littoral transport are constant. They are one of the most widely used countermeasures against coastal erosion in the world. The best results have been shown by the spikes in Nevis and the Caribbean islands. In Madagascar, they have already proven their effectiveness in protecting the new Ehoala port where accumulations of sand on both sides were observed (Fig. 13.12).

The structures, which soften the action of the waves on the shore, are used on all Fort Dauphin's bays. However, in the case of Libanona, the location of the structures and possible intensity of ocean currents in this small space could further reduce the space available for recreational activity. The beach is the closest recreational area to the city and the most popular beach among the residents.

Fig. 13.11 Groins installed close to the Ehoala port

Fig. 13.12 Image showing the groins installed close to the Ehoala port from space



13.4.2 Subaerial Erosion

To mitigate the subaerial erosion, in addition to setting up protective walls at the cliffs, an adequate drainage system needs to be established in Fort Dauphin. Moreover, the current provision for sanitation should be improved, particularly in sensitive areas (near the coast).

13.4.3 Wind Erosion

Wind erosion areas are mainly on the sides of the dunes, and now this erosion also happens on the ridges. This means that the action of wind erosion has reached its peak and may not extend back to the dunes. The affected areas are all unconsolidated dunes. Planting of plant species capable of growing rapidly and transmitting their roots deep into the dunes is proposed. For this solution to be effective, the wind direction on the areas to be protected must be taken into consideration during implementation, as well as the most favorable times to avoid wind washout of the dunes later. At the same time, siltation should be reduced to stabilize the soil. Preliminary

Fig. 13.13 Casuarinas trees planted near the Ehoala port

steps such as mulch techniques are necessary to prepare the ground before the actual planting of plant species. This entails covering the sand with a uniform layer to stop the action of the wind on the ground and especially to block siltation. First, a fixative (mulch) must be prepared with straw, local herbs, or agricultural residues, and the area subject to erosion must be covered until revegetation occurs. Regular watering of the soil is then undertaken to create cohesion between the grains, making soil much more resistant to erosion.

Once the dunes are stable, planted trees can withstand the actions of the wind over time. Use of Vetiver has already shown great success in watershed protection in Madagascar. This species is capable of sinking its roots up to three meters deep and grows almost everywhere. The same is true for casuarinas, which have already been planted in Fort Dauphin along the road leading to the Ehoala port as a kind of windbreak (Fig. 13.13). To date this species has grown well and met expectations.

13.5 Conclusion

Recently this municipality has been threatened by a rise sea level, landslides, and coastal erosion. These natural phenomena have worsened since 2004, resulting in damage to and loss of agricultural land, houses, roads, and recreational beaches. In 2011 and 2012 widespread diminishing of beaches was observed around Fort Dauphin, with the southern areas severely damaged. A combination of satellite imagery analyses and climatic survey enabled us to identify development of coastal erosion in Fort Dauphin. These analyses indicated that average loss of coastal area was about 5 m/year, but coastal erosion activity became stronger during the period between 2004 and 2011.

In this area, coastal erosion was characterized by a combination of coastal, subaerial, and wind erosion. This combination occurs especially during rainy seasons and in particular during cyclones. Indeed, the wave height is much greater during these periods, and it is the same for the ocean currents and rainfall. In general, coastal erosion is at its peak when the effects of the three types of erosion (coastal, subaerial, and wind erosion) are combined.

Causes of coastal erosion in Fort Dauphin might result from a combination of factors, both natural and human-induced, which have different patterns in time and space. They are probably due to the cyclone passage that has generated storms and tides over recent years in Madagascar. Simulations of waves and their height indicate that south-west and easterly wave directions are responsible for the damage. Human activity such as dredging and river damming in the south and north of the study area might have contributed to the intensity of coastal erosion during 2004–2011. The movements of these parameters depend on wind direction and dynamism.

The PIC project made it possible to understand the key processes of coastal dynamics and how coasts function both in spatial and temporal time scales, allowing solutions to fight against coastal erosion to be proposed. Meanwhile, some solutions have already been implemented mostly as individual or collective initiatives. These initiatives have demonstrated the efficacy of constructing groins and planting species such as vetiver or casuarinas trees, with accretion resulting in some places.

The combination of offshore and onshore techniques such as groins and vegetation in coastal areas will improve slope stability, consolidate sediment, and diminish the amount of wave energy moving onshore, thereby protecting the shoreline from erosion.

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