CHAPTER 6
SYNTHESIS

Thematic paper: Synthesis of the protective functions of coastal forests and trees against natural hazards

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This paper argues that coastal forests and mangroves need to be restored and even created to enhance the capacity of estuaries and coastal waters to provide ecological services to the human population living on their shores. Further, coastal forests and mangroves protect the coast from wind damage, salt spray, coastal erosion, typhoons, and can even save human lives during a tsunami. It is stressed that these coastal bioshields cannot provide complete protection; they must be part of a regional plan to reduce the risk of loss of life, property and infrastructure to an acceptable level. A sacrificial zone within this bioshield must be incorporated in the management plan. The appropriate choice of vegetation depends on the severity of the natural hazards, bathymetry, the climate, the local land use and the available options to survive extreme events. It is stressed that the solution to protecting the coast from natural hazards is not just local; it also involves the whole river catchment. Indeed, vegetation must be used to protect the coastal population from landslides in mountainous areas and along river banks, and large dam operations must ensure that the coarse riverine sediment flow necessary to prevent coastal erosion is maintained. Bioshields, including mangroves, provide important ecohydrological services such as creating self-scoured navigable channels, sheltering coastal seagrass beds and coral reefs from excess sedimentation, and enhancing fishery capacity; these are all resources that human populations living along tropical estuaries and coasts rely on for their livelihoods and quality of life.

1 Introduction

Throughout human history, coastal plains and lowland river valleys have usually been the most populated areas throughout the world. This is due to the use of the rivers and estuaries as transport routes and to their very high biological productivity, sustaining a high level of food production (Wolanski *et al.*, 2004). Coastal waters, including those covering continental shelves, supply about 90 percent of the global fish catch. Worldwide, there is an increasing migration towards the coasts; this has resulted in a doubling of the population along many coasts over the last 20 years. At present, about 60 percent of the world's population lives near estuaries and the coast (Lindeboom, 2002). This rapid population growth near the coast is posing new and increasing challenges for humanity, through pollution, eutrophication, increased turbidity, overfishing and habitat destruction. Pollutants number not only nutrients, but also mud from eroded soil, heavy metals, radionuclides, hydrocarbons and a number of chemicals, including new synthetic products.

By aggregating near the coast, the human population is increasingly threatened by risks from natural hazards typical to the coast, which may not exist, or would generally be milder, in the hinterland. Some natural hazards in coastal areas originate from the hinterland such as floods that are of longer duration in low-relief coastal plains than in steep mountainous zones, and siltation, including mud flows; dams also contribute to coastal erosion. Other natural hazards are maritime in origin, namely typhoons and storm surges, salt spray, erosion and tsunamis. They are the focus of this synthesis paper.

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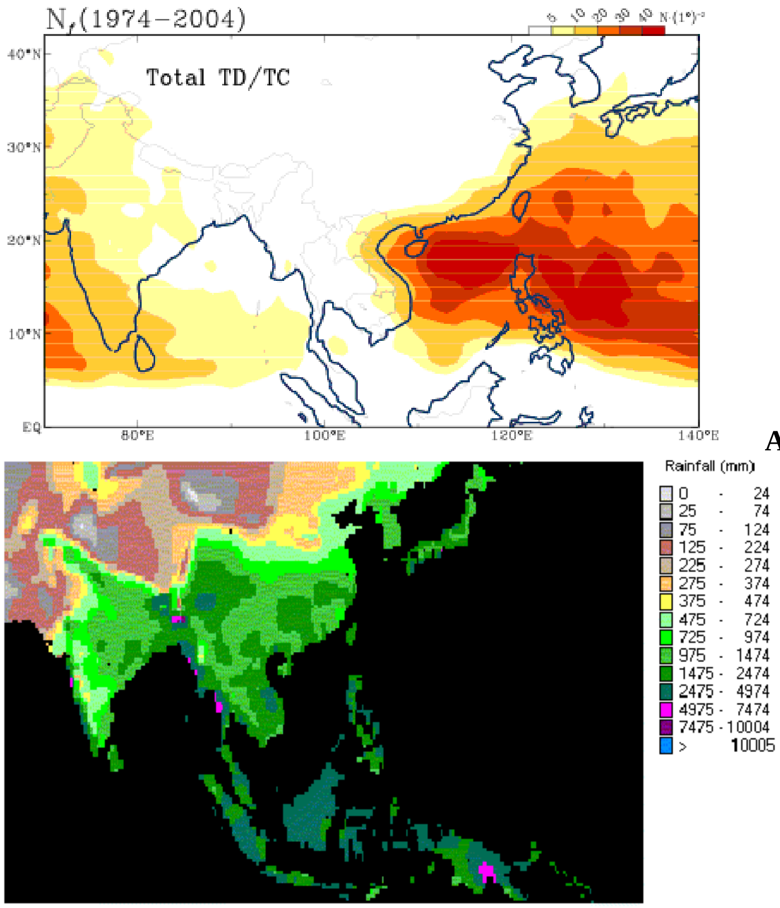
2 Natural marine hazards

Storms and typhoons generate storm surges and waves, winds and heavy rains mainly in regions at 10º to 40º latitude. Along the seaboard, the high impact area might be 30 kilometres wide, with extensive damage at lesser impact over 100 kilometres or more. The incidence of significant tropical cyclones in various regions varies spatially (Figure 6.1); Indochina, southern China, Taiwan Province of China and the Philippines experience the most tropical cyclone landfalls. Storm surges of up to eight metres can occur in the Bay of Bengal, and up to six metres throughout the “cyclone belt”. Typhoons also generate extreme rainfall, adding to coastal flooding, and wind waves with periods of ten to twenty seconds and heights reaching 25 metres at sea. The highest waves break as they run into shallow water; smaller waves penetrate inland with the storm surge and attack the vegetation and structures. Storm surge inundation typically lasts for six to twenty-four hours. The mitigating effect of a coastal forest on the duration of inundation of a storm surge itself is negligible. A forest will have a major effect in attenuating water currents, waves and wind. The vegetation can protect against scour and may be more effective and less expensive than “hard” solutions of rocks and concrete, provided a sacrificial zone is planned.



A

B

Figure 6.1 (a) Frequency of typhoons in Asia (1974–2004). Southeast Asia and the Bay of Bengal are the most threatened (from Takle *et al.* [this volume]) (b) Mean annual rainfall in Asia. The areas with rainfall of less than 0.5 m/year and offshore winds are most threatened by salt spray Source: *http://www.fao.org/ag/AGL/swlwpnr/reports/v_a/amp131.htm*

A tsunami is a solitary wave group generated by sudden tectonic movements and volcanoes, with a wavelength of many kilometres, wave height of less than one metre at sea, and traveling at speeds of several hundred kilometres per hour in the ocean. In shallow water, the tsunami shoals and its height increases to several metres or even to tens of metres. It damages the coast through inundation for typically five to twenty minutes and causes physical damage to vegetation and structures (Latief and Hadi, this volume). Loss of human lives is usually due to drowning and impact by debris.

Coastal erosion and coastal sedimentation are natural processes (Prasetya, this volume). Most coasts are naturally eroded during storms. In short time scales (years to decades), the coast can be protected from natural hazards by a sacrificial mangrove forest (Figure 6.2a), by hard engineering structures (Figure 6.2b), or by sea plantation of mangroves protecting smaller hard structures (Figure 6.2c). In the long term (decades to centuries), the movement of the coast (eroding landward or prograding seaward), and hence the success or failure of bioshields, depends on tectonics, the wind and wave regime and the coastal sediment wedge that receives sediment from the land and exports sediment (Figure 6.4). Large-scale human-induced soil erosion will increase the riverine sediment load and favour seaward progradation of the coast; large dams will trap the sediment and favour landward coastal erosion (Syvitski *et al.*, 2005).

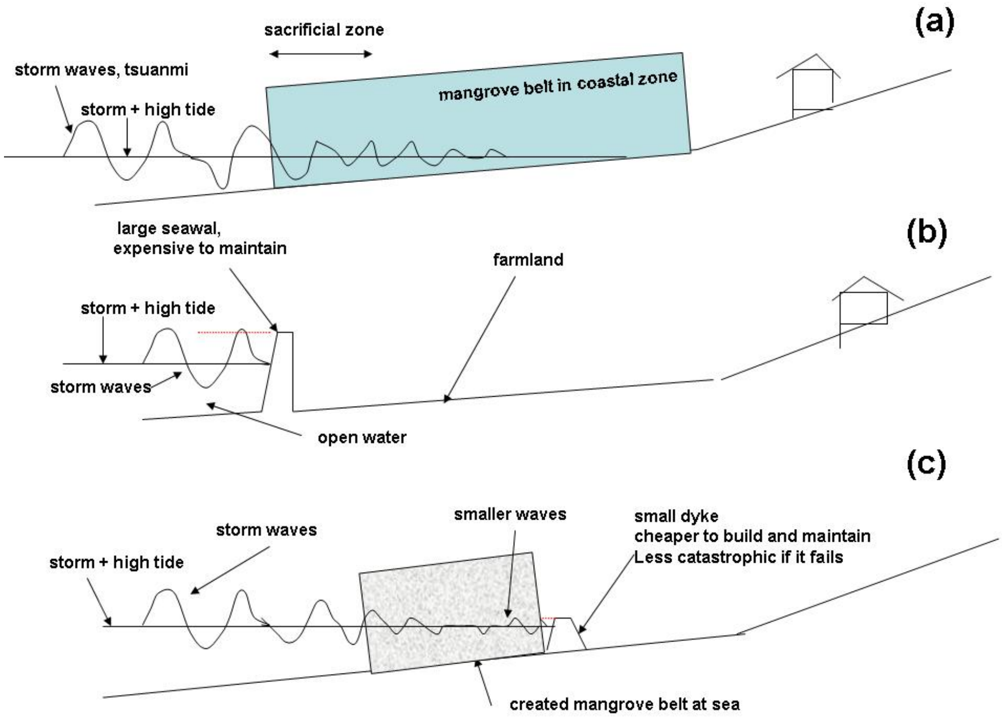


Figure 6.2 The role of coastal bioshields — (a) is the natural balance that, on a seaward prograding coast, can be mimicked by revegetating and relying on a sacrificial belt to absorb extreme waves (b) is the protection of the coast using hard engineering structures (expensive to build and maintain and when they fail, the consequences can be catastrophic) (c) is the protection of the upper coastal belt by a small dyke and creating a mangrove forest bioshield at sea, used successfully in the seaward prograding Gulf of Tonkin in Viet Nam

Salt spray originates from seawater droplets entrained in the air from whitecaps (Takle *et al.*, this volume). The seawater evaporates and leaves salt particles moved by the ambient wind. Most salt particles reside in the lower 200 metres over the coast. Salt-laden air will encounter the bioshields and deposit salt. The seaward edge of the shelterbelt or forest will be most highly impacted and this will also enhance soil salinity. Turbulent motions above the canopy will increase salt deposition as the air traverses inland from the coast. Salt propagates further inland in drier climates. Damage to growing plants from sea-spray salt can be due to higher water stress and leaf or needle necrosis, as well as inhibition of growth depending on the species. Some species (for example pines) are particularly vulnerable to "salt-pruning" on their ocean-facing sides. Salt spray impacts significantly on farming activities in semi-arid coastal areas with onshore winds and rainfall of less than 0.5 metre per year, such as in Pakistan (Figure 6.1b). It is less of a problem in wet areas (rainfall greatly in excess of 0.5 metre per year), such as in most of Southeast Asia (Figure 6.1b), where rainfall reduces salt accumulation problems by washing salt from the vegetation and leaching salt from the soil (Takle *et al.*, this volume).

3 Bioshields

The effect of coastal forests, including mangroves, is to slow the progress of water from storm surges and tsunamis by reducing the height and speed of the wave and reducing water currents as seawater propagates inland. They also protect the coast from wave erosion (Mazda *et al.*, 1997, 2006; Prasetya, this volume) and helped to save human lives in the 2004 Indian Ocean tsunami. This latter finding was first suggested by Kathiresan and Rajendran (2005); it was criticized by Kerr *et al.* (2006) on statistical grounds but its validity was finally confirmed by Vermaat and Thampanya (2006).

Coastal forests also protect the hinterland from salt spray, and this effect is particularly important in arid and semi-arid areas (rainfall less than 0.5 metre/year; Takle *et al.*, this volume).

These coastal forests also provide essential ecological services to the environment and the human population by trapping sediment, converting nutrients to plant biomass, trapping pollutants, providing wood, fodder and medicine and enhancing estuarine and coastal fisheries (de Graaf and Xuan, 1998; Wolanski *et al.*, 2003, 2004; Manson *et al.*, 2005). However, these services are diminishing because mangroves and coastal forests are increasingly being destroyed and degraded by human activities (see review papers by Preuss; Prasetya; and Latief and Ladi, this volume).

4 Hazards from the hinterland — the role of vegetation and dams

In wet river catchments, intense rainfall coupled with deforestation, overgrazing and other poor farming practices, as well as roadworks and mining activities, have increased soil erosion and sediment loads in rivers typically by a factor of 10 (Table 6.1; Wolanski and Spagnol, 2000). Land clearing also increases peak flood flows by up to 30 percent and decreases dry season flows, thus exacerbating flooding in the wet season and droughts in the dry season.

The effect of deforestation on estuaries is much more rapid in the tropics than in temperate zones because of intense rainfall. The catchments of the Cimanuk and La Sa Fua rivers are small and profoundly modified by human activities. The Ngerdoch River drains a hilly, forested area. The sediment yield is largely determined by the climate, the topography and human activities, and is weakly dependent on the catchment size (Table 6.1, data from Wolanski and Spagnol 2000; Syvitski *et al.* 2005; Victor *et al.* 2005).

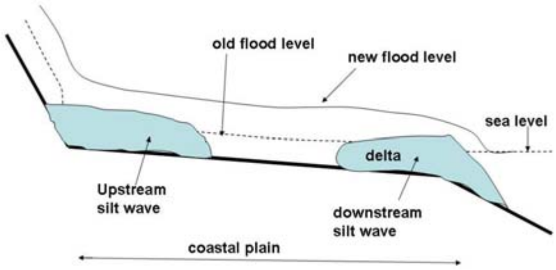
Table 6.1 Comparison of drainage areas, sediment load and yield for various rivers

River	Area (106 km^2)	Yield (tonne/km^2/year)
Minimal land use		
Ngerdoch (Palau)	39 x 10^{-6}	2
King Sound (Australia)	0.12	50
Moderate land use		
Yangtze (China)	1.9	252
Amazon (Brazil)	6.1	190
Mississippi (USA)	3.3	120
Mekong	0.79	215
Extensive land use		
La Sa Fua (Guam)	5 x 10^{-6}	480
Ganges/Brahmaputra (India)	1.48	1 670
Cimanuk (Java)	0.0036	6 350

In some cases the effects are catastrophic in coastal areas (for example, mud slides, Figure 6.3). Even without such catastrophes, and except where dams capture the sediment, the future for tropical estuaries and coasts is increased muddiness and increased flooding. This in turn reduces primary productivity and impacts the tourism industry with the inherent loss of aesthetics.

Increased water turbidity also leads to environmental degradation from the smothering of coral reefs and seagrass beds (Duke and Wolanski, 2001; Wolanski *et al.*, 2003). The mud also affects the biological properties of the water and the benthic food chains in river deltas, which economic planners have generally chosen to ignore. The impact can be dramatic and is sketched in Figure 6.3b for the case of the Cimanuk River in Java, Indonesia (Wolanski and Spagnol, 2000). Deforestation of the mountainous upper catchment in the Second World War resulted in two silt waves, one at the base of the coastal strip and the other in the river delta; these two silt waves are progressing towards each other and have raised the bed and flood levels by up to four metres in the past 40 years. In the coastal area, the bed level is higher than the surrounding coastal plains that are heavily populated. To prevent flooding of the coastal plains, 3–4-metre-high levees have been constructed along the lower 30 kilometres of the river; when they break, which they do occasionally, catastrophic floods result.


a



b

Figure 6.3 Hazards to the coastal zone from erosion in the hinterland (a) Mud slide originating from the hinterland that devastated a coastal area in the Philippines (b) Changes in the Cimanuk River, Java, over 40 years following deforestation of the mountains. The river has silted by up to 4 m vertically, increasing flood levels in the coastal belt also by 4 m, and the delta has grown seaward by 5 km

This situation contrasts with that in the presence of large dams, where estuaries are generally suffering from sediment starvation. The dams trap much of the coarse sediment, such as sand; this creates coastal erosion by starving the coastal sediment wedge (Figure 6.4). Such examples abound (Wolanski *et al.,* 2004; Syvitski *et al.*, 2005). For instance, about 90 percent of Nile River sediment is trapped by the Aswan High Dam; as a result, coastal erosion is intense — the Rosetta and Damietta promontories are eroding at rates of 106 and 10 metres/year respectively. The Ribarroja–Mequinenza Dam on the Ebro River in Spain traps about 96 percent of the riverine sediment; this has led to coastal recession at the river mouth area, reversing the previous seaward progradation of the delta. Water diversion from China's Luanhe River has decreased the riverine sediment load by 95 percent and resulted in the delta receding at a rate of approximately 17.4 metres/year. The Mississippi River's suspended sediment load decreased by about 40 percent between 1963 and 1989; this may be the major cause for the recession of the Mississippi deltaic coast. It is also likely that the Three Gorges Dam in China, under construction, will generate coastal erosion and recession. The ongoing rapid shoreline retreat in several segments of the Atlantic coast of Portugal is mainly caused by dams.

Therefore, to protect the human population living near the coast from excess sedimentation and erosion, a governance system needs to be established to regulate human activities in the whole river catchment as the fundamental planning unit. The aim is to decrease soil erosion, largely by the use of vegetation, as well as to maintain sediment fluxes when rivers are dammed.

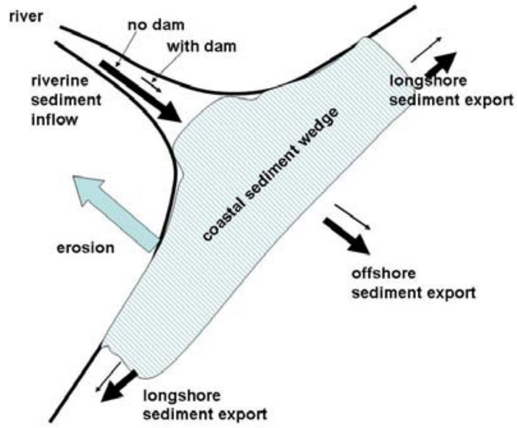


Figure 6.4 In the long term, the net movement of the coast as seaward progradation or landward erosion is determined by the balance between riverine sediment outflow to the coastal sediment wedge and the outflow of sediment from that wedge as longshore and offshore exports. Large dams will trap sediment and cause coastal erosion; deforestation and poor land use in the river catchment will increase the riverine sediment load and increase seaward coastal progradation.

5 Protection against coastal erosion by absorption of wave energy

5.1 Wind waves and typhoon waves

Typhoons are a natural hazard because they produce large waves, swift currents, strong winds and a storm surge. Storm surge effects are exacerbated by flooding due to the heavy rain accompanying the typhoon. Storm surges up to eight metres in depth can occur in the Bay of Bengal. Water currents reach 1–2 metres/second.

Mangroves and other trees can provide some flow reduction and significant mitigation of wave action. They have the potential to provide better protection than “hard” solutions of rocks and concrete. Mangroves are blunt bodies that can absorb water wave energy as a result of wave-induced reversing and unsteady flows around the vegetation. The reduction of wave energy can be estimated from fluid mechanics’ principles (see Appendix A). Mangroves thus protect the coast from wave erosion by absorbing wave energy through drag and inertial forces (Massel *et al.*, 1999). Probably the best data set on this process is that of Mazda *et al.* (1997) at the muddy coast of Viet Nam where *Kandelia candel* mangrove trees have been planted at one-metre intervals in a strip 1.5 kilometres wide (towards offshore) and three kilometres long (along the coast) (Figure 6.5a). A typhoon-driven swell lasting 5–8 seconds entered the forest. Measurements were taken of the rate of wave reduction, r, per 100 metres of mangroves in the direction of wave propagation,

$$r = (HS - HL) / HS \quad (1)$$

where HS and HL are the wave heights at the offshore edge of the mangrove forest and 100 metres inshore in the mangroves respectively; r varied between 20 percent per 100 metres for 5–6-year-old mangroves and five percent for one-year-old mangroves. Within six years after planting, the trees have grown sufficiently so that a wave height of one metre in the open sea has been reduced to 0.05 metre at the coast (Figure 6.5a), enabling aquaculture ponds to function behind a coastal levee. Without the sheltering effect of mangroves, the waves would have arrived at the coast with wave heights of 0.75 metres (Figure 6.5b) and the levees would have been eroded and breached.

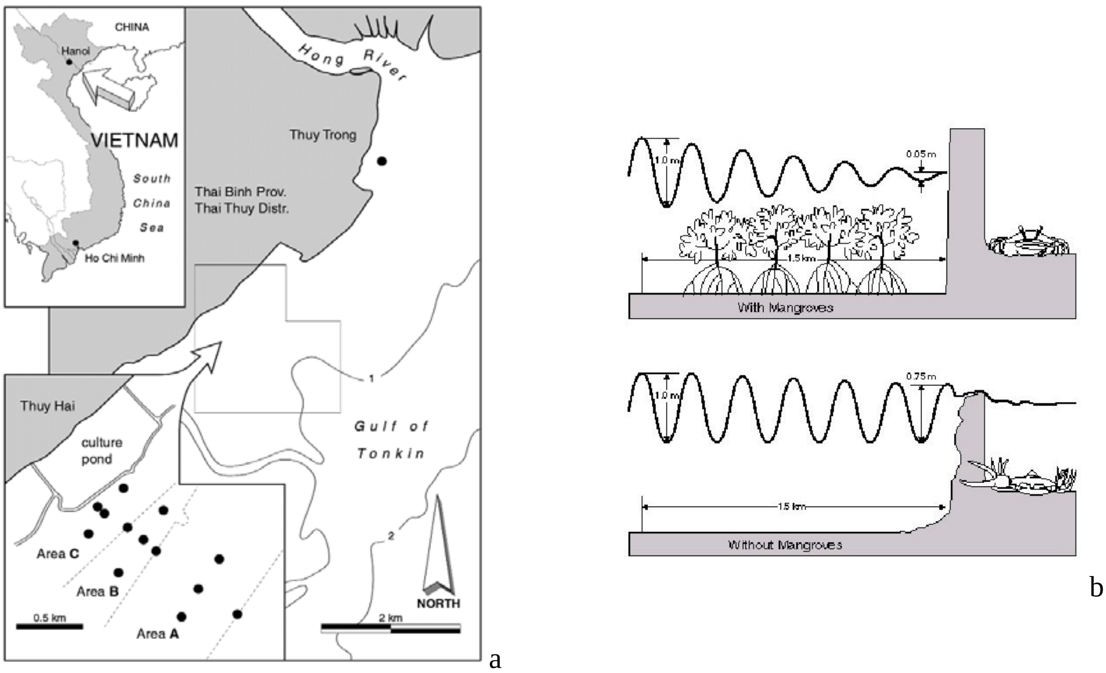


Figure 6.5 (a) Mangrove-fringed Thuy Hai coast in Thai Binh Province, Viet Nam. Groups A, B and C are mangrove plantations comprising, respectively, 0.5-year-old trees, 2–3-year-old trees and 5–6-year-old trees. The symbols • indicate the field measurement sites of tides, waves and currents of Mazda *et al.* (1997a). (b) The wave field at that site with (top) and without (bottom) mangroves. Adapted from Mazda *et al.* (1997)

Mazda *et al.* (2006) repeated the study for a *Sonneratia* plantation at the sea protecting the Vinh Quang coast, also in northern Viet Nam. They found that (Table 6.2) because of their pneumatophores, the rate of wave reduction is much higher by up to a factor of 3 for *Sonneratia* forests than for *Kandelia candel* forests (Mazda *et al.*, 2006); leaves are also important in absorbing wave energy. The typhoon created a storm surge that flooded the coastal dykes. These dykes survived and protected the coast because there were negligible swell/waves in the shadow of the mangroves.

Table 6.2 Wave reduction, r (in %) per 100 m of adult mangrove plantation (data from Mazda *et al.* 1997, 2006). The value of r without mangroves was about 5% next to the *Kandelia candel* site and 10% next to the *Sonneratia* site

Mangrove species	Water depth (m)			
	0.2	**0.4**	**0.6**	**0.8**
Kandelia candel	20	20	18	17
Sonneratia	60	40	30	15–40

The use of mangrove plantation at sea is successful in Viet Nam's Gulf of Tonkin because the coast has extensive shallow water areas that absorb some of the typhoon wave energy, so the waves do not exceed one metre.

Mangroves only slightly diminish peak flood levels, but their drainage systems can accelerate the draining of storm surge water back to the ocean; thus, they reduce the duration of a storm surge on land (Fritz, this volume). Mangroves also protect the human population on the coast from swift water currents when an area is inundated by a storm surge. An example comes from India's Bhitarkanika mangroves following the October 1999 super cyclone with a windspeed of circa 260 kilometres/hour and a storm surge of about nine metres that hit the Orissa coast. The economic impact of this cyclone was evaluated by Badola and Hussain (2005) for three villages equidistant from the seashore and with similar aspects but with different protection; village A was not sheltered by mangroves and had a dyke that failed; village B was not protected by mangroves or by a dyke; village C was in the shadow of mangroves. The damage included household damage by the wind, inundation of crops, loss of fingerlings and salt intrusion. The losses incurred per household were greatest (US$154) in village A, followed by village B (US$44) and were least for village C (US$33). The high cost for village A is attributed to the swift currents after the dyke breached. Thus, mangroves are efficient in measurably, but not totally, protecting the coast against typhoon swell and in reducing the duration of a storm surge flooding the land.

5.2 Tsunamis

When a tsunami encounters shallow water, the wave steepens and the wave height increases severalfold. It breaks and sends a surge of water landwards, destroying vegetation and human assets, which in turn become debris that increases the destructive power of the tsunami. Such damage to vegetation was documented in the worst-affected areas in the 2004 Indian Ocean tsunami (Plate 6.1; also the photographic evidence of Latief and Hadi, 2006).

During the Indian Ocean tsunami, trees along some coasts did not break and offered frictional resistance. This reduced the depth and velocity of flow overland. Because of the long duration of the tsunami wave, trees cannot stop it. They can, however, transform the broken wave into a flood; the shock wave effect is reduced, human lives can be saved and damage to property is reduced, as long as the trees survive flattening, trunk breaking or overturning.

There are two bodies of evidence for the beneficial role of mangroves: (1) fluid dynamics modelling; and (2) empirical evidence.

The propagation of a five-metre tsunami at the shore over flat terrain that was either bare ground or heavily forested with mature trees of either *Kandelia candel* or *Sonneratia* was calculated using fluid dynamics. The prediction used a dam break model (Chanson, 2005). The predictions (Figure 6.6) suggest that at a point 500 metres from the shore, water depth rises one metre in 77 seconds for bare ground, in 343 seconds for *Kandelia candel* and 727 seconds for *Sonneratia*.

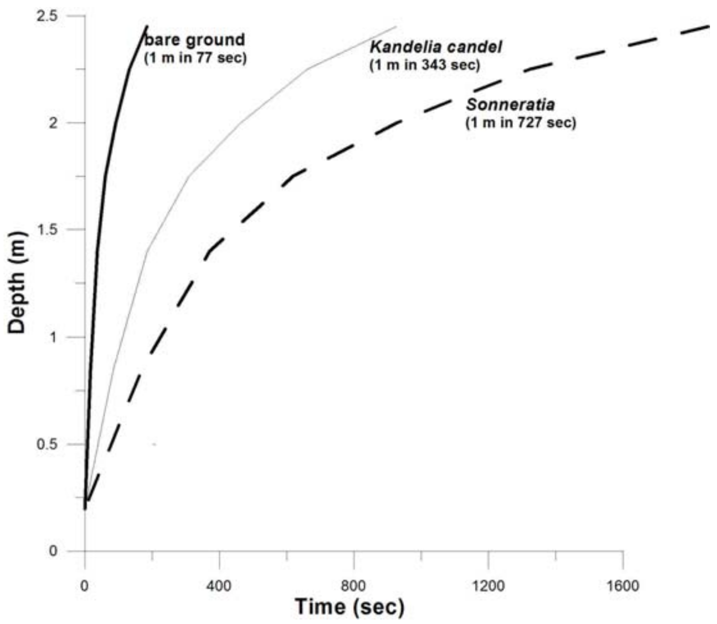


Figure 6.6 Model predictions of the rise of water level at a point 500 m from the shore for flat terrain following a 5-m tsunami at the shore. Three scenarios: Bare ground, mature *Kandelia candel* forest and mature *Sonneratia* forest. The trees are assumed not to be destroyed by the wave. Time starts when the tsunami arrives at that point.

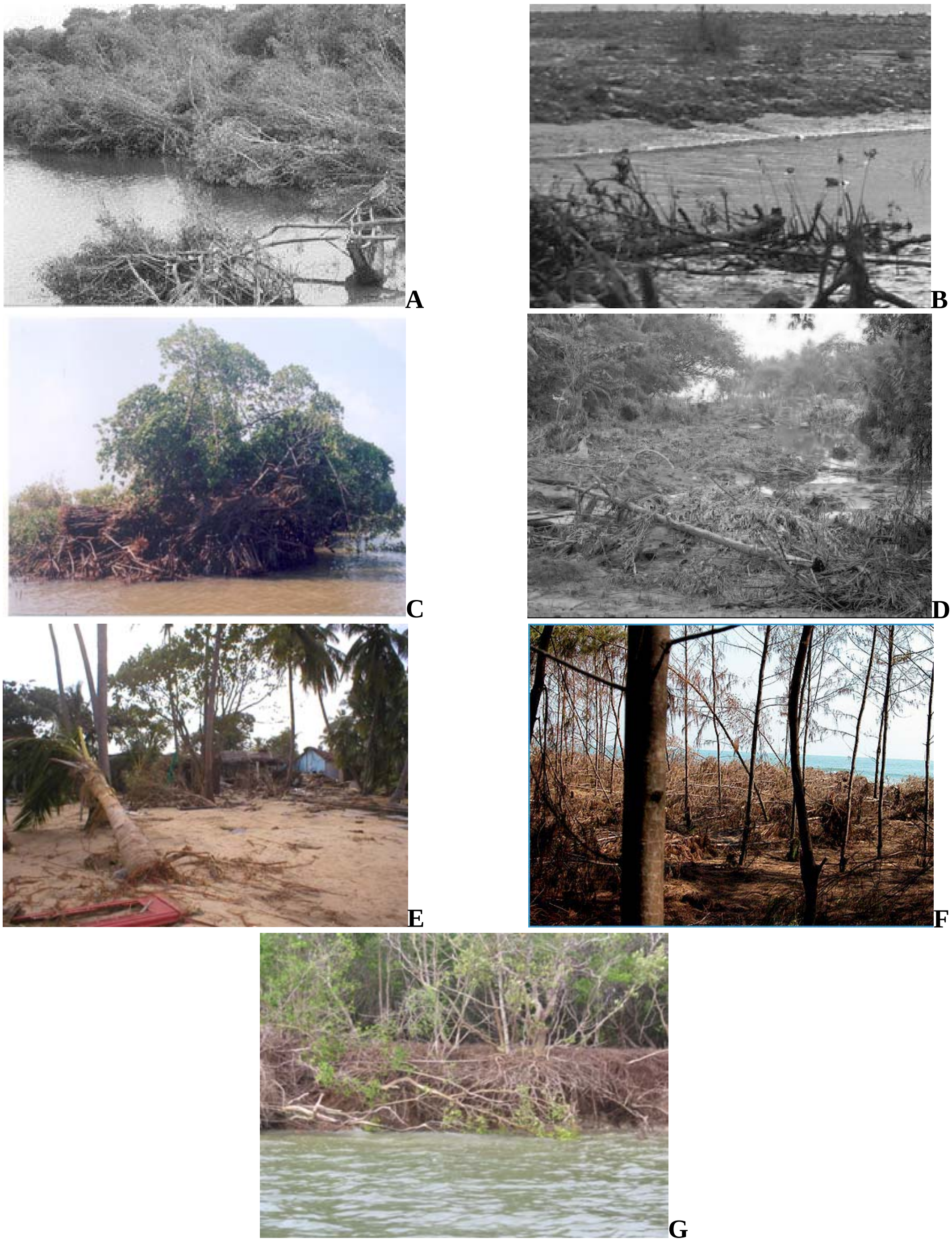


Plate 6.1 A–D: Mangroves damaged by the Indian Ocean tsunami. A–B: Mangroves that snapped; in A the mangroves in the background were sheltered by the 20-m-wide coastal strip of mangroves that were flattened by the tsunami. C: Mangrove tree uprooted exposing roots. D: Catastrophic failure of mangroves — large trees broke and formed destructive debris. E: Other trees were also uprooted or snapped by the 2004 event. F: Flattening of plantation trees in Sri Lanka was limited to a coastal strip for a small (3-m) tsunami in 2004. G: Mangroves destroyed by small wind-driven waves in shallow water undercutting the banks at low tide on Daly Estuary, Australia; boat wakes have the same effect. Sources: Muntadhar *et al.*; V. Selvam; the Internet; the author

The empirical evidence that mangroves attenuated the tsunami as it propagated landward, and in the process saved human lives, is very strong. For instance, Sri Lanka data suggest that in the Yan Oya River the seven-metre tsunami in December 2004 was reduced to 0.5 metre, 3.5 kilometres upstream in the mangroves (point b in Figure 6.7a). In the Mahaweli Ganga River, the tsunami wave was 12 metres at the coast, four metres in Mudduchchenal Village (point b in Figure 6.7b) protected by a sand dune and only two metres at a point a similar distance as the village from the shore but additionally protected by trees. Another body of evidence is the statistical analysis of the saving of human lives; this evidence is shown in Figure 6.8. Similar findings were also suggested by Danielsen *et al.* (2005).
See also http://eqtap.edm.bosai.go.jp/useful_outputs/report/hiraishi/data/papers/greenbelt.pdf).

Clearly, mangroves helped to save some human lives, but not all (see Figure 6.8). Thus, their protection is beneficial but not perfect.

There is considerable spatial variability on the impact of a tsunami wave (Siripong, 2006) and this is largely due to the local bathymetry, the angle of attack and the presence of headlands and bioshields that can deflect the tsunami wave towards high impact zones.

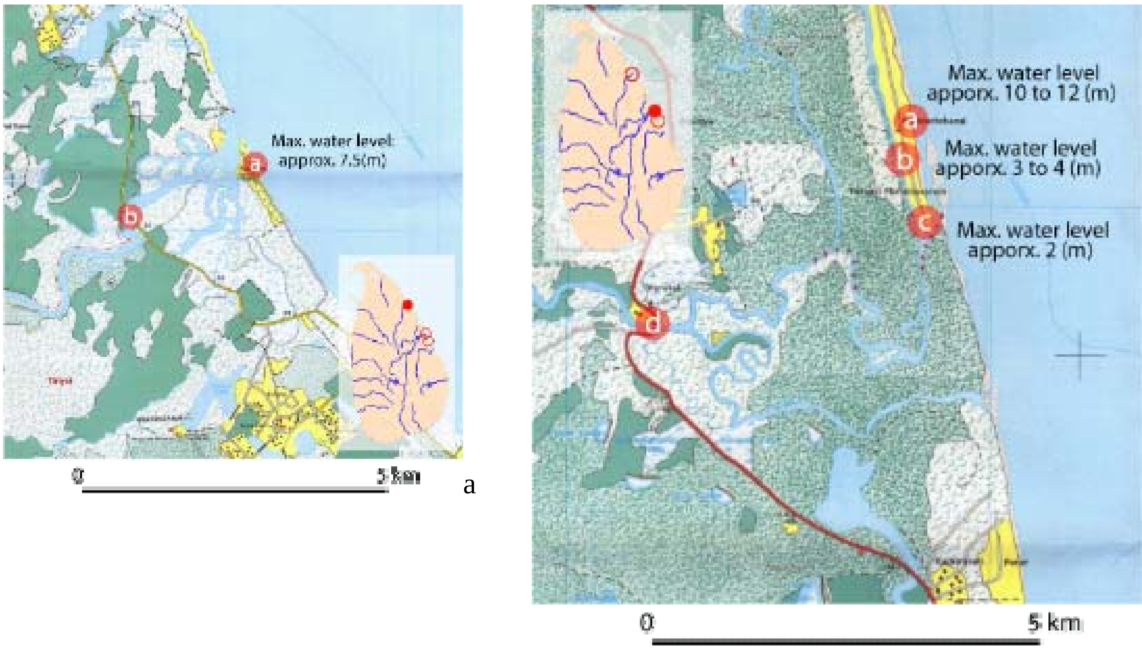


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Figure 6.7 Mouths of the (a) Yan Oya River and (b) the Mahaweli Ganga River, together with an estimate of maximum water level during the Indian Ocean 2004 tsunami. Source: *http://river.ceri.go.jp/rpt/asiantsunami/en/survey.html*