Title: Analysis of the Dynamics of the Potentials of Mangrove Forests for Coastal Stability and Protection

Abstract:

The contribution of mangrove forest for coastal stability and protection has been highly recognized in the recent times. Naturally occurring in the estuarine areas of tropical and subtropical regions, mangrove forests display high efficiency for sedimentation and wave attenuation. The high complexity of the root system, dense stem and canopy covers interact with current and tide properties to create such effects. Studies concerning the mechanics of these two processes are presented in this paper. Recommendations and concerns for future use of mangroves for coastal protection are also discussed.

I. Introduction

A. Description of mangrove

1. Structure and adaptations

Taxonomically diverse, salt-tolerant tree, shrubs and other plant species growing in brackish to saline tidal waters of tropical and subtropical coastlines comprise a mangrove swamp (Hayes-Conroy, 2000; Jan de Voz, 2004; Mitsch and Gosselink, 2000). The term mangrove comes from the Portuguese word *mangue* for ¨tree¨and the English word *grove* for ¨a stand of trees¨ referring to the dominant tree and the entire community respectively.

Since mangrove species thrive in a unique environment, they have developed several adaptations to survive with the conditions. Mangroves are considered to be facultative halophyte, which means they do not require salt water for survival but are able to tolerate high salinity (Mitsch and Gosselink, 2000). This allows them to out-compete freshwater tree species in estuarine areas. Thus, mangrove forests are the main vegetative support along the coasts. To adapt with the high salinity water, mangrove trees have the ability for salt exclusion and salt secretion. In order to prevent salt from getting into the roots, the membranes of the root hairs are allowed to absorb only freshwater from the saltwater through the process of reverse osmosis. This process is observed in species of *Rhizophora*, *Avicennia*, and *Laguncularia*. In cases when salts get into the root system, some mangrove species such as those of *Avicennia* and *Laguncularia* excrete salt by the salt-secreting glands in the leaves. Another method for salt secretion is by leaf fall, which is important for sediment accretion considering that mangrove forests can produce two crops of leaves per year. Water loss in mangroves can also be stopped by coating their leaves with thick waxy cuticle that makes them waterproof and the breathing pores (stomata) are confined to the lower leaf surface and are highly specialized (Park, 2004). The variations in the salinity of the water and the corresponding ability of different species of mangroves have a significant influence on the growth and zonation patterns of the mangrove forest. Susilo (2005) reported that mangroves growing in areas frequently inundated by the tide or growing in lower salinity regions of the estuary are likely to grow more rapidly than those living in regions where the swamp is rarely inundated and where groundwater salinity is very high.

Because of high litter decomposition and semi-stagnant nature of the mangrove forest, the substrate is usually of anaerobic nature (Park, 2004). The muddy substrates are also soft and unstable. Mangrove trees have special adaptation called aerial roots that facilitate the ventilation of the root system and allow mangroves to fix themselves on loose soil. These aerial roots have small pores called *lenticels* that enhance exchange of gases between the roots and the atmosphere (Mitsch and Gosselink, 2000). The main types of aerial roots are the following:

a. Stilt roots

Common to the mangrove species of genus *Rhizophora*, these stilt roots are branched, looping aerial prop roots that arise from the trunk and lower branches of the trees. They function to provide aerial ventilation but more importantly provide added support to the lower part of the trunk as the name implies. The number of roots and complexity of root structure are hypothesized to be the response to the intensity of wind and wave stresses.

b. Pneumatophores

These visible erect lateral branches of the horizontal cable roots growing underground are common to the species of *Avicennia* and *Sonneratia.* The pencil-like pneumatophores are spaced at regular intervals along the primary root cable.

c. Root knees

These are common to *Bruguiera* and *Ceriops*, where the horizontal cable component of the root system surfaces periodically while growing away from the tree. Loops are formed by the surfacing roots before continuing horizontal growth.

d. Plank roots

Present in *Xylocarpus granatum*, the horizontal roots become extended vertically over their entire length due to eccentric cambial activity propagating sinuous in their course. A series of wavy, plank-like structures growing away from the tree results from this growth activity.

Aerial roots may vary morphologically but they have the same function, which distinguishes mangroves from other trees (Figure 1). These functions are highly significant for coastal stability and protection.

(a) (b) (c) (d)

Figure 1. Four types of aerial root structures of mangroves: *a*, stilt roots; *b*, pneumatophore; *c*, knee roots; *d*, plank roots. (*Jan de Voz, 2004*).

Mangrove species have also developed specialized and unique dispersal mechanisms. Being the only true viviparous plant, the seed of the mangroves remains attached to the parent plant until it germinates into a propagule or embryo. After it falls from the tree, it drifts with the currents until it encounters a suitable place to grow (Hayes-Conroy, 2000). This mechanism is important because seeds could not basically germinate in the submerged anoxic sediment deposits and usually in a well-developed mangrove forest, the matured mangrove trees prevent further development of the propagules. Thus, by being light enough to be carried by currents, they can colonize new areas.

2. Distribution

Fifty different varieties of mangrove thrive in the intertidal zones of sheltered shores, the overwash islands, and the estuaries of tropical and subtropical areas of Africa, Asia, Australia and the Americas (Katherisan, 2003) usually between 25^{o}N and

25°S latitude (Mitsch and Gosselink, 2000) (Figure 2). The Indo-Pacific region is considered the most diverse with 40 different species (Hayes-Conroy, 2000). Asia contains 27% of the 240,000 km^2 (Mitsch and Gosselink, 2000) global mangrove forest, which is only 0.9% of the total tropical rain forests (Furukawa and Baba, no date). Mangrove species are intolerant to frost, thus extreme low temperature limits their latitudinal distribution.

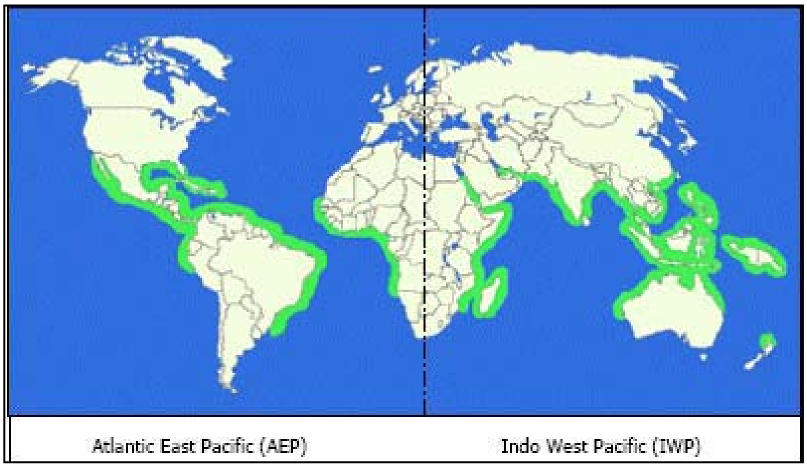

Figure 2. Distribution of the world´s mangrove forests (*Source: Burger, 2005*)

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3. Ecology

The maximum seaward extent of mangroves has been estimated to be around mean sea level while the landward extent is limited by the high water level mark (Burger, 2005; Furukawa and Baba, no date). Propagules cannot take root in waters below the mean sea level (Othman, 1991). The mean sea level limit is controlled by the availability of habitat affected by physiological limitations related to immersion time. Other factors such as current and wave damage create further restrictions (Park, 2004; Ross, 2000).

Mangroves are considered slow growing and are usually out-competed by faster growing mesophytic tropical trees in non-saline area (Jan de Voz, 2004).

Mangroves usually occur parallel inshore of seagrass, sand and mud flats. In subtropical areas, salt marshes are usually situated inshore from the mangrove (Ross, 2000). Zonation patterns of mangrove species parallel to the shoreline are usually observed within the mangrove forests with transitions zones of mixed species from two adjacent communities (Burger, 2005). There is no general agreement yet on the cause of zonation patterns. Othman (1991) described the successional colonization of mudflats by mangrove species. *Avicennia* sp., considered as a pioneer species, grows first on the mudflats serving as the resistance to the waves and currents, which results to the deposition of debris and sediments behind the *Avicennia* line and restriction of the ebb flow thereby creating a permanent tide pool. Decrease in salinity in the tide pool due to freshwater run-off from land and rain and decrease in oxygen prevents new *Avicennia* from colonizing into it. Furthermore, the increase water depth in the tide pool prevents *Avicennia* propagules from rooting. Another species of mangrove especially *Rhizophora* and *Brugeria* can colonize the available space in the tide pool resulting to a zonation pattern (Othman, 1991)

Davis in 1940 also recognized succession of species parallel to the shore as the main cause (Jan de Voz, 2004), however instead of *Avicennia* being the pioneer species, he proposed *Rhizopora*. As *Rhizopora* grows towards the sea, accretion takes place allowing *Avicennia* to take over at the inner portion of the forest, which is replaced by *Laguncularia* and eventually a freshwater swamp.

Other authors suggest that instead of mangrove, external physical forces such as frequency of tidal inundation, tidal range and salinity influence zonation patterns. In this hypothesis, mangrove species can grow anywhere within the normal tidal range but differences in favourable conditions cause species to dominate the habitat where they grow best. Thus, competition between species in settings established by external forces is considered as the main cause of zonation patterns (Figure 3). This hypothesis puts mangroves as mere followers of changes in their habitat and that active colonization occurs only when a shoreline has ample amount of sediment to sustain mangrove growth (Jan de Voz, 2004).

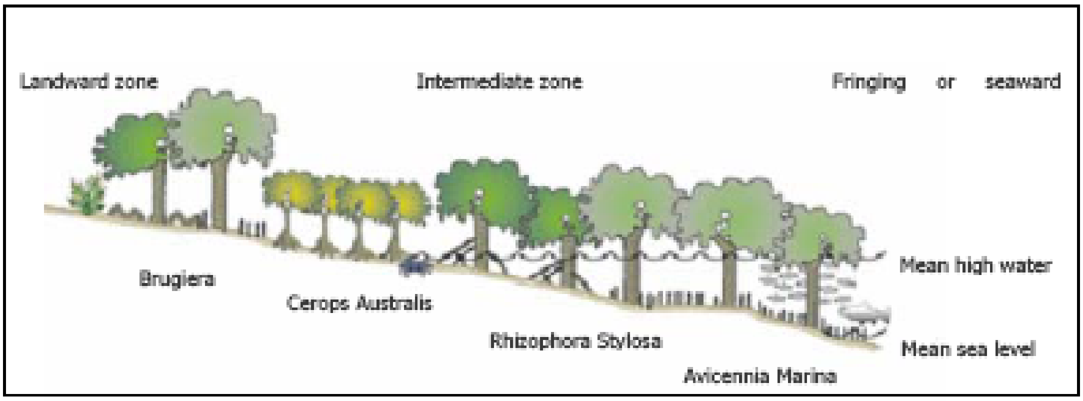


Figure 3. Hypothetical schematization of zonation in a mangrove forest
(*Source: Burger, 2005*)

Mangroves are considered as opportunistic species taking advantage of sediment deposits in sheltered areas. Because of these conditions, estuaries and deltas are best areas for mangrove colonization. Jan de Voz (2004) cited the five geomorphological settings of deltas identified by Thom (1982) where mangrove colonization occurs (Figure 4). This classification emphasizes the interactions between waves, tides and rivers.

a. River-dominated deltas along coastlines of low tidal range

In this setting, there is rapid deposition of sands, silts, and clays that causes progradation over a flat, gently sloping continental shelf, where wave energy along the shoreline is low. The river outlet and its branches are not colonized by mangrove because of high freshwater discharges, however the adjacent tidal flats with series of sandy or shelly ridges are ideal sites for mangrove colonization.

b. Tide dominated

Numerous tidal creeks, which are usually funnel-shaped, feed the main river branches. The tidal creek are also separated by extensive tidal-flat surfaces and dominated by strong, bi-directional tidal currents. Due to dissipation along the tidal flats, wave energy is low. Mangroves colonize the tidal flats and the shores of the river branches in this setting.

c. Wave dominated with relatively low river discharge

High wave energy results in a more steeply sloped continental shelf than in the other settings. The wave-dominated setting is characterized by the presence of barrier islands that enclose drowned river valleys or lagoons, and act to dissipate wave energy. Mangroves are found on the protected leeward side of the barriers and along the shores of the lagoon or drowned river valley.

d. Combination of wave and river dominated processes (settings 1 and 3)

The coastal plain is characterized by sand beach ridges and narrow coastal lagoons. Abandoned river branches, river mouths, and lagoon shores are colonized by mangroves.

e. Drowned river valley system with low river discharge, low wave action, and low tidal range

An open estuarine system is created due to minimal sediment deposition. The heads of the drowned river branches and the shores of lagoons behind bay barriers near the mouth of the estuary are suitable areas for mangrove growth.

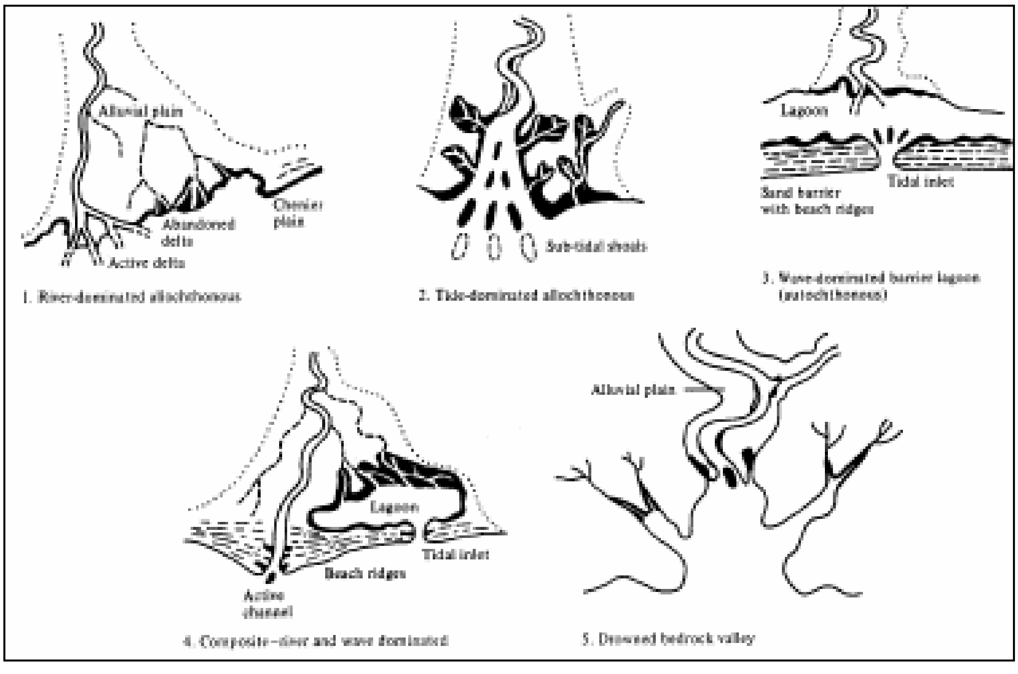


Figure 4. Five geomorphological settings where mangroves tend to colonize. (*Source: Jan de Voz, 2004*).

Although, mangrove forests commonly grow in river deltas, they also inhabit the exposed shores such as coralline tidal flats or sandy beaches open to the sea, but no extensive forests are likely to develop (Jan de Voz, 2004). Mangrove swamps can only develop in areas with adequate protection from high-energy wave action. This is provided by physiographic settings such as protected shallow bays, protected estuaries, lagoons, leeward sides of peninsulas and islands, protected seaways, behind spits and behind offshore shell or shingle islands (Mitsch and Gosselink, 2000).

Based on the interaction of topography, substrate and physical hydrologic conditions, mangroves can be classified as fringe, riverine, basin or dwarf mangroves (Figure 5) (Mitsch and Gosselink, 2000).

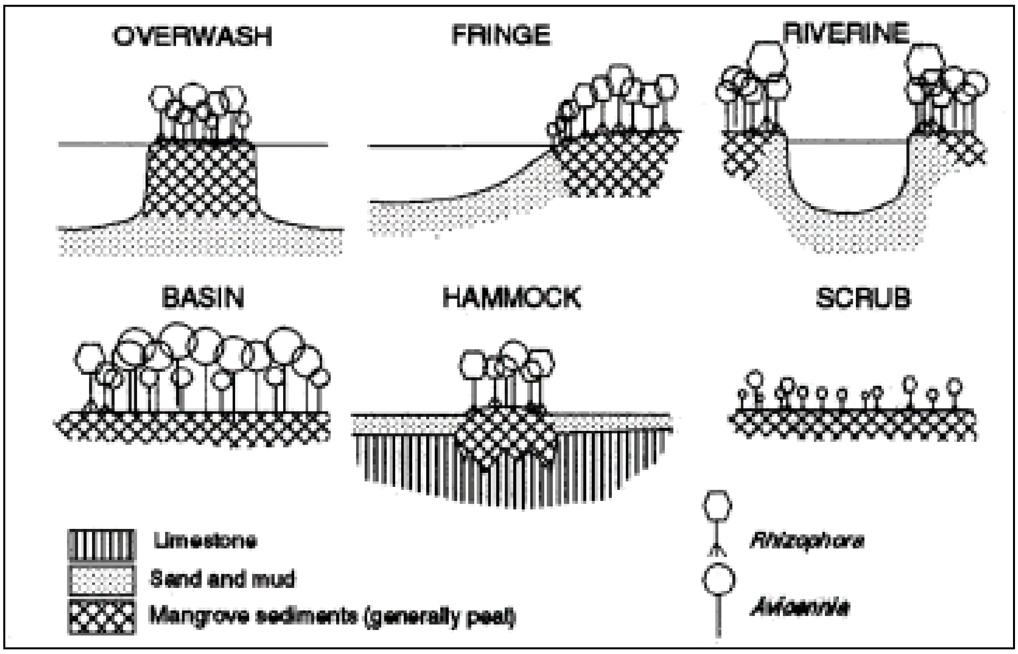


Figure 5. Different types of mangrove forests based on hydrological conditions. (*Source: Jan de Voz, 2004)*

1. Fringe mangroves

These are found along protected shorelines and along some canals, rivers and lagoons and common along shorelines that are adjacent to land higher than mean tide but are exposed to daily tides. These are often exposed to storms and strong winds because the shoreline is open. A special type of fringe mangrove is the overwash mangrove island dominated by *Rhizophora mangle*, where tidal velocities are high enough to wash away most of the loose debris and leaf litter into the adjacent bay.

2. Riverine mangroves

Along the edges of coastal rivers and creeks, often several miles inland from the coast, tall and productive riverine mangrove forests occur. This mangrove system is highly affected by freshwater and nutrient inputs from both upland and estuarine sources, thus they are highly productive and with lesser salinity compared to the other types.

3. Basin mangroves

Basin mangroves located in inland depressions often behind fringe mangrove wetlands, has stagnant or slowly flowing waters that are often isolated from all but the highest tides. Due to these conditions, soils have high salinities and low redox potentials, which mainly *Avicennia* and *Laguncularia* tend to dominate resulting to dense pneumatophores on the ground.

4. Dwarf mangroves

These are usually located in isolated with low nutrient or freshwater inflow areas where mangrove growth is stunted often less than 2 meter tall. Such nutrient-poor environments can be a sandy soil or limestone substrate.

B. Importance of mangrove for coastal stability

Since mangrove forests thrive in the intertidal area between the sea and the land, they are seen by most engineers as highly significant natural barriers for coastal stability. Having a highly efficient sediment trapping mechanism, they are considered as an important sink of suspended sediment, thus important for maintaining coastal stability (Katherisan, 2003; Furukawa and Wolanski, 1996). A mangrove forest under a moderate sedimentation rate can accelerate the process of land formation (Cahoon *et.al.*, 2002). Another important feature of mangroves significant for coastal stability is their ability to dissipate surface wave energy, reduce wave heights, and decelerate flow of water, thus minimizing soil erosion and damage to properties along the coast (Brinkman, 1999; Hayes-Conroy, 2000; CCRU, 2005; Burger, 2005). Mangroves also act synergistically with adjacent ecosystems such as seagrass and coral reef communities for coastal protection.

C. Philippine situation

Philippine mangrove forests feature at least 40 of around 54 species in the Indo-Pacific. The main tree species are *Rhizophora apiculata*, *Rhizophora mucronata*, *Ceriops tagal*, *Ceriops roxburghiana*, *Bruguiera gymnorrhiza*, *Bruguiera parviflora*, *Bruguiera cylindrica* and *Bruguiera sexangula*. Further upstream, where the water is not so brackish, nipa palm (Nypa fruticans) may form extensive and dense stands that are major sources of roofing materials in coastal areas (FAO and UNEP, 1981).

The mangrove forests in the Philippines have faced massive deforestation from about 450,000 hectares in 1918 to about 100,000 hectares at present (Primavera, 2002). This has resulted from the indiscriminate cutting, land clearing and habitat conversion of mangrove forests to give way to aquaculture activities largely shrimp ponds, salt beds and human settlements. Mangrove depletion rate of 3,700 hectares per year was observed from 1980 to 1991 mainly due to the Blue Revolution program of the government that promoted mangrove conversion for aquaculture in order to increase fish supply, provide livelihood and alleviate poverty. Around half of the 279,000 ha of Philippine mangroves that disappeared between 1951 and 1988 were converted into ponds mainly for milkfish, but also for shrimp (Primavera, 2005). Less than 20,000 hectares of mangrove forests is considered old growth.

D. Analysis of the Problem

Awareness on the role of mangrove forests to coastal stability and defense has significantly increased in the recent years, however, the mechanisms and processes associated with it are not sufficiently understood (Jan de Voz, 2004). Hydrologic and morphological processes operating in the mangrove ecosystem still need to be quantified and modelled. Among these processes are interaction between fine-grained mangrove forests with the incoming waves (Moller and Spencer, 2001) and currents, wave transmission and attenuation (Burger, 2005), mechanism and degree of sedimentation, and the degree of interrelationship with adjacent ecosystems. Knowledge on these processes is vital to achieve sustainable coastal defense management and planning (Moller and Spencer, 2001). This will also allow the prediction and simulation of the natural hydraulic behaviour and evaluation of the consequences of any artificial measure in mangrove forests (Burger, 2005). Most importantly, this will guide the sustainable conservation of mangrove forests by providing information on the ecological and geomorphological responses of marshes to climate change or direct human interventions (CCRU, 2005).

II. Objectives

Given the importance of mangrove forests to coastal stability and protection, it is rationally relevant to understand the dynamics of the processes related with it. Thus, the main aim of this paper is to provide a review of the different processes operating in the mangrove forest for coastal protection.

Specifically, the paper aims to achieve the following:

1. Analyze the processes relevant to sedimentation and wave attenuation in the mangrove;
2. Understand the responses of the mangrove ecosystem to the changes in the sedimentation and wave processes; and
3. Provide scenarios for effective use of mangrove forests for coastal protection.

III. Presentation of evidences

A. Sedimentation-related Processes

1. Sources of sediments

Sediments in the mangrove forest can either be allochthonous or autochthonous. Mangrove forests with allochthonous sediment supply are usually located in deltaic systems with high river discharges or in coasts with high-sediment current transport. River discharges carry fine silt and mud, which are deposited along the coast building alluvial plains suitable for mangrove growth (Othman, 1991). Sediments from dumping of dredged materials and re-suspension of bottom sediments by waves can also supply sediments (Katherisan, 2003; Furukawa and Wolanski, 1996) as well as direct result of historic clearance of native catchment vegetation around the harbour margin (Park, 2004). On the other hand, mangrove forests near rivers with low discharges or in islands receiving little sediment supply from currents mainly rely on autochthonous production of sediments by peat or organic matter accumulation.

2. Mechanisms

a. Sediment transport to mangrove

The mechanisms of hydrodynamic process rather than biological process serve as the basis for sediment transport in mangrove waters. These mechanisms include the asymmetry of the tidal currents, the baroclinic circulation and shear-induced destruction of flocs. The tides also control the water-flows that carry the sediments in the mangrove forests, wherein the water from the estuary spills over to inundate the forests at high tide and drains back to the estuary at low tide. This is driven by the sloppiness of the surface from the estuary into the forests (Katherisan, 2003). This supports the argument that mangroves are opportunistic and mere followers of sediment deposition and vertical accretion or erosion because if there is no sediment supply, mangroves are unlikely to initiate (Jan de Voz, 2004). Nonetheless, this does not discredit the role of the mangrove forest in the accretion or build-up of sediments.

b. Role of mangrove forest in sedimentation

Although mangrove forests are not considered as actual land-builders, they have a significant contribution in the build-up of adjacent mudflats and preparation for their own advance (Jan de Voz, 2004). The following are mechanisms by which this contribution is achieved.

1) Decrease in water-flow or current velocity

Jan de Voz (2004) cited the observations of Bird (1980) that offshore winds hardly moved the water surface in a zone of up to 20 meters wide in front of a mangrove forest, but where mangroves are absent, these winds brought sediments toward the shore. The mangrove forest created a sheltered zone of still water that provided an opportunity for sediment to sink.

Katherisan (2003) observed that velocity of water flow in the mangrove-lined bank (0-9 cm per second) is much lower compared to those in the estuarine proper (16-23 cm per second) and non-mangrove bank (18-20 cm per second) (Figure 6). It was concluded from this study that mangrove structures inhibit the tidal flow resulting from friction due to high vegetation density (Furukawa and Wolanski, 1996).

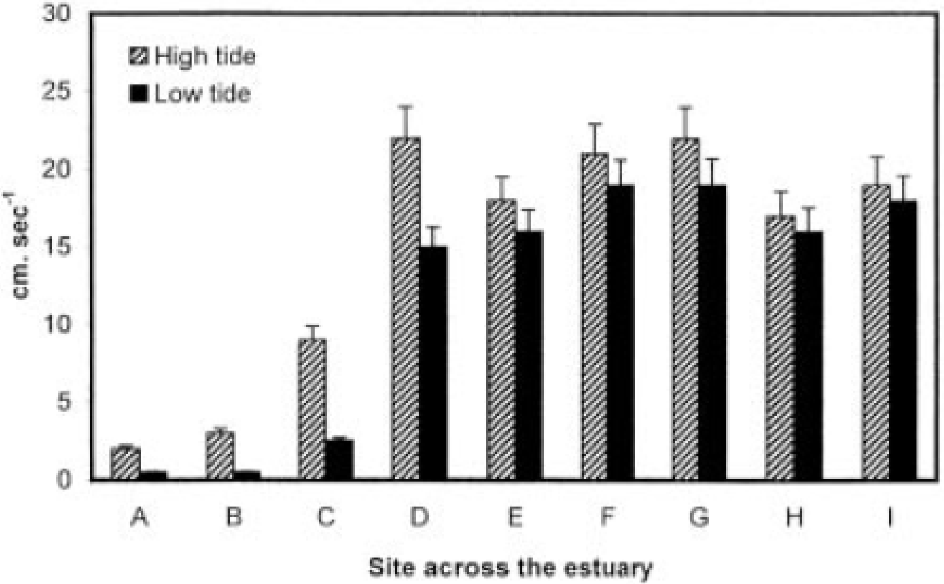


Figure 6. Average velocity during low and high tides across the Vellar estuary (values between mangroves and estuarine proper or non-mangroves are highly significant at 1%; and the values between tides are significant at 1% in the mangrove sampling sites; between tides are significant at 5% in estuarine proper, and or in non-mangrove site) Legend: A-C Mangrove-lined bank; D-H estuarine proper; I Non-mangrove bank. (*Source: Katherisan, 2003*)

This friction can be attributed mainly to friction caused by the vegetation and not the bottom friction. This can be shown by the measured Mannings friction coefficient, an important parameter for hydraulic engineering in rivers and channels used to calculate water velocity in the formula:

$$u = \frac{1}{n} h^{2/3} I^{1/2}$$

where u is the water velocity, n is the spatially-averaged Mannings friction coefficient, h is the water depth and l is the water surface slope.

The value of the Mannings friction coefficient is expected to diminish with decreasing grain size such that sandy channels have a range of 0.025-0.035 and muddy estuaries such as in mangroves is 0.015. However, values of Mannings friction coefficient measured in a heavily vegetated mangrove swamp in Hinchinbrook Island, Australia ranged from 0.2-0.4. Based on the formula, as Mannings friction coefficient increase the water flow velocity also decreases (Furukawa and Wolanski, 1996).

2) Sediment trapping

The water that spills over the mangrove forest usually carries sediments in the form of suspended sediments such as clay and fine silt. These sediments are cohesive and may form flocs, which remain in suspension due to turbulence created by the flow around vegetation (Furukawa and Wolanski, 1996). This results to higher concentration of suspended particles in the water column within a mangrove-lined bank than outside the mangrove forest. In the study by Katherisan (2003), concentration of suspended particles inside the mangrove-lined bank ranged from 0.09 to 0.15 g/l while in the estuarine and non-mangrove varied only from 0.008 to 0.01 g/l (Figure 7).

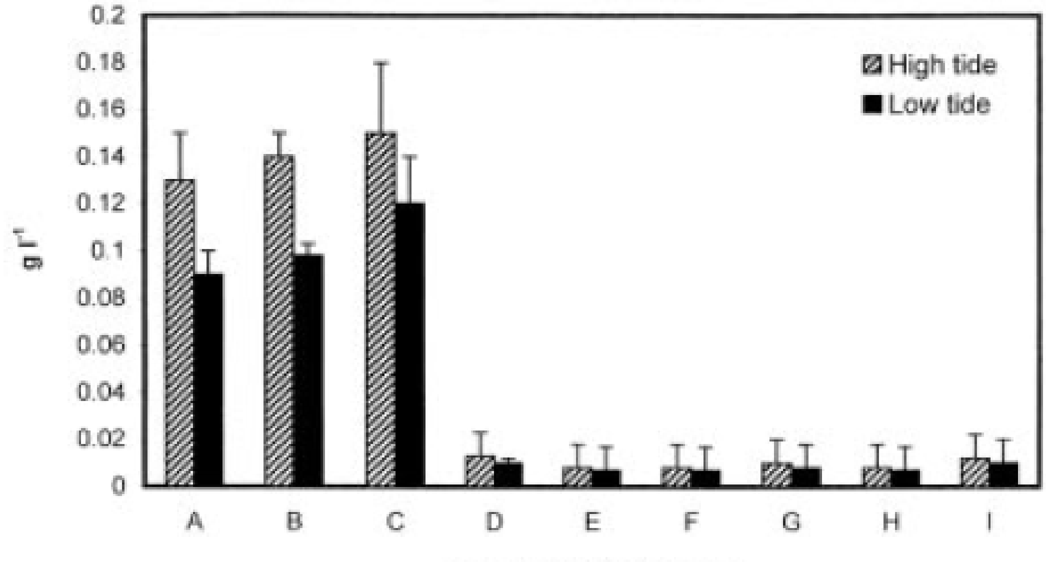


Figure 7. Average concentration of suspended sediment during low and high tide waters across the Vellar estuary (values between mangroves and estuarine proper or non-mangrove are highly significant at 1%; between tides are significant at 1% in the mangrove sampling sites; between tides are non-significant in estuarine proper and or in non-mangroves site. Legend: A-C Mangrove-lined bank; D-H estuarine proper; I Non-mangrove bank. (*Source: Katherisan, 2003)*

The ability of the water to carry sediments decreases as the current is slowed down by the vegetation resulting to settling of sediments during the slack of high tide (Othman, 1991). A significant difference in the suspended sediment concentration was observed between high and low tides in the mangrove forest but not in the estuarine and non-mangrove bank because the velocity of water-flows during low tide is small and sluggish to carry the sediment back to the estuary. Furukawa and Wolanski (1996) also showed that suspended sediment concentration in the waters in the mangrove decreases with distance from the border of the mangrove to the interior due to the progressive settling of sediments. The mangroves, thus act as sediment traps during low tide. Furukawa and Wolanski (1996) asserted that with such evidences, mangroves are not just opportunistic trees colonizing mud banks but actively participate to the creation of mud banks.

The high settling velocity of the suspended sediment is due to flocculation. Using Stoke´s Law, the calculated settling velocity of muddy silt typical of mangrove forests and composed mainly of fine silt (diameter 5.6um) would be around 0.00008 meter per second without flocculation. However, with flocculation of around 100um, the settling velocity was 0.005 meter per second, which is 100 times larger than individual clay and silt particles. Furukawa and Wolanski (1996) observed that at least 99% of the suspended sediment was flocculated. Flocculated particles are also hard to resuspend again.

It was stated earlier that the vegetation created turbulence, which maintained the flocs in suspension before settling. The turbulence is basically created by the water flow around the tree trunks, roots and pneumatophores (Figure 8). Turbulent velocity is considered as the important parameter for calculating sedimentation rates. With water flow velocity of 0.2 meter per second, more complex flows of jets, eddies and stagnation zones are formed. The jets are deflected by the vegetation to interact with each other creating a three-dimensional turbulent velocity 2-3 times larger than the mean velocity. This is more than sufficient to keep 100 um flocs in suspension. Sedimentation occurs preferentially in the stagnation zones (Furukawa and Wolanski, 1996).

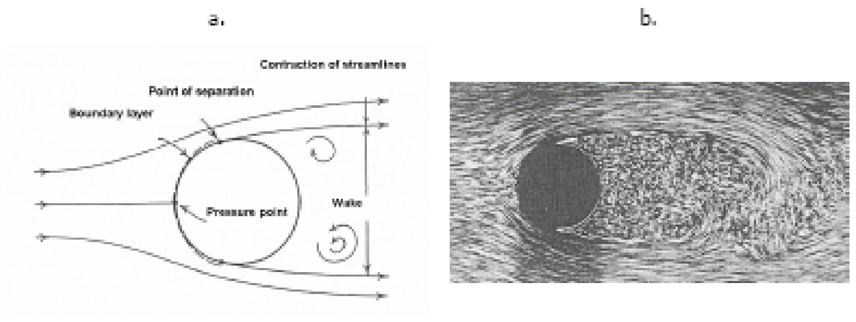


Figure 8. Flow around a cylinder for *a*, theoretical and *b*, experimental. (*Source: Burger, 2005*).

Spacing of mangrove trees specifically their roots and stems also have impact on the sedimentation rate. The drag coefficient in sparse vegetation approaches the value for flow around one cylinder, but with increasing density the drag coefficient decreases due to wake interference and sheltering (Burger, 2005). Jan de Voz (2004) cited the work of Spenceley (1977) showing the effects of spacing. A spacing of 10 centimeters between 0.6-centimeter pegs was shown to have no effect on the sedimentation pattern. On the other hand, 1-centimeter spacing was too dense for deposition causing a scour and eventual toppling over the structure. When vegetation is so dense, the water flow will prefer the way of least resistance and flows primarily over the vegetation field instead of through it. The current might experience the vegetation as a ¨raised semi-impermeable bottom causing the flow lines to contract and the velocity to increase decreasing turbulence (Burger, 2005). Significant effects where observed with 2.5-centimeter spacing, which is an approximate of average pneumatophore spacing in dense accumulations.

c. Species and zonation variation

Mangrove trees with complex matrix of roots such as *Rhizophora* cause higher intensity of sedimentation compared to single trees like *Ceriops* (Furukawa and Wolanski, 1996).

In the mangrove study area of Katherisan (2003), the effects of zonation and species variation to sedimentation rate were shown. *Avicennia* zone located landward is efficient by removing 25% of the sediments while *Rhizophora* zone along the intertidal area settled only 20%. The highest sedimentation efficiency (30%) was observed in the *Avicennia-Rhizophora* zone, which was attributed to wide spread occurrence of numerous pneumatophores in *Avicennia* and to compactly arching stilt roots of *Rhizophora.* The difference between the respective zones of the two species is that *Rhizopohora* experiences more tidal inundations and relatively higher waterflow velocity as it grows in water-front areas while *Avicennia* experiences the opposite since in occurs widely towards the upland.

3. Effects of sediments to mangroves

a. Mangrove expansion

Park (2004) showed that there is good correlation between average mud content of an estuary and the proportion of mangrove cover. Increase in the rate of mangrove spread can be attributed with the higher rates of sediment input to sheltered estuarine habitats in Tauranga Harbour, New Zealand. The estuaries with higher mud content are associated with larger river catchments. On the other hand, areas with lesser mud and have cleaner sands in open exposed areas have fewer mangroves. This is due to the fact that muddy sediments contain higher amount of nutrients needed for plant growth.

The recent increased human activities in the catchment areas of Tauranga Harbour further increased the sediment load of the estuaries allowing mangroves to trap more sediment and increase in coverage. An exponential increase in mangrove coverage was observed in all the sub-estuaries within the Tauranga Harbour. An example is the area north of Tanners Point, where the 0.2 hectare mangrove in 1943 increased rapidly to 26 hectare in 2003 (Figure 9). It was estimated that a sedimentation rate of 2 millimeter per year on a wide shore profile could result in mangroves colonizing an additional 1 meter per year, which in fifty years time can mean an advance of 50 meters.

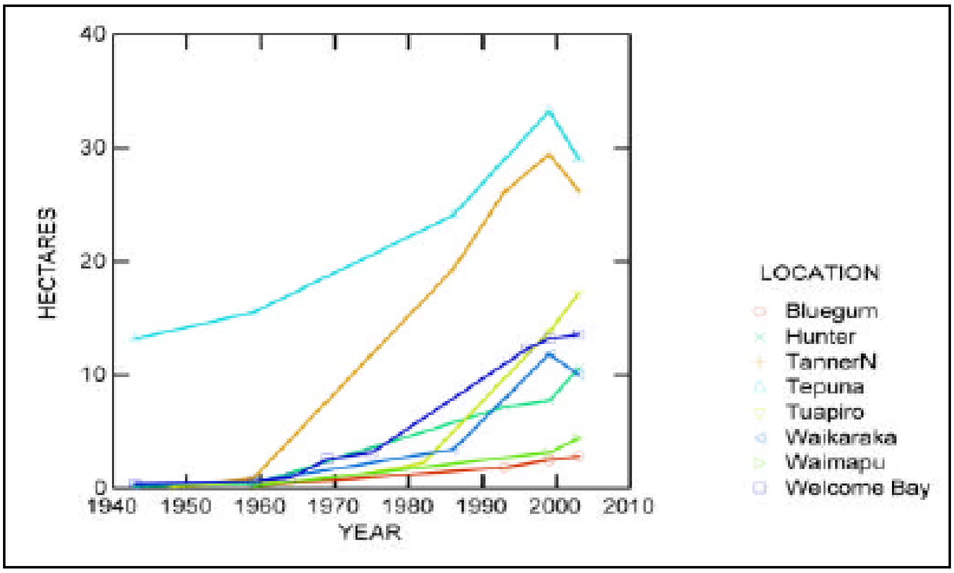


Figure 9. Mangrove canopy cover (hectare) over time within a number of estuaries in Tauranga Harbour, New Zealand. (*Source: Park, 2004*)

This increased in mangrove coverage created conflicts between end-users of Tauranga Bay. Some people would want to maintain an open beach area while others move for the preservation of the mangrove. It was recognized that mangroves are simply reacting in natural way the unnatural increase in sediment inputs. Thus, solution must be focused on the prevention of additional land inputs rather than proposing to cut the mangrove forests. However, this case does not discredit the possible effects of other factors like climate change and supply of propagules for colonization.

b. Mangrove death and land subsidence

Certain areas might experience too much sedimentation due to severe river flooding and high intensity storms leading to mangrove mortality as the sediments prevent oxygen supply to be in contact with respiratory structures such as the lenticels and aerenchyma. The deposited high amounts of sediment may be unstable and erode over time since no sufficient root growth can hold them. The high velocity winds from the storm also destroy much of the canopy cover of the mangrove decreasing the peat accumulation capacity of the forest. This can cause land subsidence in the mangrove forest affecting also the coastal stability of the area. It has been experienced in southwest Florida, USA that after the 1935 Labor Day Hurricane low intertidal mudflats developed from the peat collapse of high intertidal mangrove forest. After more than 60 years, natural recolonization has not occurred in these mudflats despite plentiful supply of propagules. Based on model simulations, in situations below the critical sediment elevation, additional mineral inputs alone had much less of an overall effect on wetland elevation change. This condition is likely to be aggravated with sea-level rise (Cahoon *et.al.*, 2002). According to Furukawa and Baba (no date), the Asia-Pacific mangrove forests had experienced rapid sea level rise since 2,000 years BP, or stable sea level rise since 1,000 years BP. The effects of such sea level rise have been counteracted by the maximum peat accumulation speed measured at 2 millimeter per year. If more rapid sea level rise occurs, the mangrove forests are expected to sink while some can retreat upland.

Other areas like the Bay Islands of Honduras are far from continental sources of sediment, thus relying primarily on organic soils derived from mangrove root growth and litter fall for the fibrous soil production. Due to the constant decomposition and turnover of these organic materials, continual addition of organic matter is needed to maintain elevation and keep pace with sea level rise (Cahoo *et.al.*, 2002).

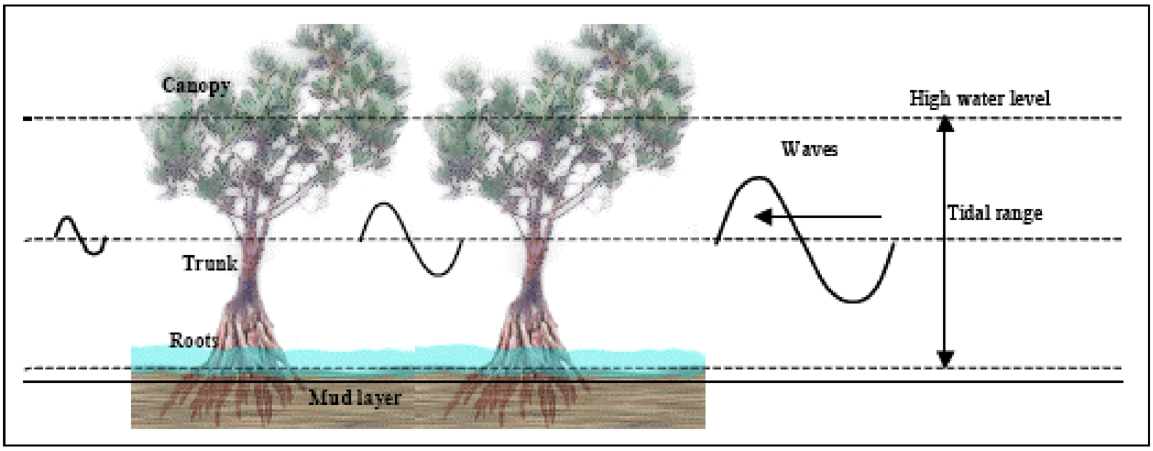
B. Wave attenuation related processes

1. Mechanisms

Vegetation properties and hydraulic conditions are the main factors for wave attenuation processes in the mangrove forest (Burger, 2005).

a. Role of mangrove in wave attenuation

Numerical model of wave attenuation by Brinkman (1999) showed that substantial attenuation of wave energy occurred within the mangrove forest with attenuation strongly dependent on the density and height of the mangrove forest, diameter of mangrove roots and trunks, canopy density, and on the spectral characteristics of the incident waves (Massel *et.al.*, 1999) (Figure 10).



Figue 10. Schematisation of wave attenuation through a mangrove forest.
(*Source: Burger, 2005*)

Mangroves attenuate waves by obstructing the orbital motion of the water particles i.e. the mechanism transmitting the wave energy by their roots and trunks (Othman, 1991). Othman (1991) observed that 50-meter wide belt of *Avicennia* in Sungai Besar, Selangor Malaysia is sufficient to reduce 1-meter high waves to less than 0.3 meter. To reduce the total wave energy of the 1-meter high waves, 150-meter wide mangrove belt is needed. Another study in the Thai Binh Province in Vietnam showed that over a 1500-meter wide mangrove forest with 5-6 years old trees, incident waves with average height of 1 meter are reduced to no more than 0.05 meter at the landside of the forest. The wave height would still be 0.75 meter if no mangrove forest is present over a 1500 meter mudflat (Figure 11) (Jan de Voz, 2004).

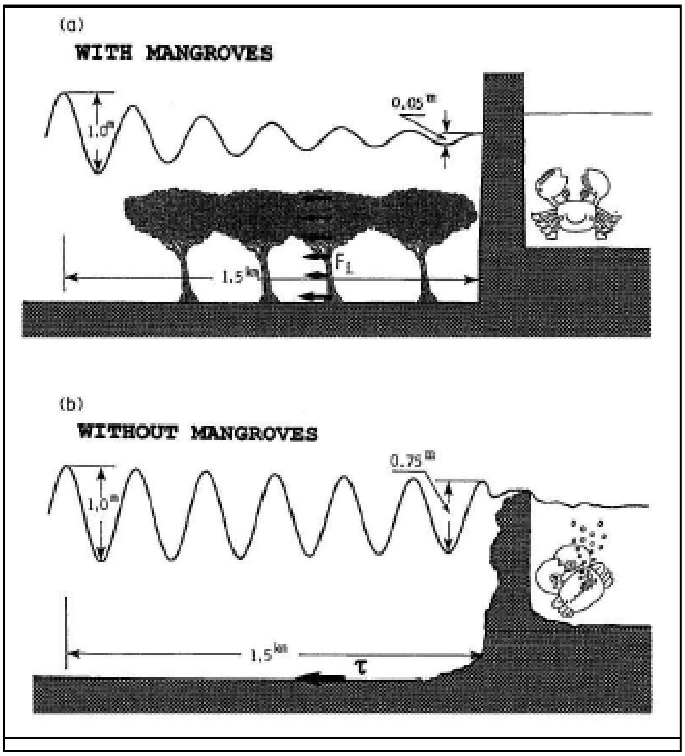


Figure 11. Variation in the wave attenuation between areas with and without mangroves. (*Source: Jan de Voz, 2004*)

The contribution of the different parts of the mangrove tree to wave attenuation is dependent on water depth. At low water depths, the exposed aerial roots cause the largest part of the drag force. Pneumatophores are effective wave dissipaters of small waves (<0.15 meter) in combination with low water levels (<0.30 meter) (Jan de Voz, 2004). During higher water depths, trunks and canopies play more significant roles. Canopies start to grow from around the high water level upwards. Thus during storms when high water level exists, more wave energy is attenuated by the high density canopy of the mangrove (Burger, 2005).

There is a linear relationship between the amount of wave energy dissipation and increasing vegetation height. Since bottom friction is negligible, the dissipation is mainly caused by the wave-vegetation interaction. When the vegetation is vertically sub-divided, the total dissipation can be obtained by adding the dissipation of each segment, which is the usual case in mangrove forests (Burger, 2005).

It is also important to mention that wave energy dissipation by mangrove trees differ by growth stages. Young trees in the mangrove forest along the coast of Thuy Hai, Vietnam have hardly any effect on wave energy reduction compared to sufficiently tall mangrove trees with rate of 20% wave reduction per 100 meters. However, mangroves need not be very old to significantly dissipate wave energy as long as the trees are sufficiently close together and as high as the in-coming waves. Othman (1991) reported that 5-year new growth of *Avicennia* can already effectively act as wave attenuators.

b. Hydraulic conditions

The most important parameters for hydraulic conditions include wave characteristics (amplitude and horizontal orbital velocity) and water depth.

1) Wave properties

It has been shown from field and model results that longer period waves such as swells are subject to less attenuation while short period waves with frequencies typical of locally generated wind waves lose substantial energy due to interactions with the vegetation (Brinkman, 1999; Burger, 2005). Waves with longer wavelength, in a certain time frame, have less flow accelerations and decelerations than short waves. During deceleration of flow in high tide, more energy is dissipated due to more turbulence than in accelerating flow (ebb tide). For longer wavelength waves, the energy lost in the first deceleration is not immediately followed by the next deceleration. Thus, more short waves dissipate more energy than a longer wave. Furthermore, more wave energy attenuation is expected in waves with bigger amplitude than smaller ones because of the larger influence depth interacting with the vegetation (Burger, 2005).

2) Interaction with water level

Wave energy is transmitted further into the forest when water level increases since the ratio of the projected area of obstructions by mangrove roots and trunks to the total cross sectional area of flow decreases rapidly with elevation. Thus, there is proportionally less drag caused by the oscillatory wave induced currents and less attenuation of wave energy (Brinkman, 1999). This has been observed by Massel *et.al.* (1999) in the mangrove forest of Iriomote Island in Japan, where less normalized wave energy is associated with less water depth. However, the decrease in wave energy attenuation as water level increases can be compensated by the increase in the density of the mangrove forest at different layers. Burger (2005) stressed that due to the high density of vegetation distributed through out the whole water depth, the effect of wave reduction is large and even when the depth increased.

Wave energy dissipation in the mangrove leads to wave induced setup of the average water level (Burger, 2005). Wave radiation stresses decrease as waves approach shallow water due to energy dissipation induced by bottom friction and breaking. To compensate the decrease in radiation stress, an increase in hydrostatic pressure force causing rise in water level towards the shoreline occurs. Added energy dissipation takes place when vegetation is present resulting to larger gradients in radiation stress and establishment of wave setup (Figure 12). In patchy mangrove forests, different wave setups may occur between vegetated and non-vegetated areas resulting to secondary flows. This wave-induced setup can induce currents, which might be responsible for important morphologic processes such as sediment transport and deposition as well as dispersal of propagules to adjacent areas where new mangrove can colonize.

The interaction of wave attenuation with water level is crucial particularly during storm setup where high water level is coupled with high storm waves. Such combination should be understood and perhaps quantified in order to provide sound assessment of the impacts of storms to coasts lined by mangrove.

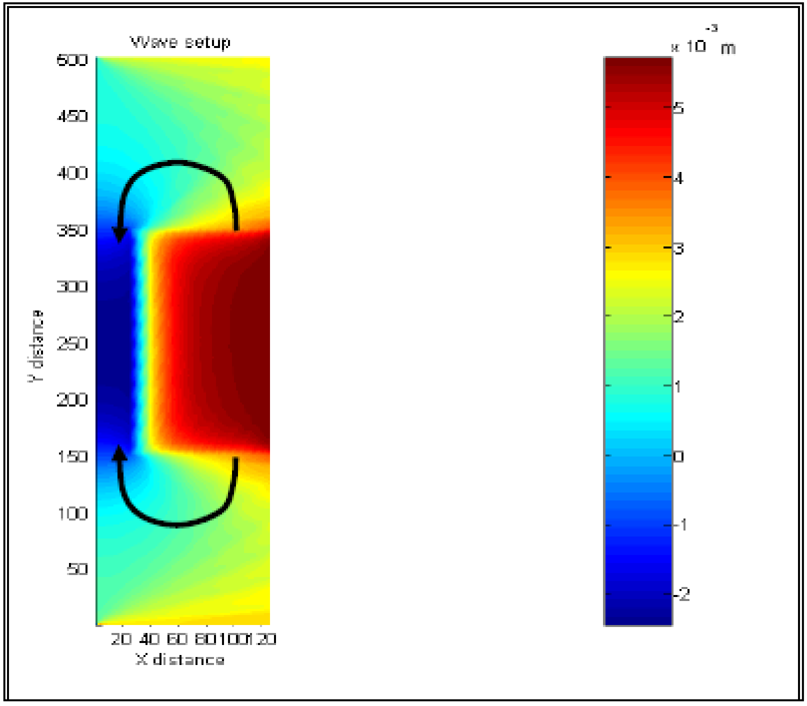


Figure 12. Top view wave setup with possible flow pattern.
(*Source: Burger, 2005*)

C. Effects of mangrove to adjacent ecosystems

With the high efficiency of mangroves to facilitate sedimentation and attenuate wave energy, the mangrove forests have profound impacts to adjacent ecosystems and vice versa affecting their survival and ecological functioning. Seagrass beds, which are usually located in front of the mangrove forest seawards, also influence water flow patterns resulting in increased sedimentation and reducing the degree of resuspension (Buillon *et.al.*, 2004). Because mangrove forests prevent most of land-derived sediment from spreading into the sea, seagrass beds and coral reefs are able to thrive in clear waters. High turbidity waters prevent the photosynthetic reactions in seagrass resulting to mortality of the plants, thereby increase resuspension and loss of sediments. An example of this is the protection derived by the seagrass communities from the Mangrove Bight on Guanaja, Honduras during the Hurricane Mitch in 1998. No significant burial by mangrove sediments was recorded in the adjacent seagrass communties (Cahoon *et.al.*, 2002). Such relationship is also exhibited between mangroves and coral reefs. Coral reefs in turn serve as wave breakers minimizing forceful impacts of high energy waves into the mangrove forest (Hayes-Conroy, 2000).

Mangroves also have significant contribution to the organic matter, which serves as nutrient supply, delivered to seagrass beds. An estimated 21-71% of the sedimentary organic matter pool across different seagrass beds is derived from the mangrove forests (Buillon *et.al.*, 2004).

IV. Summary and Recommendations

In areas with natural capacity for mangrove colonization, mangrove forests have a significant contribution for coastal stability and protection. The main factors that are important in the engineering point of view are the mangrove´s natural capacity to accumulate sediments and attenuate wave energy.

Recently, mangroves have not been considered anymore as ¨land-builders¨, thus colonizing only areas that are suitable for growth. However, their ability to retard water flow velocity and enhance sediment accretion is recognized to contribute a lot for land building. This also allows them to prepare adjacent areas for colonization as well as maintain the integrity of sediments along the coasts. Several things must be considered in using mangrove forests for such purpose. For example, in planting mangrove trees, the species and spacing must be taken into account. Planting of species not suitable for a given estuarine condition might lead to mortality of propagules as well as loss of financial resources. Propagules might grow but without proper spacing, the density required to enhance sediment accretion might not be obtained. In other case, mangrove forest might be too dense that it will serve as a barrier to the water flow instead of letting the water pass through it thereby trapping the sediments inside. It must also be taken into account that mangrove expansion is a natural reaction to conditions, which may either be natural or man-made. Such case is observed in the mangrove forests of Tauranga Harbour, New Zealand, where anthropogenic inputs of sediments lead to rapid expansion of mangrove forests.

The wave attenuation potential of mangrove forests has been seen as highly efficient if certain conditions are satisfied such as density and height of the mangrove forest, diameter of mangrove roots and trunks, and canopy density. Knowledge on the tidal properties in the area is also important. The species of mangrove planted or the width of the mangrove forest might be too small to attenuate effectively the given waves in the area.

Concern must also be raised with regards to the use of mangrove species that are not naturally occurring in an area because they might act as invading species. Since estuarine conditions are suitable for mangrove growth, they have high potential to out-compete native species leading to their displacement. Introduced mangrove species might also carry other species of organisms that have the potential to become pests due to absence of natural predators in the new environment. It is recommended that mangrove species naturally existing in a particular place must be used instead of using exotic species. It is also important to allow the mangrove forest to respond naturally with their environment especially in response to sea level rise wherein man-made structures landward from the mangrove might impede their retreat. However, unnatural or man-made impacts must be minimized.

The present amount of information relevant to the use of mangrove forests for coastal stability and protection is far from complete. Further studies must be conducted in order to fully utilize the potentials of this natural resource.

References

Bouillon, S., T. Moens, and F. Dehairs. 2004. Carbon sources supporting benthic mineralization in mangrove and adjacent seagrass sediments (Gazi Bay, Kenya). Biogeosciences Discussions. Vol 1: 311-333

Brinkman, R. 1999. Wave attenuation in mangrove forests. AIMS-IBM-KEPCO Project. http://www.aims.gov.au/ibm/pages/news/mangwave.html

Burger, B. 2005. Wave attenuation in mangrove forests: Numerical modelling of wave attenuation by implementation of a physical description of vegetation in SWAN. MSc thesis. Delft University of Technology

Cahoon, D.R., Hensel, P., Rybczyk, J. and Perez, B.C. 2002. Hurricane Mitch: impacts on mangrove sediment elevation dynamics and long-term mangrove sustainability: USGS Open File Report 03-184, 75 p.

Cambridge Coastal Research Unit. 2005. http://ccru.geog.cam.ac.uk/research/projects/intertidalsedimentation/

FAO, UNEP. 1981. Tropical Forest Resourcess Assesment Project, Forest Resources of Tropical Asia. FAO, UNEP, 475 pp.

Furukawa, K. and S. Baba. No date. Effects of sea level rise on asian mangrove forests. http://66.102.9.104/search?q=cache:tScpDrry3UsJ:www.survas.mdx.ac.uk/pdfs/3furukaw.pdf+Furukawa+K+and+S+Baba+Effects+of+sea+level+rise+on+asian+mangrove+forests&hl=es

Furukawa, K. and E. Wolanski. 1996. Sedimentation in mangrove forests. Mangroves and Salt Marshes Vol 1 (1): 3-10

Hayes-Conroy, J. 2000. Why the world needs its Mangroves: A look into the natural and human relationships with mangrove forests. On Serendip. Biology 103 Third Web Report. http://serendip.brynmawr.edu/biology/b103/f00/web3/hayesconroyj3.html

Jan de Vos, W. 2004. Wave attenuation in mangrove wetlands: Red River Delta, Vietnam. MSc thesis. Delft University of Technology

Katherisan, K. 2003. How do mangrove forests induce sedimentation? International Journal of Tropical Biology and Conservation. 51 (2): 355-360.

Massel, S.R., K. Furukawa, and R.M. Brinkman. 1999. Surface wave propagation in mangrove forests. Fluid Dynamics Research. Vol 24 (4): 219-249

Mitsch, W.J. and J.G. Gosselink. 2000. Wetlands. 3rd Edition. John Wiley and Sons, Inc. USA. 920 pp.

Moller, I. and T. Spencer. 2001. Wave dissipation over macro-tidal saltmarshes: Effects of marsh edge typology and vegetation change. Journal of Coastal Research SI 36: 506-521

Othman, I.M.A. 1991. Value of mangroves in coastal protection. Department of Irrigation and Drainage, Malaysia. 9 pp.

Park, S. 2004. Aspects of mangrove distribution and abundance in Tauranga Harbour. Environment Bay of Plenty Environmental Publication 16: 40 pp.

Primavera, J.H. 2002. Management and Conservation of Mangroves in the Philippines. Joint UNU-Iwate-UNESCO International Conference. Conserving Our Coastal Environment 8-10 July 2002

Primavera, J.H. 2005. Global Voices of Science: Mangroves, Fishponds, and the Quest for Sustainability. Science vol. 310 (5745): 57-59

Ross, R. 2000. Mangroves and salt marshes in Westernport Bay, Victoria. Natural Resources and Environment, Australia. 48 pp.

Susilo, A. 2005. A new method in determining bulk hydraulic conductivity of mangrove forest sediment. WIT Transactions on Ecology and the Environment. Vol 83: 65