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Chapter

The Role of Mangroves in Coastal and Estuarine Sedimentary Accretion in Southeast Asia

Punarbasu Chaudhuri, Subhamita Chaudhuri and Raktima Ghosh

Abstract

Mangroves provide a distinctive mechanism of trapping sediment and accelerating land-building processes in tide-dominated coastal and estuarine environments. The complex hydrodynamic and salinity conditions, accumulation rates of both organic and inorganic sediments, primary surface elevation, and hydroperiod influence sediment retention mechanism within mangrove ecosystems. Abundant terrigenous sediment supply can form dynamic mud banks and the complex aerial root system of mangroves may lead to accretion of sediment by weakening the tidal velocity. Such mechanisms are often enhanced by organic flocculation. The efficiency of sediment trapping by mangroves is species specific. Adaptability and resilience of mangroves enable them to cope with the moderate to high rates of sea level rise. However, subsurface movements and deep subsidence due to autocompaction may augment the effects of relative sea level rise. Increasing population pressure and forest-based economic activities have caused global reduction of mangrove coverage challenging the sedimentation processes. Marker horizon techniques and surface elevation table (SET) tests have facilitated assessment of spatial variability in patterns of sediment accretion and surface elevation in various coastal sites of species-diverse Southeast Asia, especially coastal Malaysia and Thailand. The mangroves of the eastern coast of India have witnessed sediment retention, having an association with the seasonal rainfall regime.

Keywords: mangrove zonation, sediment accretion, estuarine, flocculation, turbidity maximum zone, bioturbation, propagules, autocompaction, sea-level rise, surface elevation, marker horizon

1. Introduction

Mangroves form the coastal and estuarine wetland ecosystem in the tropical and subtropical regions of the world. This unique intertidal ecosystem acts as a safeguard to the coastlines from the disastrous effects of storm surges, erosion, and floods. Some mangroves occur along open coasts, subject to moderate wave processes, while most of them grow in sheltered, muddy tracts that are either regularly or occasionally immersed by tides [1]. The extent and biomass of the

mangrove forests are determined by variations in rainfall, tidal influence, wave energy, duration of tidal inundation, and salinity levels at both local and regional scale which further modify the physical and biological setup within a single coastal or estuarine area by affecting the water circulation pattern as well as sediment mixing and trapping [2]. There are 9 orders, 20 families, 22–27 genera, and roughly 70 species of mangrove, among which 40 exclusive and 65 non-exclusive species are found in Southeast Asia [3]. The zonation pattern of different species is attributed by salinity, tidal flooding, and land elevation. They develop in monospecific bands, parallel to the coastline. In Andaman and Nicobar island group, the mangroves depict a unique assemblage with the coral reefs. A general description of mangrove zonation extends from shore to the inland areas where at the edges the species are mostly salt-tolerant and at the interior parts the species are more adopted to nonsaline environment. There are four major hypotheses explaining the zonation—(i) land-building and plant succession hypothesis by Davis [4] elucidated the succession process by which the pioneer species of mangroves mold the substrate by trapping sediments in the intertidal zones and progressively mature mangrove species develop to compete with the colonizing species at established substrate; (ii) Woodroffe [5] has demonstrated the geomorphologic influences and long-term stratigraphic configuration to be dominant factors in species zonation; (iii) in 1980, Ball [6] has discovered the influence of salinity among other physicochemical determinants (seed dispersal, water logging, and tidal inundation) on species competition and growth which ascertain the forest structure; and (iv) Rabinowitz [7] laid emphasis on the propagule dispersal. Tidal action is responsible for delivering propagules of all sizes to their specific and suitable areas. Survival, establishment, and growth of propagules, therefore, play a significant role in dictating mangrove zonation. Predation of propagules by small crabs is correlated with the conspecific dominance and tree distribution. *Avicennia marina* is most heavily preyed upon, followed by *Ceriops tagal*, *Bruguiera gymnorrhiza*, and *Rhizophora stylosa* [2].

Woodroffe [9] outlined the relationship between the role of mangroves and the morphodynamic response of the shoreline. Sedimentation process including deposition of fine-grained, clay-dominant particles within the forest floor is considered to be one of the driving factors of land-building and shoreline progradation. Sedimentation modifies the geomorphological setup and influences the soil characteristics, groundwater reach, and substrate salinity determining mangrove zonation and species distribution. Mangrove vegetation favors the sedimentation process by resisting the tidal water flow and trapping the sediments through the network of their roots. The resistance offered by mangrove trees to water flow has been experimentally tested in a flume [8]. This makes the mangrove shorelines as remarkable sediment sink, characterized by long-term import of sediments, especially recent sediments which underlie the mangrove forests and coastal plains. The mangroves are mostly associated with muddy shorelines of the tropical deltas, but they may grow on a wide variety of substrates, including sand, volcanic lava, or carbonates. The carbonate sediments are derived from calcareous skeletal remains or coral reef substrates, but often the mangrove forest floor is underlain by organic peat, acquired mostly from mangrove roots. These sediments which are generated within the ecosystem are termed as in situ or autochthonous [9]. Allochthonous sediments are transported from the catchment through fluvial discharge or inflow of tidal current and littoral drift. The accumulation rates of allochthonous and autochthonous sediments, both inorganic and organic, differ between and within different geomorphological setups [9]. Dumped dredged material and other bottom sediments also contribute to allochthonous sediments when these are re-suspended by waves, turbulence generated by ships, and also dredging [10].

Country	Area ($\times 10^5$ ha)
Brunei	0.17
Cambodia	0.60
Indonesia	45.4
Malaysia	6.4
Myanmar	3.8
Philippines	1.6
Thailand	2.6
Vietnam	2.5
Total	63.2 (34.9% of the world)

Data from Spalding [11].

Table 1.
Mangrove areas in countries of Southeast Asia.

South and Southeast Asia represents some 42% of the total mangrove areas in the world and is typified by highest diversity of mangroves [11]. A large number of islands and a considerable total length of coastline permit mangrove growth and development in the coastal Southeast Asia. In most of the regions, coastlines are characterized by high rainfall and a large amount of riverine sediment input. The Ganges-Brahmaputra delta, constituted by a complex network of estuaries, tidal creeks, and islands, supports the world's largest continuous single-area mangroves—the Sundarbans [12]. The sediment input of this delta plain is mainly sourced by delivery from overbank flooding of the large rivers and their distributaries [13]. Almost 70% of the total mangroves of India exist in the deltaic region. Mahanadi delta constitutes the second most developed mangrove forests within India after the Indian Sundarbans [11]. Other mangrove areas of Southeast Asia include the Philippines, Brunei, Cambodia, Myanmar, Pakistan, Indonesia, Thailand, Malaysia, Singapore, Japan, China, and Vietnam (**Table 1**).

The goals of the chapter include (1) the review and reassessment of the sediment accretion pattern and processes of the Southeast Asian mangrove forests, (2) understanding the role of mangroves both as plants and ecosystem in accreting sediment in different geomorphic settings, and (3) relating surface elevation changes with relative sea-level rise patterns.

2. Tidal dynamics within mangrove forest

Estuarine circulation is often influenced by the asymmetry between the ebb tide and flood tide, mixing of saline and fresh water, and tidal range. The duration of the flood tidal current is of shorter span, but with stronger peak currents than the ebb tide in most of the extensive vegetated coastal wetlands [2]. The velocity of the tidal current is ultimately determined by the ratio of the forest area to waterway area and the slope from the tidal creek into the forest [14]. Sedimentation in the world's most extensive mangrove regions is a function of retarded flow velocity of the ebb tide due to the bottom friction generated by the mudflat and flow around tree trunks, roots, and pneumatophores [5] and thus directly related to the density of vegetation [15]. These flows are complex with eddies, jets, and stagnation zones.

Manning coefficient is a popular engineering parameter to measure the flow velocity in relation to friction within the forest. Thus,

$$U = \frac{1}{n} h^{2/3} I^{1/2} \qquad (1)$$

where U is water flow velocity, n is spatially averaged Manning friction coefficient, h is water depth, and I is water surface slope [14].

Value of n is within the range of 0.025–0.035 in typical sandy channels. It is two to three times lesser in the muddy estuaries as it diminishes with the grain size [14]. But in the mangrove forest, the friction generated by vegetation becomes prominent along with the bottom friction which increases the value of n. Drag forces and trapping of water is another characteristic of mangrove forests. Some amount of this incoming and outgoing tidal water is temporarily retained within the forest floor, for being returned to the main channel later (**Figure 1**).

Demuren and Rodi [16] have observed that meanders create a secondary circulation which sorts the sediment according to size ranging from fine-grained mud to gravel. It is driven by stratification of flow by density or salinity and particle concentration. Due to the secondary circulation, fine-grained silt and clay are accumulated on the sloping banks, whereas sand and gravels remain on the bed. This secondary circulation along with tidal pumping promotes flocculation of sediments in the estuary, and these mechanisms altogether create mudbanks.

The drag force and delayed water flow is enhanced during the wet season due to the freshwater buoyancy, and it is slowed down during dry periods. Wolanski and Cassagne [17] have observed high evaporation rate, decline of freshwater input, and higher salinity accompanied by slower rate of tidal flushing during the dry seasons in Konkoure River delta in Guinea. In addition to this physical complexity of water circulation, some estuaries with mangrove dominance exhibit floating mangrove debris including propagules which are likely to be accumulated upstream. Hence, the presence of tree roots, animal burrows, mounds, and debris exert a drag force and resistance to water flow [2, 14].

The sediment transport by the attenuating tidal flow is largely managed by several interrelated processes such as (i) tidal pumping and mangrove tidal prism, (ii) secondary circulation, (iii) flocculation and trapping of small particles at the turbidity maximum zone (TMZ), and (iv) microbial production of humus. The relative
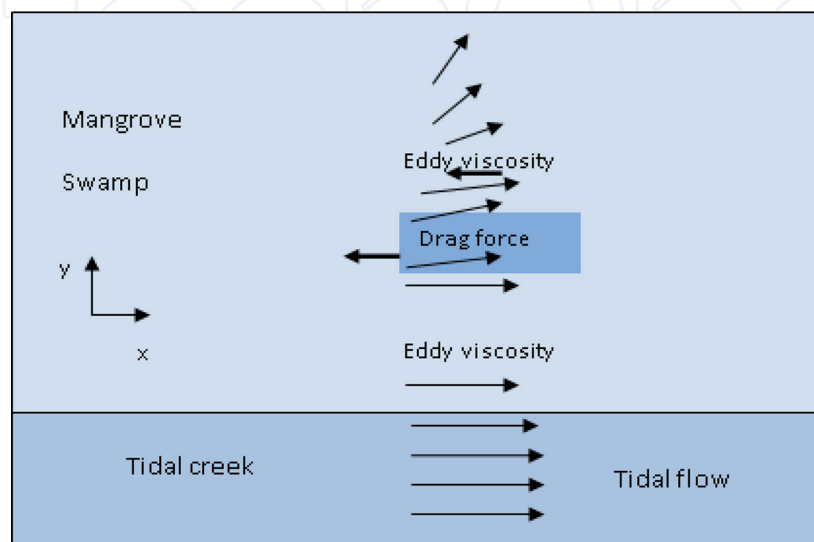

Figure 1.
Schematic view of the flow distribution and hydrodynamics in a mangrove swamp near a tidal creek, after Mazda et al. [15].

importance of these processes is site specific [2]. For example, an estuary with narrow fringe of mangrove has different tidal flushing characteristics and is unlikely that they play a significant role in sediment dynamics, whereas in the estuaries with extensive mangrove forest, sediment transportation and accretion are prominent.

Salinity stratification and salinity gradient determine the estuarine water circulation. In the presence of small freshwater input and small tidal range, a salinity maximum zone can develop which isolates the upper reaches of the estuary from the coastal edges creating an inverse circulation pattern, such as in Klong Ngao mangrove creek in Thailand. Reference [18–20] demonstrate the dynamics of an extensive, mangrove-fringed estuary in Malaysia which receives a large and sufficiently steady freshwater incursion. They found that the salinity stratification is strong during neap tide, but the system de-stratifies during spring tide. Water flooding the mangroves has low salinity at neap tide and is saltier at spring tide.

2.1 Flocculation and sediment trapping at the turbidity maximum zone (TMZ)

The fine-grained sediment particles, brought by the rivers or produced due to coastal erosion, are deposited predominantly at the vicinity of TMZ of the estuary as either individual grains or in aggregated (flocculated) form [21–23]. TMZ usually marks the landward limit reached by the saline water where the inward bottom flow meets the outward river flow, thus creating a shallow convergent water layer [2]. It encompasses a large variation in suspended particulate matter, which varies from $0.1\ gl^{-1}$, occurring at moderate to low freshwater flow situation, to more than $200\ gl^{-1}$, occurring at a prominent fluid mud layer with stationary suspension [20]. The turbidity maximum is not similar for all types of estuaries. It is largely controlled by degree of freshwater flow, salinity gradient, tidal dynamics, suspended particles at the upper reaches, etc. Researchers have attempted to investigate the pattern of sediment transport and characteristics of the turbidity maximum at different estuarine systems of the world through both laboratory-based and remote sensing-based methods. The degree of flocculation or colloidal stability [24] is largely dependent on a number of parameters including mineralogy [25], electrolytic levels which may alter with the changing salinity in estuary [26], organic content [27], suspended sediment concentration [28], and turbulent mixing [29, 30].

A cyclic occurrence of processes involved in sediment movement—suspension, flocculation, settling, deposition, erosion, and resuspension. Laboratory experiments revealed that flocculation occurs more readily when salinity increases [26]. However, salinity has an inverse relationship with settling velocity of the suspended particles. Laboratory analysis by Mhashhash et al. [31] reveals that settling velocity becomes faster with the increase in sediment concentration and decrease in salinity (**Figure 2**).

Cohesive sediments are composed of granular organic and mineral solids in a liquid phase [25]. In the estuaries cohesion of clay minerals is facilitated by the flat shape and size of particles with their surface area and electrical charge interacting with ambient water [32]. An important outcome of the cohesion property of sediments in the seawater is that particles can be adhered together and produce aggregates or flocs of several times greater than the size of the original or primary particles and can also be disaggregated. This reversibility between aggregation and disintegration of cohesive sediment is called flocculation [25, 33].

Flocculation leads to gentle mixing which increases the size from submicroscopic to microfloc, which grows in size after being merged with other microflocs [34]. The flocculated particles often provide surface area for absorbing heavy metal, pollutants, and nutrients. These processes control the size, density, and form of suspended particles [24, 35] and finally determine the settling velocity of flocs.

Once the floc gains its optimum size and strength, it is ready for sedimentation. Differential settling is the consequence of large particles with higher settling velocity colliding with smaller particles, having lower velocity [25, 33].

According to Winterwerp and Kesteren [25], a turbulent flow is responsible for introducing the particles into eddies, and the particles collide to produce flocs. Within the mangrove forests, turbulence is generated by flow around the trees, resulting in flocs which are composed of clay and silt particles. The settling of suspended sediment particles within the forest takes a shorter time (<30 minutes) during the transition from flood to ebb condition, when the water flow becomes relatively inactive [2]. Settling is also enabled by sticking of microbial mucus and by pelletization of invertebrate excreta. Mucus is not rare in mangroves, being found on rotting tree trunks and leaves, on the sediment surface, and in the density-driven lines of organic material [36] (**Figure 3**).
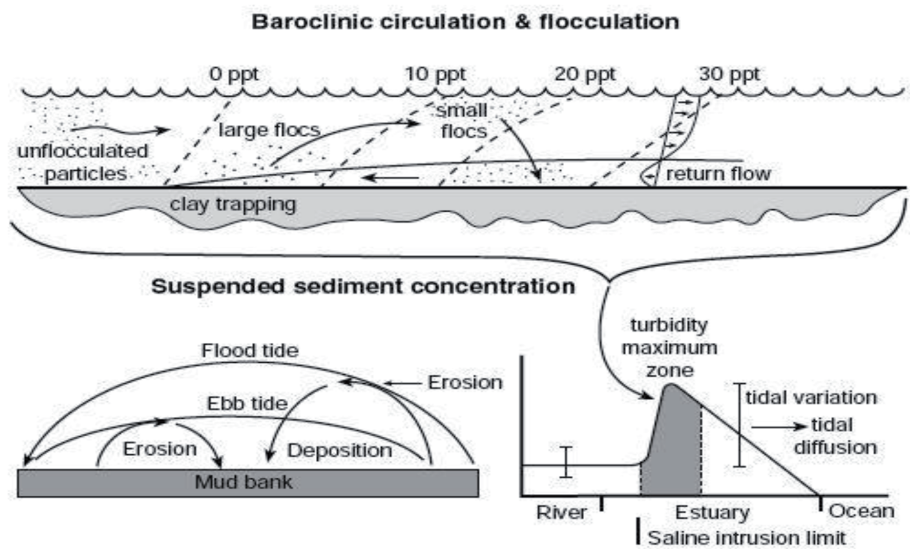
Figure 2.
The effect of baroclinic circulation, tidal pumping, mixing, and flocculation in the turbidity maximum zone of a model mangrove estuary, after Alongi [2].
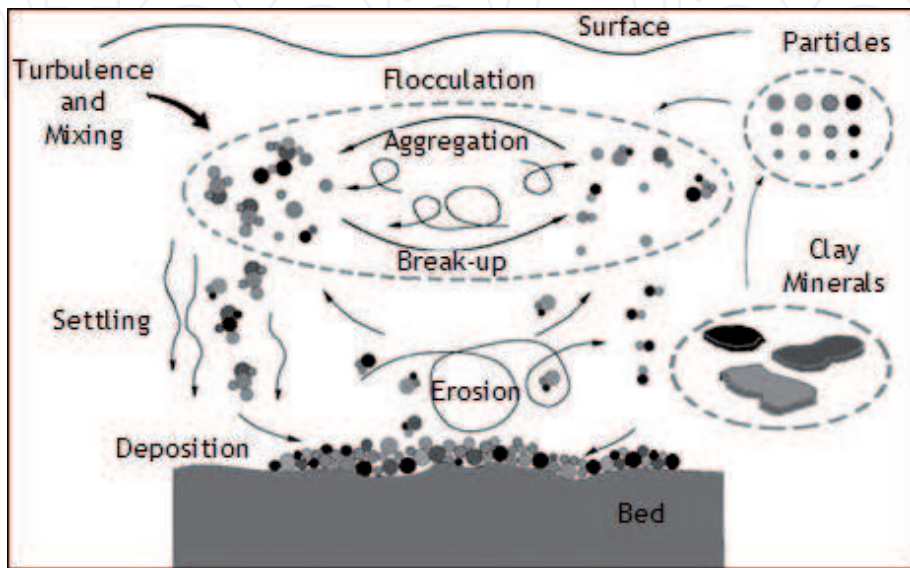

Figure 3.
Flocculation process, after Mandoza [32].

3. The role of mangrove in sedimentation

3.1 Sediment accretion among different root types

The most remarkable adjustments of the mangroves to the coastal and estuarine environment are the robust root structures which largely contribute to the geomorphological stability of the mudflats through trapping and binding of sediments [37]. The aboveground complex root structures of mangroves facilitate sediment accretion by increasing friction and reducing tidal current velocities [38]. According to Furukawa and Wolanski [14], mangrove forest acts as a "pump" of fine-grained sediments from coastal edges toward the forests. Pumping, here, indicates the turbulence generated by different mangrove root structures at the time when water enters into the forests as flood tide [39]. During slack tide the tidal current velocity slows down, ultimately becoming zero and resulting in deposition of flocs. The flocculated materials often grow in size and sometimes attain a size which the ebb tidal currents are unable to re-suspend [14].

The aboveground aerial roots are generally exposed in the tropical mangrove swamps [3]. However, the mangroves facing the waterfront have their aerial roots submerged during flood tides [3]. Tomlinson described "pneumatophores" as the upward extended erect root forms of the subterranean root systems. In *Avicennia* (**Figure 4b**), the pneumatophores are of limited height, commonly less than 30 cm. Cone roots also belong to pneumatophores and are developed by *Sonneratia* spp. and *Xylocarpus moluccensis*. The cone roots of *Sonneratia* (**Figure 4f**) attain greater heights (exceptionally up to 3 m) due to longer period of root development [3]. The size of pneumatophores of *Laguncularia racemosa* is of 20 cm in height. Root systems of *Avicennia* type (*Avicennia* species, *Sonneratia* species, and *Laguncularia racemosa*) offer the stability through their star-shaped network of cable roots radiating out from the trunk at a depth of 20–50 cm [40]. Apart from aerial roots (or pneumatophores) and cable roots, *Avicennia marina* possesses nutritive roots (or feeding roots) and anchor roots [41]. However, Spenceley [42] suggested that pneumatophores are likely to have better sediment-retaining properties than other root types. Buttress roots, developed mainly by *Heritiera littoralis* (**Figure 4d**) *and Pelliciera rhizophorae*, provide a strong tree stability in deltaic plain. Prop roots or stilt roots of *Rhizophora* spp. (**Figure 4a**) arch out from the tree trunk and often anchor within 30 cm of depth [43]. Stilt roots develop to a limited extent in *Bruguiera* and *Ceriops*. At the sapling stage, they grow at the stem base and form shallow buttresses in old trees [3]. *Ceriops* and *Bruguiera* possess aboveground knee roots (**Figure 4e**) with lenticels. Horizontally extended surface roots, developed by *Excoecaria agallocha* (**Figure 4c**), are prevalent in the tropical mangrove wetlands. Sedimentation potential around various mangrove species with differing cross-sectional root area is studied by Furukawa and Wolanski [14]. Species with prop roots, such as *Rhizophora* spp., tend to capture more sediments than *Ceriops* spp. which have smaller root knees. Moreover, the magnitude of sedimentation is greatest for trees forming a complex matrix of roots such as *Rhizophora* spp. and smallest for single trees like *Ceriops* spp. [14]. According to Scoffin [44] *Rhizophora* roots are the strongest binders of sediment as they reduce flow velocity to a degree which restricts sediment transportation. Specific root length and longevity of roots are other contributors to soil volume and thus to elevation gains [45]. Accumulation of long-lived roots through the loss, decomposition, and compression of cell contents often promotes the increase in soil volume [45] (**Figure 5**).

Mangrove seedling density induces sediment accretion [47]. Experiment carried out at Palakuda, Sri Lanka, by Kumara et al. [48] unfolded that accretion rates and aboveground biomass accumulation were highest among the highest density of planted *Rhizophora mucronata* seedlings for more than 3 years.
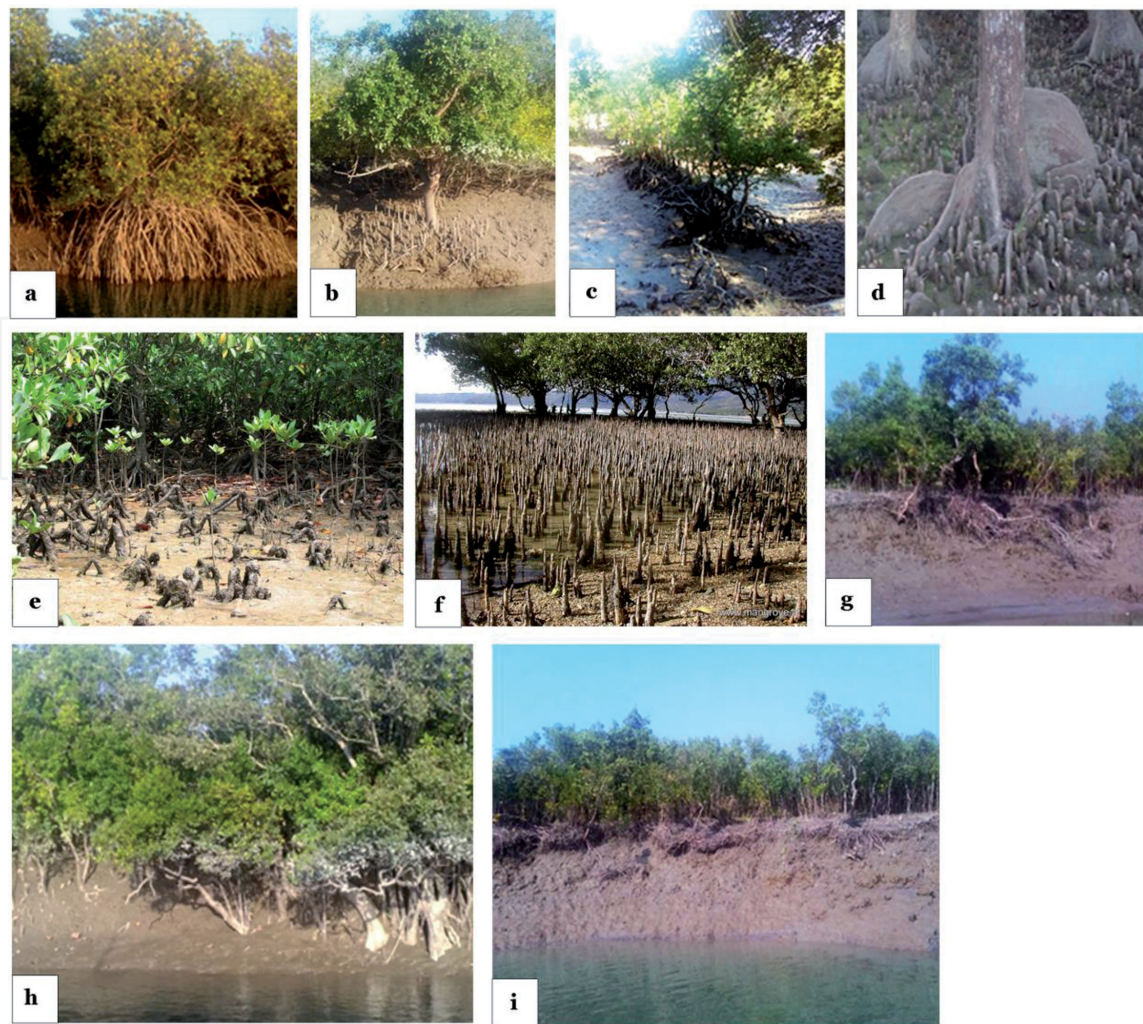
Figure 4.
(a) Rhizophora spp. with stilt roots; (b) pneumatophores of Avicennia spp.; (c) surface roots of Excoecaria spp.; (d) buttress root of Heritiera littoralis; (e) knee roots of Bruguiera gymnorhiza; (f) cone roots of Sonneratia alba; (g) root system exposed due to erosion of substrate; (h) discolored leaves, roots, and trunks indicating tidal submergence level; (i) thick muddy substrate due to sediment accretion. Photographs a, b, c, d, g, h, and i—Indian Sundarbans—are taken in November 2017 by Subhamita Chaudhuri. Photographs e and f—http://www.mangrove.at/mangrove_roots.html [46].

3.2 Spatial variability of sediment accretion

Within the coastal wetlands, sediment accretion pattern varies spatially. It negatively relates with the distance from mangrove edge [39]. Sedimentation is associated with the suspended sediment concentration during tidal inundation which reduces from seaward fringe to the scrub zone [14]. Reed [49] postulated that the front mangroves are situated at the slurry zone which is the depository of sediments both from the rivers and estuaries. Hence, sediment accretion is concentrated more at the tidally regulated front mangroves than back mangroves. Victor et al. [50] from their experiments at Ngerdorch and Ngerikiil estuaries of Micronesia have documented the efficiency of mangroves in trapping 44% of riverine fine-grained sediment. These estuaries are subject to high rates of sediment erosion resulting from land clearing and poor farming practices, and this erosion is largely affecting the growth of coral reefs. Through the radionuclide experiment at the Ganga-Brahmaputra delta, Allison and Kepple [51] show the decreasing pattern of sedimentation from inland to the shoreline, indicating that the sediment has its source at the marine side and it is introduced through tidal inundation, storm surges, and seasonal monsoon setup of sea level. This tidal delta plain accounts for
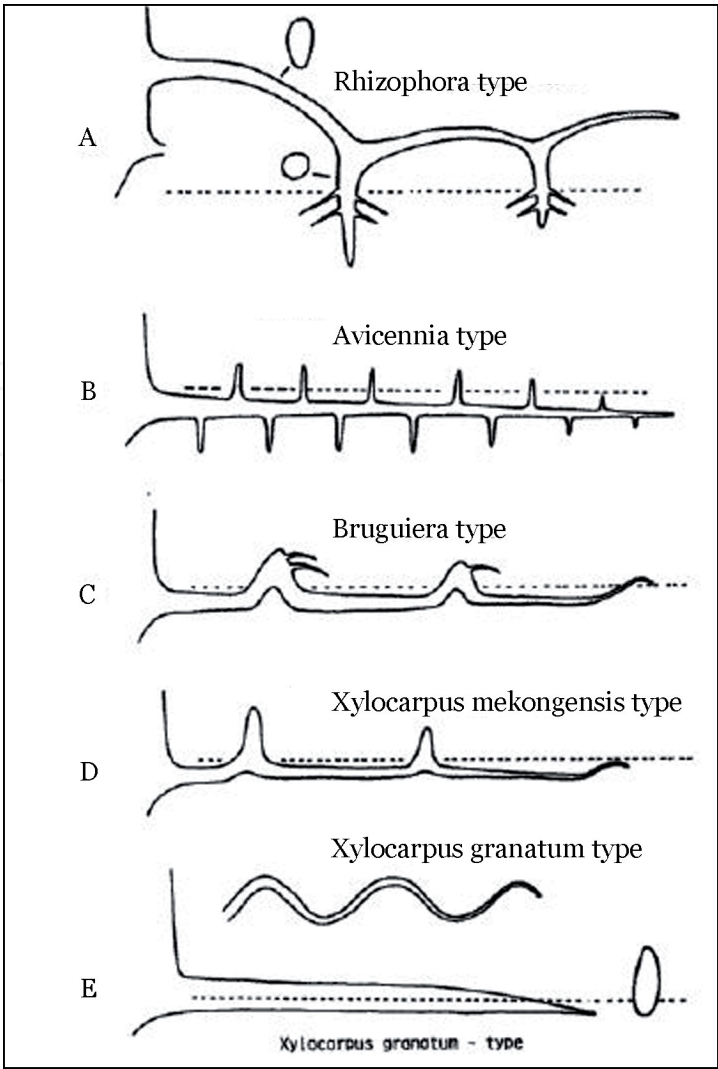
Figure 5.
Schematic diagram demonstrating aerial roots in mangroves, after Tomlinson [3]. All have developed from left to right. Dotted line represents substrate level.

a widespread mean annualized accretion rate of ~1.1 cm year^{-1}, and the heterogeneous sedimentation depositional pattern is influenced by tidal creek networks and topography [13, 51, 52]. However, researches of Santen et al. [53] demonstrate that in Red River, Vietnam, sediment accretion in some wave-dominated mangrove regions alternates with erosion in the fringe zones, and deposition mostly occurs in the riverbank mudflats.

Saad et al. [39], in their study at Kemaman River of Malaysia, found that the coarser and poorly sorted sediment accumulates at the front mangroves, while back mangroves are dominated by finer grains ranging from medium silt to very-fine-grained silt. The high energy waves at the front may lead to the deposition of medium sand at the front mangroves. The grain size often increases with the magnitude and frequency of storm surges [54].

Mangrove, as a community, influences sediment accretion in the different geomorphological units which are regularly modified by the physical forces and shoreline processes. Thom [55] has classified mangrove communities on the basis of their geomorphological setup as river-dominated, tide-dominated, wave-dominated and composite river-wave-dominated. The riverine mangrove areas, having a unidirectional flow, possess lesser sediment retention capacities. In contrast, tide-dominated fringes have the bi-directional flow facilitating net sediment import, sediment suspension and retention. Wave-dominated mangrove forests often

possess distinctive sediment properties than others as because different bedform types promote strong erosion-accretion alternation within the forest [56].

Hydrogeomorphic variability along with variation in soil type in different topographic setups has led to the classification of mangroves as fringe, riverine, basin, scrub, and overwash. In Sri Lanka, these five types of mangrove systems are prominent [11]. Lugo and Snedaker [57] have demonstrated that dwarf mangroves exist in the environment with considerable scarcity of external nutrients. Both mineralogical and biological accretion are affected by the hydroperiod and complex morphodynamic feedbacks within these differentiated mangrove zones. The vertical elevation changes within these mangrove zones are not only the result of vertical accretion but also relate to the subsurface processes, such as compaction, decomposition, and shrink-swell cycles [58] (**Figure 6**).

In their studies at Southwestern Florida, Cahoon and Lynch [58] have observed that basin mangroves are often separated by berms, and the hydroperiod is mostly controlled by rainfall rather than tidal flushes except at extreme high-tide conditions. The accumulated sediment is mostly autochthonous, where organic matter inputs are prevalent and elevation changes are mainly caused by accretion and substrate shrink-swells due to cycles of flooding and drying. On the other hand, erosion and accretion processes are equally important for surface elevation changes in tide-dominated, fringe, and outwash mangroves [58] (**Figure 7**).

3.3 Seasonal change impacts on sediment accretion

Apart from the physicochemical properties present along the shoreline such as soil and water temperature, salinity, and pH, sedimentation processes are largely controlled by seasonal changes of the river discharge pattern and tidal regime. Due to notable increase in current velocity and river discharge, net sediment and organic matter transport rate progressively increase during the rainy months. At this time, buoyancy effect is important as the freshwater is captured in the forest during high tide [2]. Moreover, increasing erosion rates during wet seasons contribute to the
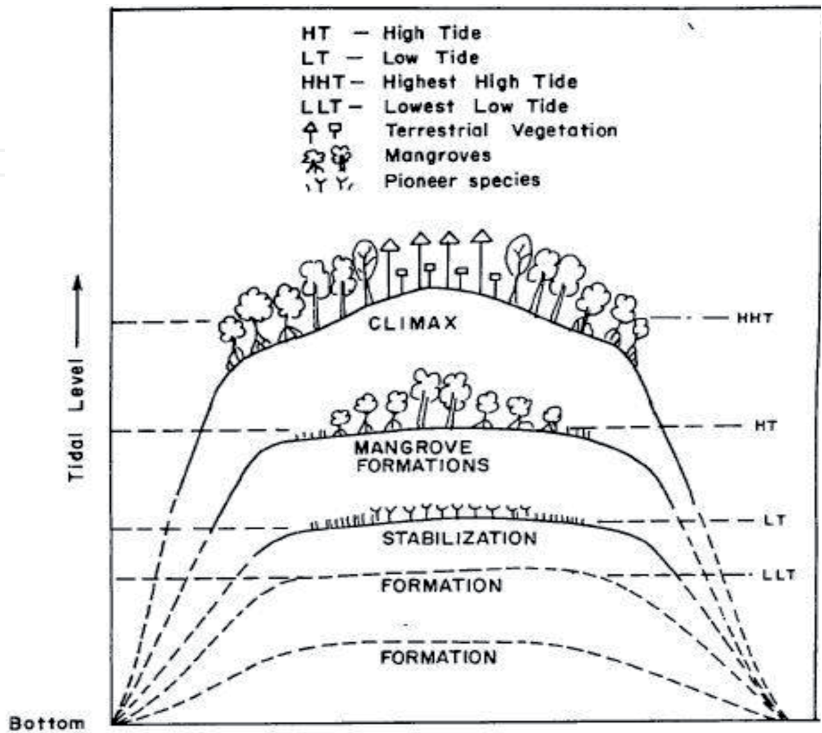

Figure 6.
Stages in the formation of mangroves in deltas, after Untawale and Jagtap [56].
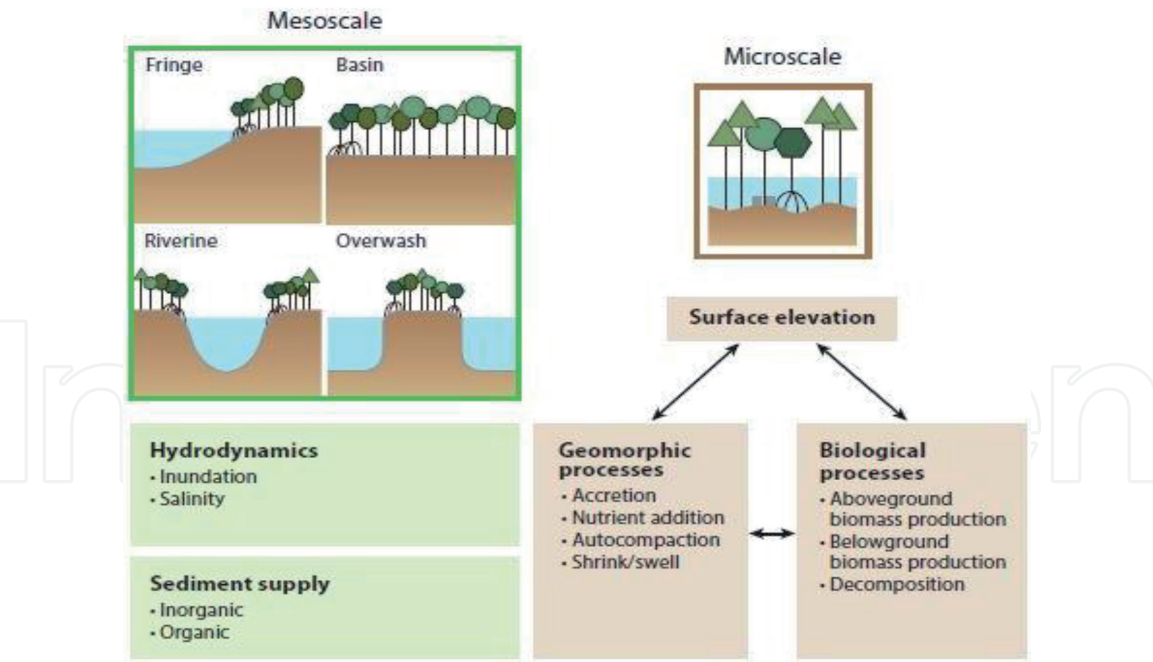
Figure 7.
Mesoscale processes represent interaction of mangroves mainly with hydrodynamics and sediment supply; microscale processes depicts mangrove stand interaction mainly with surface and subsurface processes, after Woodroffe et al. [1].

sediment budget at the foreshore. Relatively weak stratification of sediment is often recorded at the headwaters of mangrove-fringed waterways due to dominance of freshwater input during the wet season [2]. At spring tides, the ebb current directs the surface and bottom velocities for the whole tidal cycle in the upper estuary [59].

Degraded mangrove forests of the monsoon-influenced regions induce considerable sediment erosion which is ultimately followed by accumulation. Occasional storms often deliver the sediments within the forest and promote sediment deposition. Saad et al. [39] have observed the seasonal impact on sediment accretion rates in Kemaman, Malaysia, where the sediment accretion rate was 2.6 mm per month during the monsoons between November and January.

The low discharges during the dry season result in the landward transport of sediment. Residence time of water is long in the mangrove waterway during dry seasons. Trapping of water increases considerably as there is little freshwater to cause buoyancy-induced water circulation [2]. Spring tides often result in greater peak velocities at the surface in the middle or upper estuary. At the dry season, the saltwater reach extends to the extreme upstream section of the estuary. Reduced river discharge lowers the sediment input within the forest, resulting in slower rate of accretion. Saad's [39] observation at coastal Malaysia revealed that sediment concentrations reached only to 8–20 ppm in non-monsoon season as compared to 50–200 ppm during the monsoons. The average sediment accretion rate is eventually brought down to 1.2 mm per month during non-monsoon period.

3.4 Role of the ecosystem

Apart from diverse plant types, mangrove wetlands as an ecosystem support an incredible assemblage of fauna which, in turn, participate in land formation processes. The wide array of organisms includes barnacles, mollusks, shrimps, crabs, lobsters, jellyfish, tunicates, etc. which are often found among the roots of the mangroves. Autochthonous materials, including leaf litter, dead twigs, branches, and roots from the mangroves, accumulate on the mudflat surface and are incorporated within the soil through bioturbation by crabs [60]. This built-up material is

consumed by detritivores, such as crabs, amphipods, and gastropod mollusks [61]. Some of this whole range of organisms plays a conspicuous role in aggregating and trapping sediments in their own way.

Mucus and bacterial populations are considerably abundant and productive in the mangroves. Mucus is known to be produced by benthic and pelagic detritivores. Wolanski [62] has noticed that the clay particles in suspension are trapped by sticking to the bacterial, algal, and animal mucus and pelletization by benthic detritivore deposits. He also found that a large number of non-flocculated particle, entering into the coral creek mangroves during flood tide, were re-exported at the ebb tide by sticking to the mucus floating on the surface water. This mucus was transported during ebb tide from the swamp to the creek where it produced prominent foam lines [62].

Animal structures, such as burrows, mounds, tubes, and other biogenic structures, also impact on sedimentation within the forest [63, 64]. These bioturbation structures are engineered by crabs and other benthic organisms. Numerous burrows generate friction on the forest floor when the tidal water flows through these burrows. Various models of fluid dynamics indicate that water circulation through the burrows are highly influenced by the architecture, slope, depth of the forest floor, location of roots relative to the burrow, and number of loops within the burrows [2]. De [65] in his experiments in the Indian Sundarbans demonstrated the biophysical mechanism of intertidal beach crab. Burrowing cycles within the substratum involve construction of oriented and open-to-air burrow tube (pre-tidal phase), formation of underwater and subsurface-trapped tabular air bubble occupied by the burrower that perpetually maintains internal and external pressure equilibrium by modifying inside burrow (tidal phase), and final exposure of air bubble system to air (post-tidal phase) before deserting the previous burrow and opening of another burrow cycle [65].

Vegetated marsh substrates reduce the fluid current velocity locally near the bed resulting in reduction of the energy available to move the sediment through fluid shear stress [39]. Benthic mats, developed by algal or microbial material on the surface of mangrove soils, contribute to vertical accretion [66]. These biomats are produced locally in patches in the depressed and moist areas on the supratidal flats following algal bloom. During the experiment at Hooghly estuary, De [65] observed that the mat grounds are cohesive, leathery, and composed of slightly coherent admixtures of fine-grained sand, silt, and green algae-secreted organic glue. Substrates of coastal wetlands including marshes and mangroves are thus characterized by organic matter deposition, suggesting the major role of biological processes in soil development, soil accretion, and elevation change [67–69]. Analysis of sediment cores has helped in inferring the contributions of organic matter to soil volume and vertical accretion in marsh and mangrove wetlands [70].

4. Sea-level changes, subsidence, and sediment accretion

Mangrove distribution along the coasts or estuaries changes with time, involving the balances between subsidence and accretion, erosion and vegetative stabilization, productivity and decomposition, tidal pumping, and drainage competency [1]. The global rise in sea level is caused by thermal expansion of seawater due to climate change and melting of polar ice caps and glaciers. These lead to the increase in volume of water in the ocean resulting in substantial rise in sea level, which is called eustatic sea-level rise. On the other hand, mean sea-level rise, measured by tide gauges, also varies because of tectonic movement, such as glacial-isostatic adjustments and lithospheric flexural subsidence [71]. Subsidence can be of two

types: shallow and deep [72]. Shallow subsidence is caused by the reduction of mangrove and marsh surface elevation due to sediment compaction at the top layer, such as shrinkage of silt, clay, or peat deposits and accumulation of subsurface materials [73]. Deep subsidence is led by tectonic and isostatic processes. The measures for vertical accretion only consider the effect of shallow subsidence, whereas the methods measuring surface elevation anomalies include both shallow and deep subsidence [73]. The net effect of eustatic and isostatic sea-level changes results in the relative sea-level rise in a specific location over a specific time period [47]. Observed and projected sea-level rise has far reaching impacts on mangroves, from drowning the vulnerable wetlands to squeezing the coastal areas [74, 75]. However, satellite-based experiments of Phan et al. [74] at Mekong River showed that mangrove degradation and rapid coastal erosion has reduced the mangrove strip inducing lesser sedimentation. Krauss [45] showed that sediment accretion rates beneath some mangrove forests surpass the rates of sea-level rise. Hence, the subsurface processes play a dominant role in determining whether mangrove adjusts to sea-level rise. Subsidence led by autocompaction and areal expansion caused by mangrove root growth has important bearing on adjustment of mangroves to sea-level rise [1]. Surface elevation table measurements along with marker horizon techniques are often adopted to record vertical sediment accretion rates and substrate elevation changes and calculate short-term subsidence rates [1]. With the organic and mineral sediments, subsurface processes beneath the mangrove forests play a major role in developing surface elevation [76]. Wetland elevation is increased and inundation stress is decreased by sedimentation. Mangroves develop on the newly accumulated mudbank and facilitate soil development and elevation change [77]. Root growth dominates below-ground organic sediment accumulation, and this in turn keeps a balance with sea-level change [60, 78] (**Figure 8**).

The research findings of Cahoon and Lynch [58], based on mangrove forest of Southwestern Florida, have shown that vertical accretion is often driven by shallow subsidence and local sea-level rise. Hence, vulnerability of mangroves is described
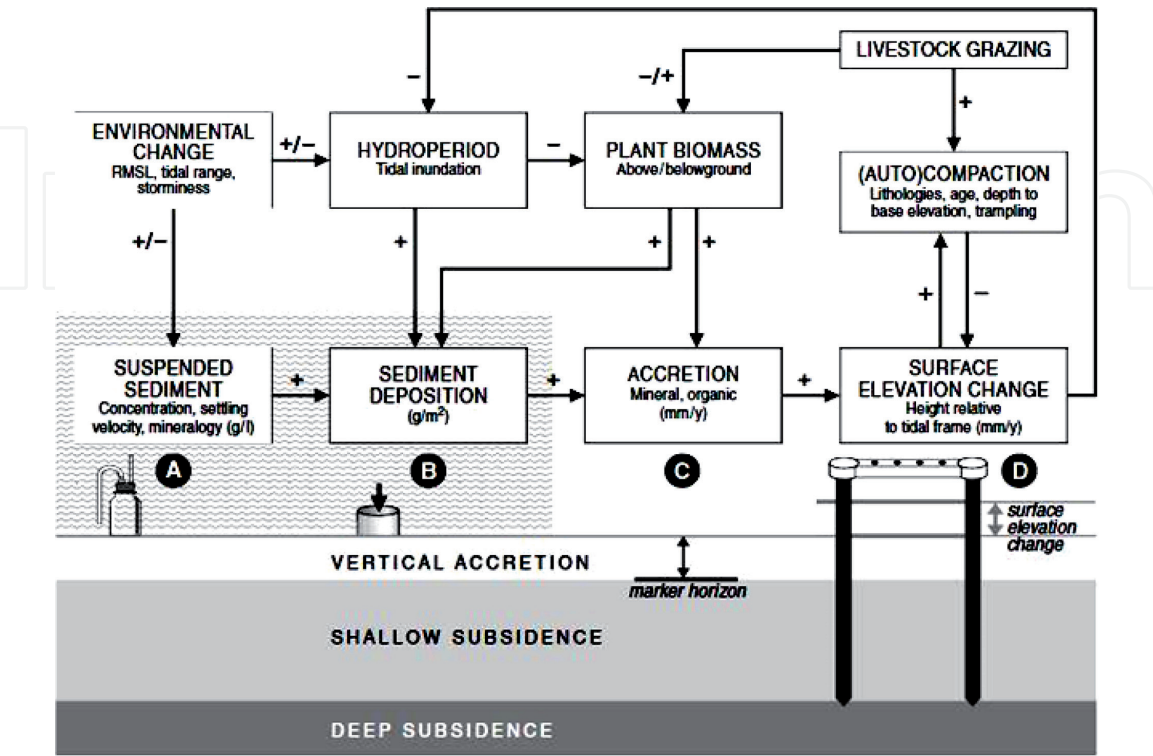

Figure 8.
Factors affecting sedimentation processes in coastal wetlands after Cahoon et al. [79].

Hydrogeomorphic setting	Surface elevation change (mm year^{-1})	Vertical accretion (mm year^{-1})	Subsurface change (mm year^{-1})
Fringe	−1.3 to +5.9	+1.6 to +8.6	−9.7 to +2.4
Riverine	+0.9 to +6.2	+6.5 to +13.0	−11.2 to −0.2
Basin	−3.7 to +3.9	+0.7 to +20.8	−19.9 to +2.8
Scrub	−1.1	−2.0	−3.1
Overwash	−0.6 to −2.5	+4.4 to +6.3	−3.8

Table 2.
Surface elevation change, vertical accretion, and subsurface adjustment for different mangrove hydrogeomorphic settings, determined using surface elevation table-marker horizon (SET-MH) methods, after Krauss et al. [45].

in terms of elevation reduction, rather than accretion deficit [58]. However, mangroves will be affected by inundation if the rate of sea-level rise is greater than vertical land development due to sediment accretion and root accumulation. In such situations, mangroves would naturally have the tendency to extend landward [1].

The mangroves respond differently to surface accretion, subsidence, and sea-level rise according to their hydrogeomorphic setting. In the experiment at Micronesian mangroves, Krauss et al. [37] found that the fringe and riverine mangroves are moderately susceptible to local sea-level rise, despite considerably high sediment accretion rates along Yela and Utwe rivers of Pacific high islands. In contrast, root and peat-based accumulation resulted in greater elevation gain in Belize [78]. Fringe mangroves are specifically vulnerable to sea-level changes than riverine or interior mangroves, partly due to physiological stress imparted by prolonged flooding [37].

According to Cahoon et al. [60], mangrove forests of the world are prone to lose surface elevation relative to sea-level rise, despite their ability to accrete sediment in some hydrogeomorphic settings. Hence, protecting the mangroves susceptible to sea-level rise in the outer margin of the estuaries from human interferences may slow the rate of soil loss [37] (**Table 2**).

5. Methodologies for measuring sediment accretion

Various methods and models have been adopted till date to analyze and understand sediment accretion rates within mangrove ecosystems of the world. Sedimentation rates, measured by short-term measurement of changes in relative sea level along with the estimates by radiotracers, provide a net sedimentation pattern [2]. There is a widespread use of radioisotopes ^{210}Pb and ^{137}Cs in analysis of long-term sedimentation within mangroves as well as salt marsh areas. Mudd et al. [80] have used the above method along with OIMAS-N model simulating the ephemeral evolution of a sediment column situated within a salt marsh [80]. Banerjee et al. [81] established the ^{210}Pb geochronology in selected four sediment cores in the Sundarbans and the Hugli estuary of India for the assessment of trace metal distribution in the sediment. The core sites were selected on the basis of different anthropogenic and hydrological parameters. Fe-Mn oxyhydroxide is observed to be the major controlling factor for trace metal accumulation as compared to organic carbon in both the sites. Fe-normalized enrichment factors (EFs) were calculated based on trace element abundance, and the result shows EF >1 for Cd, Pb, Co, and Cu indicating high enrichment in the top layers of the forest substrate. This is mostly because the core sites receive high pollution load from

various anthropogenic sources. The experiment revealed relatively less contamination in the Hugli estuary due to high energy conditions and mostly coarse-grained sediments. Chaudhuri et al. [82] determined the accumulation of various trace metals in fine nutritive roots of *Avicennia marina* under the contaminated sediments at Sydney estuary, Australia. The result showed highest metal concentrations of Cu, Pb, and Zn in the fine nutritive roots, with a mean of 153, 189, and 378 mg/kg, followed by As, Cr, and Ni with mean enrichment concentration of 16, 21, and 11 mg/kg, respectively. Cd and Cr have low concentrations in fine nutritive root tissues. Radiocarbon (^{14}C) dating is another widely used method for measuring long-term sedimentation rates for both freshwater and marine ecosystems [83]. Optically stimulated luminescence (OSL) technique is often used for dating both older and younger (<60 years) sediments of the coasts. Madsen and Murray [84] have provided a detailed analysis and review on this technique.

"Marker horizon" technique and sedimentation plates are two most popular methods of quantifying transient sediment accretion [37, 73, 85]. Krauss et al. [85] in their study used sediment pins to measure elevation change in Micronesian mangrove forests. A marker horizon, mainly consisting of degradable material as opposed to sedimentation plates, assists as a reference layer within the soil, against which deposition of both mineral and organic sediment can be measured using a soil corer [72, 85]. In the case of dense vegetation, clipping the vegetation before applying the marker material is advisable, whereas marker material can be placed at soil surface within the stems in less dense forests. Following this procedure the effect of vegetation canopy structure on sediment accretion rates can be investigated [73]. With stacked layers of the markers, autocompaction rates are often assessed [73]. However, recovery of markers may be a challenging task when the layer is disturbed by bioturbation [84], distributed by profound floods, or shuffled with darker inorganic and organic materials [68]. In the sedimentation plate method, the marker horizon consisting of a firm plate made of metal or plastic is buried horizontally within the soil just below the rooting zone [73]. For recording sediment accretion, a thin metal pin is pushed within the soil until it reaches the plate, and its length above the sediment is determined [73]. However, measurements, based on marker horizon and surface elevation tables, provide short-time perspectives, indicating shallow subsurface processes of root growth and substrate autocompaction, whereas radiometric dating measures long-term sedimentation [1]. Saad et al. [39] applied the methodology based on estimating the thickness of a sediment section divided by the time span necessary for its deposition. The study covered a span of 2 years. To estimate the amount of sediment trapped by mangroves in the Ngerdorch and the Ngerikiil estuaries of Micronesia, Victor et al. [50] measured the salinity, temperature, and suspended sediment concentration to finally quantify the freshwater flow, brackish water outflow, and net estuarine sediment transport. Backscattering nephelometer is used widely by the scientists for estimating suspended sediment concentration. Horstman et al. [86] estimated dry weight of deposited sediments on the forest floor in the Andaman coast of Southern Thailand. They used ceramic tiles covered with smooth layer of mortar and carefully leveled with the forest floor for recording sediment entrainment and deposition. Computer-aided modeling of sediment transport is a valuable tool to understand and predict morphological change and sedimentation amount [87]. Delft3D software is very popular and is applied widely for simulating hydrodynamics, sediment dynamics, morphological processes, and biotic impacts in shallow water environments [88]. The process-based Delft3D-FLOW module solves the three-dimensional and two-dimensional unsteady shallow water equations. The hydrodynamic model applies horizontal momentum equations to compute transport and deposition of sediments concomitantly with the hydrodynamics,

Location	Sedimentation rate (mm year^{-1})
Bay of Bengal	≤5
Ajkwa estuary, Papua	0.6–5.5
Sawi Bay, Thailand	10–12
Matang Mangrove Forest Reserve, Malaysia	10–31
Kuala Kemaman Forest Reserve, Malaysia	10.6
Jiulongjiang estuary, China	13–60
Data from [39, 58, 78, 90–92].	

Table 3.
Sedimentation rates in some mangrove forests focusing on Southeast Asia.

facilitating the understanding of morphodynamic feedback [86]. For measuring sedimentation rate and ratio, Adame et al. [89] used sediment traps which consisted of pre-weighed 9-cm Whatman qualitative filters placed in the ground over Petri dish lids held to the sediment by hooks. In addition, for the assessment of sediment quantity transported and deposited in the mangroves, they used glomalin—a novel terrestrial soil carbon tracer (**Table 3**).

6. Conclusion

Mangroves, acting as traps for both mineral and organic sediments, control the sedimentation and thus form their own survival ground. In the investigation at the Gulf of Thailand, Thampanya et al. [93] substantially differentiated coasts with and without mangroves. Coasts with mangroves showed prograding characteristics with low rate of erosion. The eroding coastal stretches are characterized by the absence of mangroves coupled with increased number of shrimp farms, increased fetch to prevailing monsoon, and decreased riverine inputs due to construction of dam [93]. Mangrove swamps of Southeast Asia are typified by sediment transport and circulation which is the consequence of intense anthropogenic disturbances near and around coastal regions and high rate of sediment erosion. Mangrove degradation and fluvial discharge with seasonal maxima seems to play a pivotal role in sediment erosion. Mangroves of Mekong delta have been especially affected by human activities including cutting of trees for timber and reclamation for shrimp cultivation [94]. Mandai mangroves, a small mangrove patch of Northeast Singapore, indicate an impact of urbanization. It has been a hotspot of research agenda for decades providing a broader context of Southeast Asian mangrove conservation [95]. Hence programs for plantation, restoration, and rehabilitation can alter the decline of mangrove habitat if proper hydrodynamics and sedimentary requisitions are met [1]. Alongi [96] examined the impact of climate change on mangrove forests. The Intergovernmental Panel on Climate Change (IPCC) has predicted that mangroves of arid coastlines, in subsiding river deltas, and some islands will reduce in area, though they have often proved to be either resilient or resistant to most environmental changes. The persistence of mangroves insinuates their ability to cope with moderately high rates of relative sea-level rise [1]. High sediment accretion, coupled with surface elevation change and plant survival in high densities, can facilitate shoreline protection and counter relative sea-level rise in the tropics. Moreover, continuous increment of aboveground biomass within the high-density mangrove wetlands not only advocates surface elevation gain but also acts as atmospheric carbon sink [48]. As they grow in saturated, muddy, low-oxygen soils, maximum

amount of carbon is stored in roots, resists decay, and becomes long-term sinks as mangrove peat [61]. Thus, they provide other significant ecological services such as carbon storage. These tidal forests of the tropics are unique open ecosystems for a variety of structural and functional properties as well as their distinctive adaption techniques with the hydrogeomorphic processes.

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