The Mangrove Ecosystem Utilizes Physical Processes

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Abstract

Various physical processes support the mangrove environment. In this paper, a synopsis of hydraulic systems such as tidal flow, sea waves and groundwater in mangrove areas is introduced. Further, in order to preserve the natural environment of mangrove areas, it is proposed to connect quantitatively these physical processes and the mangrove ecosystem in execution of interdisciplinary studies.

Key words: ecosystem, hydraulic system, mangrove environment, physical process

1. Introduction

Mangrove environments are formed through strong feedback relationships among biota, landforms, water flow and the atmosphere (Fig.1). Water flow plays a particularly important role in mangrove ecosystems, compared to terrestrial ecosystems.

Biotic activities within mangrove forests, where mangrove trees are the central feature of the ecosystem, have led to the development of a unique substrate (bio-geomorphology) in intertidal areas. On the other hand, colonies of mangroves have developed under the influence of physical factors such as tides that accompany alternating flooding and drying of the habitat. In turn, mangroves are sensitive to several environmental gradients and preserve themselves under pressure from those physical processes.

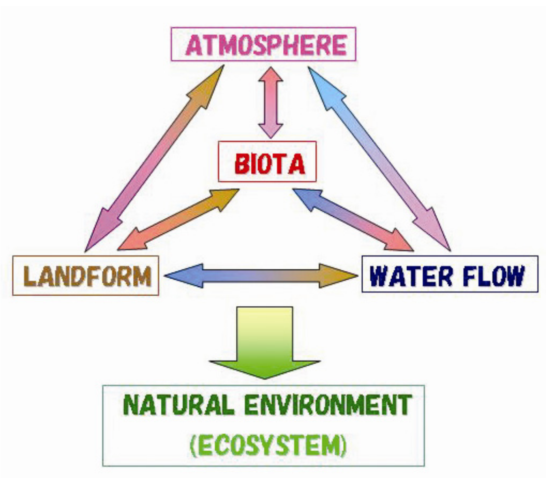

Fig. 1 Feedback system in mangrove environments.

Feedback among four factors, 1) biota in which mangrove trees themselves are the nucleus, 2) sediment topography, 3) water movement such as tidal flow and sea waves, and 4) the atmosphere, play important roles in forming and maintaining the mangrove environment.

The first study of physical processes in mangrove areas was probably that of Wolanski *et al*. (1980). Even today, however, research on those physical processes is limited compared with the amount of research that focuses on biological aspects. A summary of the past studies on the physical processes in mangrove areas is given below. The details are described in Mazda *et al*. (2007a), Perillo *et al*. (2009) and Mazda (2011).

2. Unique Hydraulic Systems in Mangrove Areas

2.1 Mangrove topography

Mangrove topography is classified into three types, riverine forest (R-type), fringe forest (F-type) and basin forest (B-type), as seen in Fig. 2. These types differ in terms of the dominant water movements of each system . In the typical R-type, swamp water within a few meters from tidal creeks is dragged by tidal flow in the creek; thus it flows parallel to the creek. Further inside mangrove swamps the flow is predominantly perpendicular to the creek due to the high vegetation-induced friction and the water surface gradient between the swamp and the tidal creek. At ebb tide the surface soil in the swamp dries rapidly (Mazda *et al*., 2005). In the F-type, the surface soil remains wet even at low tide. Sea waves are mitigated in swamps because of the resistance of thick mangrove trees and their emergent roots. The erosion/accumulation of the topography depends on the wave height (see Section 2.3). In the B-type, during the dry season, the water level in the depressions continues to descend slowly because of groundwater flow to the open sea driven by the difference in water levels between the depression and the open sea (Mazda *et al*., 1990a).

Lugo *et al*. (1988) and Adame *et al*. (2010) stated that the formation of mangrove ecosystems differs among these three types, and the growth level of R-type mangrove colonies is the highest among them, the reason for which is shown in Section 3.4.

In reality, these three types have complexities with secondary topographies such as sub-creeks and sand dunes.

2.2 Tidal flow

The physical processes that support mangrove ecosystems basically consist of the tidal motion of seawater, although the tide does deform significantly in mangrove swamps due to the high density of mangrove trees and roots. Watson (1928) recognized that the mangrove community depended on tidal inundation. However, quantitative relationships between the ecosystem and tidal action have not been apparent till now, mainly because of the delay in hydrological studies in mangrove areas.

Momentum equations applicable to tidal motion in the peculiar landforms of mangrove areas, which comprise long meandering tidal creeks and wide fringing mangrove swamps (R-type), were first proposed by Wolanski *et al*. (1980). Uncles *et al*. (1990) and Dyer *et al*. (1992) analyzed hydrodynamics of mangrove creeks from a physical viewpoint of water exchange between mangrove areas and the open sea. The tidal flow in creeks depends strongly on the magnitude of the water volume that enters the mangrove swamp during the flood tide (Fig. 3). Wolanski and Ridd (1986), Ridd *et al*. (1990) and Nihei *et al*. (2004) used schematic models to investigate the interrelationship between tidal flow in creeks and tidal inundation into fringing mangrove swamps. Arranging observational results in various field areas, Mazda *et al*. (2005) formulated mangrove hydrodynamics composed of tidal creeks and fringing mangrove swamps.

Many tidal creeks with wide mangrove swamps (R-type) record a tidal flow asymmetry (Fig. 4), in which the peak current velocity is often 20%-50% higher at ebb tide than at flood tide, though the velocity in the swamp is always higher at flood tide. This asymmetry is formed by the interaction between the tidal creek and the mangrove vegetation in the swamp (Mazda *et al*., 1995). Wolanski (2006) pointed out that this velocity asymmetry in tidal creeks helps flush out coarse sediment from the creeks, ensuring maintenance of creek depth and material exchange between the mangrove area and the open sea. The tidal flow in creeks is accompanied by secondary circulation, which occurs in the lateral cross-section of the creek, depending on the existence of freshwater runoff from the upper stream and meanders of the creek. Interactions between this secondary circulation and the tidally reversing flow affect dispersal of mangrove seeds (Ridd *et al*., 1998).

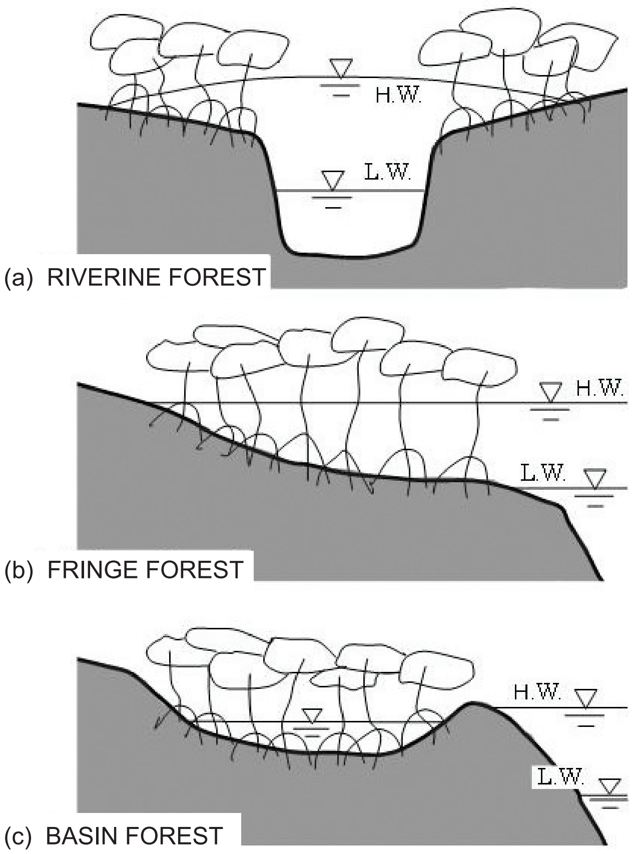

Fig. 2 Classification of mangrove topography (after Cintron & Novelli, 1984).

a. RIVERINE FOREST is defined as a mangrove swamp with tidal creeks (or rivers), which is inundated by high tides and exposed during low tides. Tidal creeks commonly run perpendicular to the coastal banks, are highly sinuous and can intertwine with other creeks (see Fig. 7).
b. FRINGE FOREST is defined as a mangrove swamp along a shoreline that faces the open sea, which is directly exposed to the action of both tidal water and sea waves. The bottom slope of the swamp is continuous to the open coast.
c. BASIN FOREST is defined as a depressed mangrove swamp, which is seldom inundated by high tides during the dry season, but is inundated by spring high tides during the wet season.

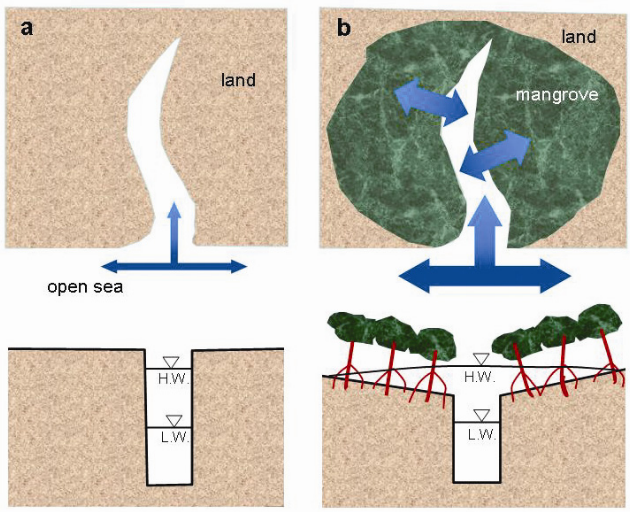

Fig. 3 Schematic views of tidal rivers (a) without and (b) with flood plains, and tidal flows around the river mouth.

At rising tide the creek water inundates the mangrove swamp, and is trapped temporarily within the swamp. On returning to the creek at ebb tide, the trapped water mixes with the creek water, and materials that are dissolved, floating or suspended in the water disperse longitudinally along the creek and toward the adjacent coastal sea with each passing tide.
The tidal flow flux in the creek depends on the extent of the flooded area and the vegetation density.

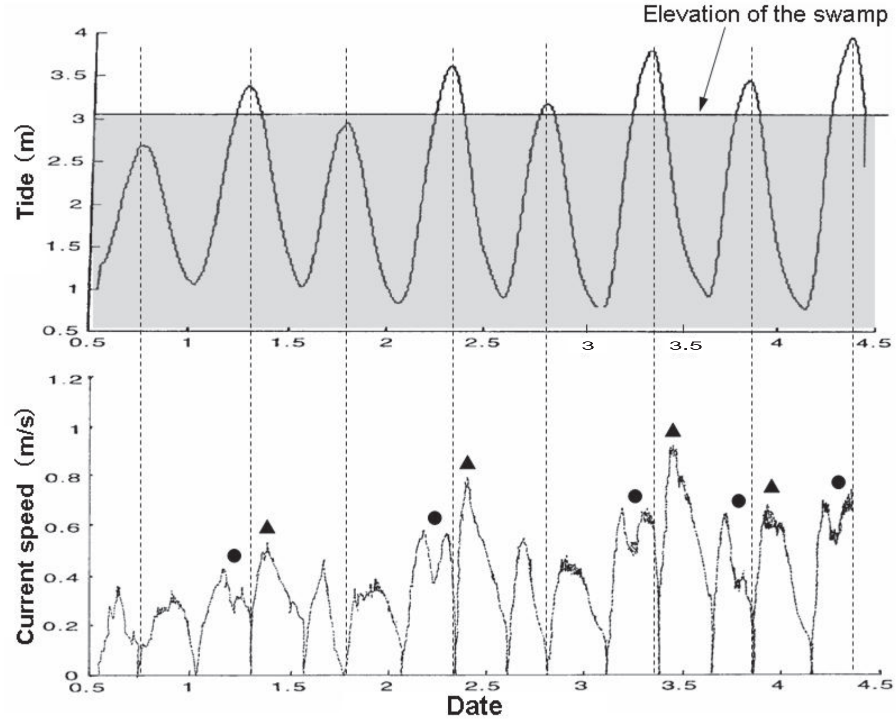

Fig. 4 Time series plots of water level and current speed in Cocoa Creek, Australia (after Aucan & Ridd, 2000).

Only when the tidal level is well over the elevation of the bottom floor of the swamp as shown in the upper figure, does the ebb flow (▲) prevail against the flood flow (●). Further, this flow asymmetry between ebb and flood strengthens with increasing tidal level. Mazda *et al*. (1995) demonstrated that the asymmetry is dependent on the difference between tidal phases in the creek and the swamp; this difference results from the drag force of mangrove roots in the swamp.

2.3 Sea waves - tsunamis

Sea waves are another important physical factor in coastal areas. In R-type topography, wind-driven waves and swells rarely propagate into swamps because of the dissipation of wave energy along long tidal creeks. Also, in the B-type, waves seldom appear because of the presence of a barrier between it and the open sea. In the F-type, mangrove vegetation reduces sea waves, resulting in coastal protection, as shown in Fig. 5. The quantitative mechanisms of wave reduction, however, are not yet well understood because of the complicated vertical configuration of mangrove trees, structural differences between mangrove species, various conditions of natural vegetation density and dependency on wave characteristics in the open sea (Mazda, 2011). Further, studies of wave action at the boundary between mangrove swamps and the open sea are important from a viewpoint of sedimentation/erosion (Massel *et al*., 1999; Furukawa, 2008).

Findings on sea waves (period typically less than 20 sec) cannot be applied to tsunami waves (seismic sea waves) with periods between ten minutes and an hour. Many studies have examined the hydraulic behavior of tsunami waves reaching various coastal areas. These studies, however, cannot be applied directly to mangrove areas, because unique conditions such as the drag force on mangrove trees and their vertical configurations are not taken into consideration. Mangrove forests with their

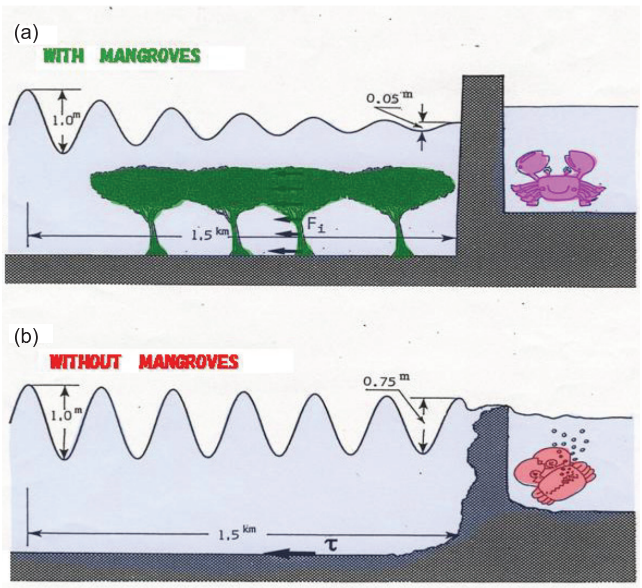

Fig. 5 Difference in the effect of wave reduction (a) with and (b) without mangroves (after Mazda *et al*., 1997).

Based on the observation on the Thuy Hai Coast, Vietnam, where mangroves (*Kandelia candel*) had been planted in a strip 1.5 km wide (toward offshore) at 1 m intervals, wave reduction was estimated. (a) A wave height of 1.0 m on the open sea decreased to 0.05 m on the coast. However, (b) without the sheltering effect of mangroves, the waves arrive with a height of 0.75 m, diminished by bottom stress alone.

unique vertical configuration protect human lives from tsunamis. For example, though tsunamis uproot underground roots of mangroves, the substantial resistance provided by these intertwining roots forms a sacrificial barrier that helps protect the land and human settlements located behind the mangrove belt (Mazda *et al*., 2007b). However, it is noteworthy that tsunamis behave differently in R-type or F-type topographies.

Hong (2006) collected articles about roles of mangroves in protecting human lives from various waves such as sea waves, storm surges and tsunamis in South Asia.

2.4 Groundwater flow

Water flow is composed of surface water flow above the substrate and groundwater flow through the substrate. Compared to surface water flow, groundwater flow tends to be ignored because of the low rate of water flux. However, the role of the groundwater flow in determining soil properties and maintaining mangrove ecosystems has been clearly documented from field observations. For example, Stieglitz *et al*. (2000) reported that a high density of crab holes supports water/material permeability and modifies soil properties. Susilo and Ridd (2005) stated that 50% of the salt that accumulates around underground roots and limits the growth of mangrove trees may be discharged to the creek via groundwater. These findings are supported by the observational results that the hydraulic conductivity (the coefficient of permeability) of mangrove swamps is two to three orders of magnitude larger than that of normal sediment substrates (Fig. 6). Further, the permeability depends on topography, particularly on the bottom slope, suggesting that groundwater behaves significantly differently between R, F and B-types.

Groundwater with a tidal period in coastal areas such as mangrove forests, particularly where the substrate is composed of loose sediment, behaves very differently from that in inland areas. The water flow has three components: first, a quasi-steady flow towards the open sea due to the tidal mean pressure gradient between the water levels in the swamp and the open sea; second, a tidally reversing flow with exponentially damped amplitude and linearly delayed phase towards the swamp; and third, a residual flow towards the swamp caused by the exponentially damped tidal flow (Mazda *et al*., 1990a).

3. Relationships between the Mangrove Ecosystem and Physical Processes

3.1 Mangrove topographies are formed by a self-organization system

Water currents forced by tides and sea waves are steered, channeled and hindered by the topography of

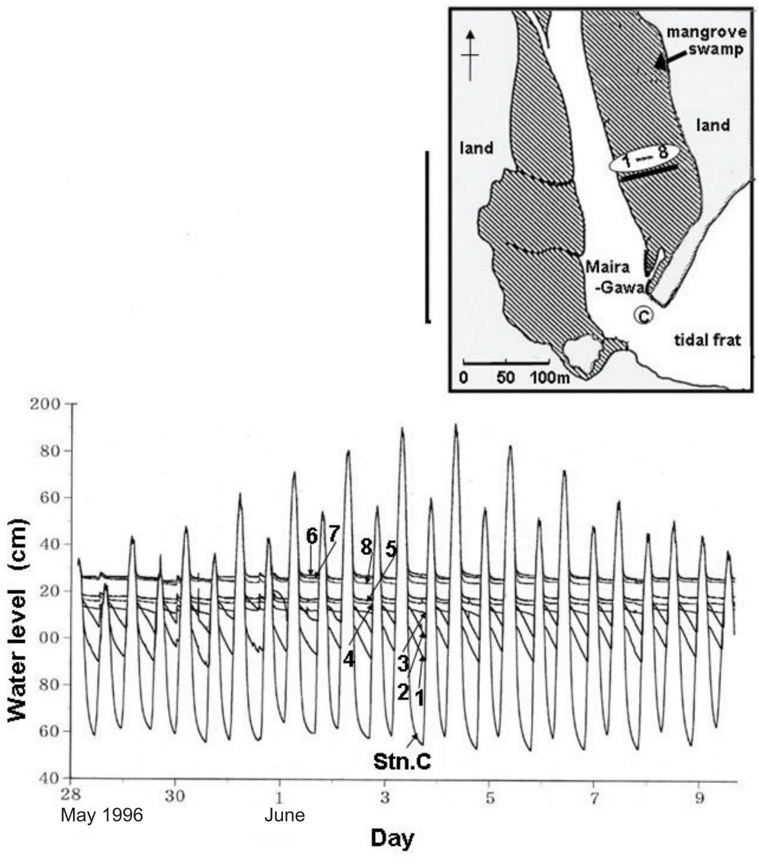

Fig. 6 Time series plots of water levels at Stns. 1-8 and Stn. C in the Maira-Gawa mangrove area on Iriomote Island, Japan (after Mazda & Ikeda, 2006).

After tidal inundation of the swamp has ceased, groundwater tables near a creek (Stns. 1 and 2) descend by up to 15 cm during the time until the subsequent flood tide. In contrast, only minor changes occur at sites far from the creek (Stns. 6, 7 and 8). This descending speed of the groundwater depends on the hydraulic conductivity and the bottom slope of mangrove swamps.

swamps and by mangrove trees and intertwining roots. In turn, the movement of sediment that accompanies water flow modifies the swamp topography, sometimes initiating meanders in creeks or eroding coastlines. However, the quantitative mechanisms of sedimentation in mangrove swamps have yet to be fully investigated.

Many mangrove areas form a remarkable fractal pattern with innumerable tidal creeks and sub-creeks, as shown in Fig. 7. The mechanisms and physical processes that form the fractal network of these creeks, however, have received little scientific scrutiny. Geologies of drainage basins and channel networks in inland areas have been quantitatively studied, but the mechanism of channel network formation in mangrove areas seems to be quite different from that in inland areas because of the unique morphological and hydrological characteristics of mangrove areas, such as the very gentle slope of the bottom substrate, loose bottom sediment and water inundation into the area with tidal period.

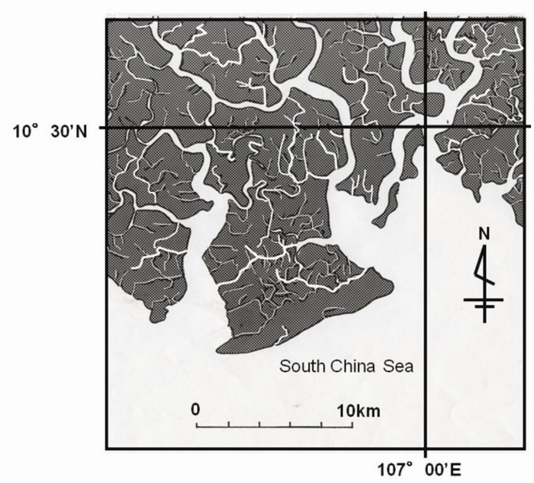

Fig. 7 Map of the area around the Long Hoa Coast in southern Vietnam.
All of this area is covered with mangrove swamps, with many tidal creeks and their sub-creeks, except for a small area facing the South China Sea which was converted into a human settlement.

Based on these considerations, Yagi *et al*. (2007) proposed the idea of "self-organization," in which the fractal pattern must be formed by feedback interactions among mangrove vegetation, loose soils and reciprocal tidal flows (see Section 3.4). Further, D'Alpaos *et al*. (2009) proposed a formation mechanism of creeks in tidal flats due to tidal flows. These ideas suggest the initial stage to form networks of tidal creeks in mangrove forests.

3.2 Roles of water circulation in the mangrove environment

Water properties such as temperature, salinity, dissolved oxygen and nutrient concentrations support mangrove ecosystems directly and indirectly. These water properties vary spatially and temporally in a manner that is strongly dependent on physical processes such as water circulation, tidal mixing and diffusion/dispersion (Fig. 8).

These water properties also depend on the peculiar mangrove topography. In the R-type, the hydraulic

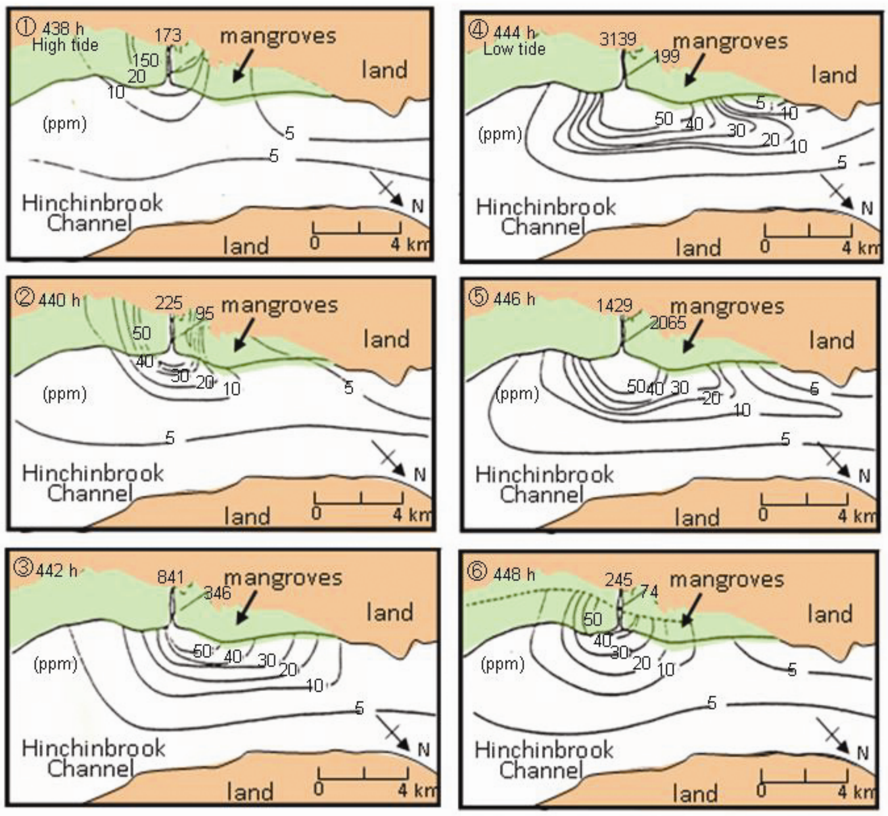

Fig. 8 Synoptic views of the predicted contaminant concentration cloud (ppm) at two-hour intervals during a tidal cycle (after Wolanski *et al*., 1990).
The contaminant cloud stays trapped along the mangrove-fringed coast at and around low tide (③–④–⑤), and is pushed back into the mangrove swamps through a tidal creek at high tide (①). This behavior is unique to tidally inundated coastal area with mangrove vegetation.

mechanisms that control water properties have been investigated, based on field measurements and numerical simulations (Mazda *et al.*, 2007a). The diffusivity of water properties along creeks is increased by the tidal trapping effect (see Fig. 3) by two orders of magnitude from its value in the absence of swamps. The material transport mechanisms have been discussed by Wolanski (1992) and Ridd *et al.* (1997) for the R-type, by Wolanski *et al.* (1990) for the F-type, and further by Twilley *et al.* (1986), Mazda *et al.* (1990a) and Susilo *et al.* (2005) for the B-type.

The mangrove ecosystem is affected by the open sea due to diurnal or semi-diurnal tidal actions, while the mangroves affect the ecosystem of the adjacent coastal waters (Fig. 9). This interaction between mangrove forests and the open sea is mainly achieved through tidal creeks in R-type topography, occurs directly in the F-type, and via groundwater flow in the B-type.

Tidal flow processes within creeks were described in Section 2.2. The role of tidal creeks in enabling the exchange of material such as nutrients, dissolved oxygen and mangrove litter between mangroves and coastal waters has been described by Woodroffe (1985a, b), Wolanski and Ridd (1986) and Wolanski *et al.* (1990).

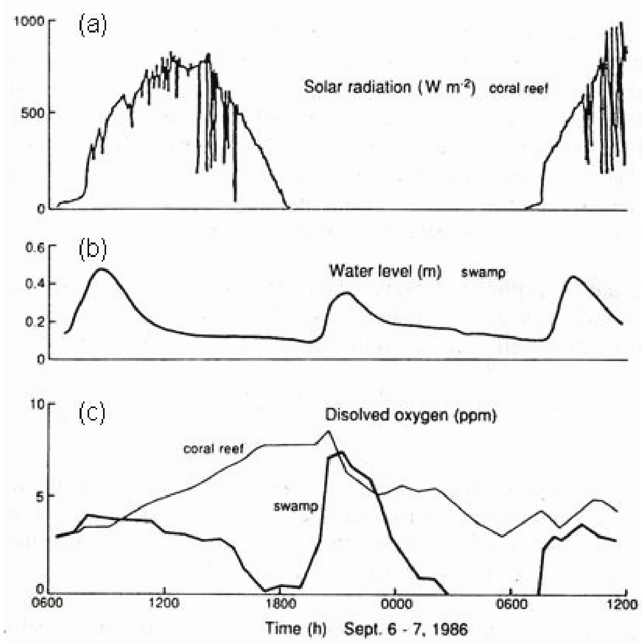

Fig. 9 Time series plots of (a) solar radiation, (b) sea level in a swamp and (c) dissolved oxygen concentrations in the swamp and neighboring coral reef in the Bashita-Minato mangrove area, Iriomote Island, Japan (after Mazda *et al.*, 1990b).

The DO in the swamp rose sharply at the commencement of the flood tide (20:00) and fell slowly thereafter until anoxic conditions were reached, irrespective of solar radiation. The DO at the reef had a diurnal cycle with a minimum value in the early morning and a maximum in the evening close to sunset, resulting from the biological activity of corals and algae due to respiration at night and photosynthesis after sunrise, respectively. It is understood that the DO from the reef strongly influences that of the swamp, which influences aquatic or benthic organisms in the swamp.

In this observation, the flood tide happened in the evening (20:00) and early morning (08:00) when the DO in the reef was at its maximum and minimum values, respectively. This suggests that if the flood tide happens several hours before or after the occurrence of a maximum in DO, the swamp will not record such high values of DO. In turn, the interrelationship between oxygen production at the reef and tidal transport processes into the swamp controls biotic activity in the mangrove swamp.

3.3 Atmospheric and terrestrial processes affecting mangrove ecosystems

Mangrove hydrodynamicists tend to neglect the effects of atmospheric elements such as sunlight, rain, evaporation, air temperature, humidity and wind on mangrove ecosystems, as they often assume that these elements are unimportant compared to the influence of hydrodynamic elements. This assumption may be made in part because the thick canopies of mangroves appear to separate the swamp area from the lower atmosphere and to self-generate a microclimate under the mangrove canopy.

Wattayakorn *et al.* (2000), however, emphasized the influence of river discharge, which varies with seasonal rainfall, on both water properties and biogeochemical processes that occur within mangrove estuaries, based on their observations. Ridd and Stieglitz (2002) stated that the formation of a salinity maximum zone in creeks due to effects of rain and evaporation affects mangrove species assemblages (Fig. 10). Wolanski (2006) discussed quantitatively the function of mangrove canopies in absorbing wind energy and intercepting the transport of salt spray to inland areas behind mangrove forests. Based on these findings, he stressed that the mangrove environment should be understood in the total ecosystem that comprises the river basin, rivers, and estuarine/coastal waters, forming a "total eco-hydrology" system that should be considered using a holistic approach.

3.4 Feedback relationships maintaining the mangrove environment

As shown in Fig. 1, four factors, namely biota, sediment topography, water flow and atmosphere, play important roles individually in forming and maintaining the mangrove environment. Further, every factor interacts with one of other factors. For example, the biology drives the physics of mangroves; the amount of water that inundates mangrove swamps depends on vegetation density in mangrove swamps, because the vegetation resists water inundation. On the other hand, the physics drives the biology in mangroves: the growth of mangrove trees and their zonation patterns depend strongly on the tides and the elevation of the substrate or the flooding frequency, duration of inundation and water depth due to tidal action (Watson, 1928).

Further, it should be recognized that all of these interactions between two arbitrary factors construct the feedback system for maintaining the mangrove ecosystem, as follows. The water flow associated with tides and rainfall helps to supply nutrients to mangrove trees. The mangrove trees, which grow with the help of solar radiation, deposit their decayed leaves around the bottom substrate as sediment, which leads to the establishment of landforms. The landform or topography modifies the water flow with their drag force.

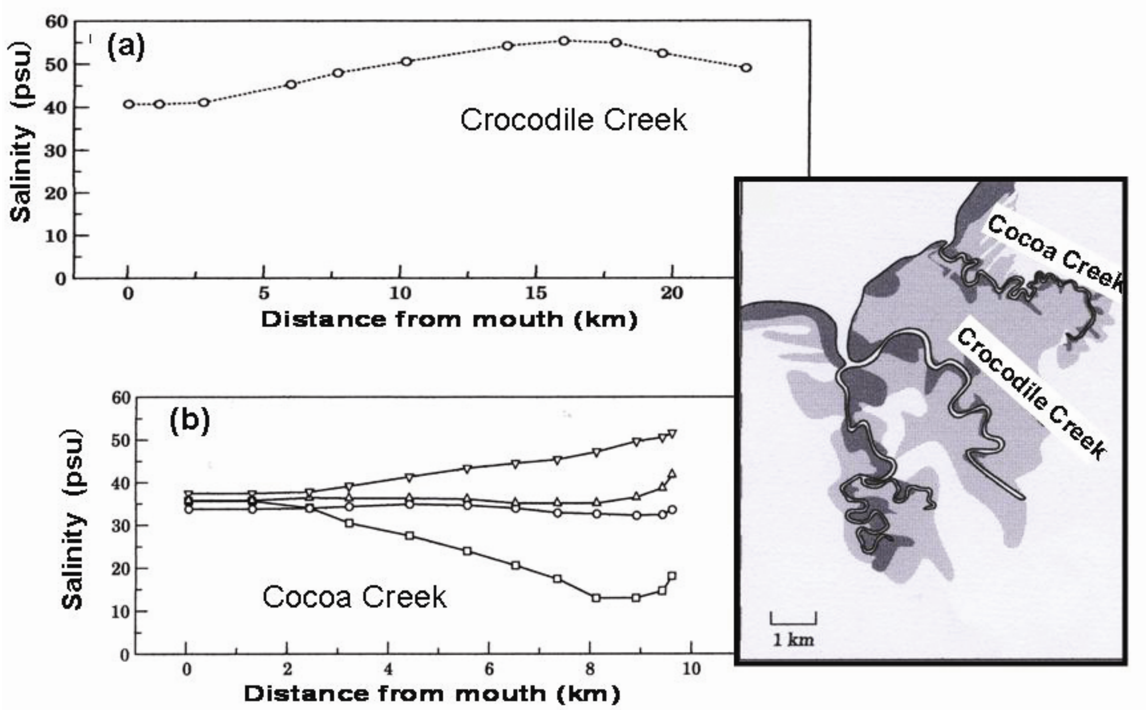

Fig. 10 Changes in salinity following major rainfall events in Cocoa Creek and Crocodile Creek, Australia (after Ridd & Stieglitz, 2002).

(a) The salinity is higher throughout the length of the creek than at the creek mouth. The salinity maximum zone in the creeks, which is affected by rain and evaporation, forms density currents, isolating the upper reaches of the estuary from the coastal waters.
(b) The creeks became completely hypersaline within one month after rainfall in late August 1998. □ 3 Sept. 1998; ○ 10 Sept. 1998; △ 16 Sept. 1998; ▽14 Oct. 1998
Both (a) and (b) suggest the strong influences of rain and solar radiation on water properties in mangrove areas.

Large numbers of tidal creeks supply various materials such as seawater, nutrients, dissolved oxygen, and fish eggs/larvae to the innermost area of the swamp. On the other hand, tidal creeks and their tributaries have been formed by the actions of tidal waters, mangrove vegetation and so on, as described in Section 3.1. The network of tidal creeks and their tributaries (see Fig.7) seems to show the result of these feedback actions. This network is similar to the capillary vessels in human bodies; that is, the network appears to sustain the natural mangrove ecosystem in the same manner as capillary vessels in human bodies sustain human activity. In turn, the mangrove ecosystem utilizes the physical systems in order to preserve the natural environment.

Aquaculture farms have been developed under these natural feedback systems (Hong, 2006; Perillo *et al.*, 2009). However, there are concerns that their artificial development may destroy the natural feedback system, resulting in a feedback that leads to the degradation of the aquaculture farms themselves.

4. In Order to Preserve and Utilize the Mangrove Environment

As described above, mangrove ecosystems are established as "total eco-hydrology." Total eco-hydrology is formed spatially by interactions among terrestrial, estuarine, coastal and offshore areas. It evolves via intertwining nonlinear interactions among biological, chemical and physical factors, each of which has different spatial and temporal scales. Thus, in order to understand the mangrove ecosystem as a whole, to preserve it, and to ensure that human activity is in harmony with it, interdisciplinary studies involving various study fields should be put into practice.

To understand nonlinear interactions among biological, chemical and physical factors, it is necessary to conduct joint studies involving researchers with different areas of expertise, especially simultaneous field work at a common site; such works have never been executed hitherto. Moreover, these interdisciplinary studies should be continued successively in the future, as ecosystems with long time scales respond to physical actions with short time scales, which are integrated in the ecosystem over the course of decades.

Furthermore, such interdisciplinary studies should be organized at an international level. This is because mangroves are distributed globally, whilst their ecosystems vary locally, depending on unique physical processes which differ locally according to the site.

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