Part I

Outline of the Physical Processes within Mangrove Systems
Chapter 1

Introduction

A mangrove is defined as an assemblage of trees and shrubs that grows in the intertidal areas of estuaries, deltas, backwater areas, and lagoons in tropical/sub-tropical regions almost exclusively within 30° of the equator (Plate 1). The total area of mangroves throughout the world is ca. 181 x 10^3 km^2 (Spalding et al., 1997). This is equivalent to just 1.0% of the global area of tropical forests; however, as mangrove forests cover approximately 75% of the world's tropical coastline (Por, 1984; Wong and Tam, 1995), they are important as a source of wood and food, a form of coastal protection in tropical/subtropical regions, and a vital component of the earth's natural environment (Robertson and Alongi, 1992; Hong and San, 1993). Since the late 19th century, human activities have led to the destruction of mangrove forests around the globe (Spalding et al., 1997). This degradation seriously threatens the sustainability of mangrove ecosystems worldwide and has also adversely affected human populations. This is particularly the case in Southeast Asia where the deforestation of mangrove areas has led to large-scale coastal erosion that seriously impacts upon the livelihood and even the lives of coastal people (Hong and San, 1993; Mazda et al., 2002 [9.5]*; Hong, 2006).

Biotic activity within mangrove forests, where the trees are the central feature of the ecosystem, has led to the development of unique substrate (bio-geomorphology; see Section 5.1 for details) in intertidal areas. Colonies of mangroves have developed under the influence of a range of physical factors such as strong tidal flows and dramatic changes in the environment that accompany alternating flooding and drying of the habitat. In turn, mangroves are sensitive to several environmental gradients that respond either directly or indirectly to particular landform patterns and physical processes (Woodroffe, 1992; Mazda and Kamiyama, 2007 [2.4]).

Since Watson (1928) first demonstrated a correlation between the tidal regime and the species zonation of mangroves in Malaysia, physical processes such as tidal regime and the elevation of bottom substrate have become increasingly recognized as important factors in the structure of mangrove ecosystems (Chapman, 1944; Lugo and Snedaker, 1974; Carlson et al., 1983; Bunt et al., 1985); however, the recognition of these relationships has been qualitative rather than quantitative. As a fundamental condition for the existence of mangroves and for the co-existence of humans and natural ecosystems in coastal mangrove regions, it is necessary to obtain a quantitative understanding of the physical processes and hydrodynamic mechanisms that take place in these intertidal areas (Wolanski et al., 1992a; Mazda et al., 1999 [9.2]).

According to Snedaker and Snedaker (1984), a total of 7000 scientific articles on mangroves had been published up to 1984; however, the overwhelming majority of the listed titles deal with the floristics, phytosociology, and occasionally the physiology of the principal mangrove tree species. In this regard, Por (1984) referred to the old saying that 'one does not see the forest for

*Numbers in square brackets ([ ]) indicate the article number in Part II.
the trees.’ The physical processes that occur within a mangrove swamp are every bit as important as the individual trees and associated biology of the area.

In Asian countries, where many mangrove forests have been extensively degraded and even completely destroyed, interdisciplinary research on mangrove ecosystems with the aim of ecosystem conservation has been carried out since 1983. This research was supported by the United Nations Development Program (UNDP) and UNESCO (Nakamura, 1992); however, physical scientists and oceanographers were not involved in this project. Although the importance of physical processes within total mangrove ecosystems is stressed in the book Hydrology of the Mangal: The Ecosystem of the Mangrove Forests (Por and Dor, 1984), few significant examples of physical research can be found in the book. The first study of physical processes in mangrove areas was probably that of Wolanski et al. (1980 [1.1]), and the first synthesis of the role of physical processes in shaping mangrove ecosystems was published in the book Tropical Mangrove Ecosystems (Wolanski et al., 1992a). Since then, a steady stream of publications has emerged on the role of physical processes and hydrodynamics in mangrove ecosystems (Wong and Tam, 1995); however, even today, research on physical processes is limited compared with the amount of research that focuses on biological aspects of mangrove ecosystems. Physical processes are thus generally under-evaluated in terms of the factors that comprise the mangrove ecosystem (Research Institute for Subtropics, 2003).

Within the quarter of a century following the first study of physical mangrove processes published by Wolanski et al. (1980 [1.1]), many phenomena and mechanisms of mangrove hydrodynamics have been studied and are now largely understood, but there remains considerable work to be undertaken; the priorities for future research in this area are summarized in the next chapter and described in detail in following chapters.

The most important purpose of this book is to provide a manual of the preservation and utilization of the mangrove environment from a physical standpoint. Accordingly, Part I outlines the physics of mangroves in relation to the mangrove environment or ecosystem, and Part II provides the results of detailed research undertaken by the authors that directly relates to the material outlined in Part I.

Part I of this book is organized as follows. The present state of mangrove physics is summarized in Chapter 2. Chapter 3 lists the important physical factors that shape the mangrove environment. The physical mechanisms composed of these factors that affect the mangrove environment are described in Chapter 4. The importance of feedback processes between physical, biological, and topographical processes are discussed in Chapter 5. Research methodology that is unique to mangrove areas is reviewed in Chapter 6, and the modeling methods used for mangrove systems are described in Chapter 7. Finally, Chapter 8 describes a number of studies that need to be carried out to ensure a sufficient science-based knowledge to enable the preservation and ecologically sustainable exploitation of fragile mangrove environments. Readers are encouraged to study individual chapters separately as desired. To accommodate this, there is minor duplication between chapters.
Chapter 2

Present State of Mangrove Studies from a Physical Viewpoint

2.1. Studies of hydraulic systems that are unique to mangrove areas

2.1.1. Tidal flow

Among the various types of water movement within mangrove areas, tidally driven currents are crucially important. The physical environment that supports mangrove ecosystems is basically formed by the tidal motion of seawater with a diurnal or semi-diurnal period, although the tide does deform significantly in mangrove swamps due to the high density of mangrove trees and roots (Mazda and Kamiyama, 2007 [2.4]). Watson (1928), Lugo and Snedaker (1974) and Bunt et al. (1985) proposed that the mangrove community is tolerant of tidal inundation and the periods of inundation and salinity that accompany tidal inundation. Based on field observations and from the perspective of the preservation of mangrove ecosystems, Boto and Bunt (1981), Woodroffe (1985a, b) noted the importance of the material exchange between mangrove areas and the open sea that accompanies tidally reversing flows.

The momentum equations applicable to tidal motion in the peculiar landforms of mangrove areas were first proposed by Wolanski et al. (1980 [1.1]), who applied the equations to Coral Creek, Hinchinbrook Island, Australia (E in Plate 1), which comprises a long meandering tidal creek and wide fringing mangrove swamps. Uncles et al. (1990), Ong et al. (1991), Dyer et al. (1992) and Medeiros and Kjerfve (1993) analyzed hydrodynamics in mangrove creeks from the physical viewpoint of water-exchange between mangrove areas and the open sea. Woodroffe (1985a, b) and Kjerfve (1990) noted that the tidal flow in creeks is strongly dependent on the amount of water that enters the mangrove swamp during the flood tide. Wolanski and Ridd (1986 [5.2]), Ridd et al. (1990 [1.2]) and Mazda et al. (1995 [1.3]) used schematic models to investigate the interrelation between tidal flow in creeks and tidal inundation into fringing mangrove swamps. Based on observational results in various field areas, Mazda et al. (1997a [2.1]), Kobashi and Mazda (2005 [2.2]) and Mazda et al. (2005 [2.3]) formulated mangrove hydrodynamics to include tidal creeks and fringing mangrove swamps.

2.1.2. Sea waves—tsunamis

Sea waves that intrude into mangrove forests from offshore areas are another important physical factor that influences the mangrove environment. Field studies of wave reduction due to mangrove vegetation, which can be utilized for coastal protection in tropical regions (Hong and Dao, 2003; Hong, 2004), were undertaken by Sato (1978), Mazda et al. (1997b [3.2]), Furukawa et al. (1997 [3.1]), Massel et al. (1999), Sato (2003) and Mazda et al. (2006 [3.3]). Sato (1978) pioneered studies of the morphological characteristics of mangrove roots from a hydraulic and geophysical viewpoint, and demonstrated the relationship between the number of prop roots and
their heights above ground level. The author summarized the unique characteristics of the prop roots of *Rhizophora* sp., from field measurements undertaken on Ishigaki Island, Japan (A in Plate 1). However, the quantitative mechanisms of wave reduction are not yet well understood because of both the complicated vertical configuration of mangrove trees and differences in vegetation density and structure between species. It should also be recognized that these findings are limited to short-period waves such as sea waves with a period of less than 30 sec at most. In particular, these findings cannot be applied to tsunami waves (seismic sea waves) with periods between 10 minutes and 1 hours, such as the waves that recently destroyed many coastal areas or alternatively were mitigated by mangrove trees along the coastline facing the Indian Ocean (Mazda *et al.*, 2007 [3.4]).

Many studies have examined the hydraulic behavior of tsunami waves upon reaching the coast (Iida and Iwasaki, 1983; Hebenstreit, 1997; Satake, 2005). These studies, however, are not applicable to mangrove areas. A welcome exception to this trend is the work of Hamzah *et al.* (1999) and Hiraishi and Harada (2003), who conducted experiments on the drag force on mangrove trees by taking into consideration the vertical configuration of trees. Mazda *et al.* (2007 [3.4]) discussed the unique role of mangrove forests and their vertical configuration in protecting human lives from tsunamis. Mangrove forests absorb much of the energy of tsunamis, sustaining considerable damage that would otherwise occur on the coastline. The mangrove can thus be regarded as a sacrificial protection fringe.

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

### 2.1.3. Groundwater flow

Water flow involves 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 groundwater flow in determining soil properties and maintaining mangrove ecosystems has been clearly documented from field observations undertaken by Wolanski and Gardiner (1981 [5.1]), Bunt *et al.* (1985), Wada and Takagi (1988), Mazda *et al.* (1990a [7.1]), Baltzer *et al.* (1994), Ridd (1996 [7.2]), Ridd and Sam (1996 [8.1]), Ridd *et al.* (1997 [4.3]), Sam and Ridd (1998 [8.2]), Hughes *et al.* (1998), Stieglitz *et al.* (2000a [9.3]), Susilo (2004), Susilo and Ridd (2005 [8.4]), Susilo *et al.* (2005 [7.5]) and Mazda and Ikeda (2006 [7.6]). For example, Stieglitz *et al.* (2000a [9.3]) and Susilo (2004) in particular reported that a high density of crab holes supports water/material permeability and modifies soil properties. Mazda and Ikeda (2006 [7.6]) proposed the dependence of permeability within mangrove swamps on topography. However, details of physical behavior and hydraulic mechanisms are not well understood, and a more detailed quantitative evaluation of groundwater flow needs to be undertaken. In particular, the rates and pathways of flow have only been studied in a limited number of mangrove setting. Rates of flow may vary significantly from site to site, depending upon mangrove or crab species, topography, and sediment type. The pathways of groundwater flow can be due to flow in soil layers below the top layer that is often populated with crab burrows, or the flow can go between the burrows in the surface layer.

Ridd and Sam (1996 [8.1]), Hollins *et al.* (2000) and Stieglitz *et al.* (2000b [8.3]) devised unique instruments that are convenient to use in measuring various properties of groundwater and in detecting the enhancement of this flow through animal burrows.

### 2.2. Studies of the mangrove environment from a physical viewpoint

#### 2.2.1. Water properties that depend on physical processes

Water properties such as temperature, salinity, dissolved oxygen, and nutrient concentrations provide direct and indirect support for the natural mangrove environment. Wolanski and Ridd
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(1986 [5.2]), Ridd et al. (1990 [1.2]), Wattayakorn et al. (1990 [4.2]) and Mazda et al. (1990a [7.1]) demonstrated that 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.

Furthermore, these water properties also depend on the peculiar topography of mangrove areas. In riverine forest-type mangrove areas, which are composed of tidal creeks and fringing mangrove swamps (defined as R-type forests in Section 3.1; Fig. 3.1a), the water properties and hydraulic mechanisms that control water properties have been investigated by Wolanski and Ridd (1986 [5.2]), Ridd et al. (1990 [1.2]), Wattayakorn et al. (1990 [4.2]), Wolanski et al. (1990 [5.3]), Wolanski et al. (1992b [6.1]), Ridd et al. (1997 [4.3]) and Nihei et al. (2004), based on field measurements and numerical simulations. However, for F-type forests, which directly face the open sea (see Fig. 3.1b), and for B-type forests, which are impounded depressions during the dry season (see Fig. 3.1c), there are few studies of water properties from a physical viewpoint. The notable exceptions are the studies of Wada and Takagi (1988) and Wolanski et al. (1990 [5.3]) for F-type forests and Twilley (1985), Twilley et al. (1986) and Mazda et al. (1990a [7.1]) for B-type forests.

2.2.2. Material exchange between mangrove areas and the open sea

Generally, mangrove forests are inundated by tidal water diurnally or semi-diurnally. Thus, the mangrove ecosystem is affected by the open sea, while the mangroves in return affect the ecosystem of the adjacent coastal waters. This interaction between mangrove forests and the open sea is mainly achieved through tidal creeks in R-type systems, occurs directly for F-type systems, and occurs via groundwater flow in B-type systems.

These tidal flow processes within creeks have been described by Wolanski et al. (1980 [1.1]), Wolanski and Ridd (1986 [5.2]), Ridd et al. (1990 [1.2]), Wolanski et al. (1990 [5.3]), Wolanski et al. (1992a), Wolanski (1992 [5.5]) and Mazda et al. (1999 [9.2]). 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 Boto and Bunt (1981), Wolanski and Gardiner (1981 [5.1]), Woodroffe (1985a, b), Wolanski and Ridd (1986 [5.2]), Wolanski et al. (1990 [5.3]), Wolanski (1992 [5.5]) and Wolanski (1995 [6.2]). Furthermore, the physical mechanisms of the exchange of these materials have been discussed by Wolanski (1992 [5.5]) and Ridd et al. (1997 [4.3]) for R-type systems, Wada and Takagi (1988) for F-type systems, and Twilley (1985), Twilley et al. (1986), Mazda et al. (1990a [7.1]), Susilo and Ridd (2005 [8.4]) and Susilo et al. (2005 [7.5]) for B-type systems.

2.2.3. Mangrove topographies that are dependent on hydraulic processes

Water currents forced by tides and sea waves are steered, channeled, and hindered by the topography of the swamps and by mangrove trees and intertwining roots (Wolanski et al., 1980 [1.1]; Mazda et al., 1997a [3.2]; Mazda et al., 1997b [2.1]; Mazda et al., 2005 [2.3]). In turn, the movement of sediment that accompanies water flow modifies the swamp topography, sometimes initiating meanders in creeks or eroding coastlines (Ridd et al., 1990 [1.2]; Mazda et al., 1995 [1.3]; Larcombe and Ridd, 1995; Wolanski, 1995 [6.2]; Furukawa and Wolanski, 1996 [6.4]; Furukawa et al., 1997 [3.1]; Ridd et al., 1998 [1.4]; Wolanski et al., 1998; Aucan and Ridd, 2000 [1.5]; Mazda et al., 2002 [9.5]; Victor et al., 2004; Brinkman et al., 2005; Winterwerp et al., 2005). For example, Wolanski et al. (1998) suggested that within a mangrove swamp fringing Hinchinbrook Channel in Australia (E in Plate 1), sediment is entrained into the swamp at spring flood tides and builds new land. Based on field studies in Sawi Bay, Thailand (I in Plate 1), Brinkman et al. (2005) stated that mangroves play a significant role in trapping fine sediment, building new land and further sheltering ecosystems from excessive turbidity and sedimentation. However, as stated by Sato (2003), the quantitative mechanisms of sedimentation in mangrove swamps have yet to be
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fully investigated.

Many mangrove areas form a remarkable fractal pattern due to innumerable tidal creeks and sub-creeks or tributaries, as shown in Fig. 5.3(b) and Plate 1 (the upper right). The flow mechanism within the network of interacting tidal creeks has yet to be investigated. Furthermore, the mechanisms and physical processes that form these creeks in mangrove areas have received little scientific scrutiny, although the equivalent mechanisms for salt marshes have been studied (Chapman, 1960; Pethick, 1992; Perillo et al., 1996). Since Horton (1945), quantitative geology of drainage basins and channel networks in inland areas have been studied (e.g., Strahler, 1964). However, the mechanism to form channel networks in mangrove areas seems to be different from that in inland areas due to the unique morphological and hydrological characteristics of mangrove areas such as a very gentle slope of bottom substrate, loose bottom sediment and water inundation into the area with tidal period. Based on these considerations, Yagi et al. (2007) are trying to develop a mathematical model for mangrove forest dynamics by Yagi et al. (2005), as shown in Section 2.3. On the other hand, Perillo et al. (1996) discussed the formation mechanism of creeks in relation to the dominant wind in salt marshes. This mechanism cannot be applied to mangrove areas, as there is little wind in mangrove swamps, but it could be important at the first stage of the colonization of mangroves; consequently, mangrove creeks may well be historical remnants of earlier formation mechanisms. The degree of similarity or dissimilarity between the formation of tidal creeks in mangroves and salt marshes remains unknown.

2.2.4. Atmospheric and terrestrial processes that affect the mangrove environment

Mangrove hydrodynamicists often tend to neglect the effects of atmospheric parameters such as sunlight, rain, evaporation, air temperature, humidity, and wind on mangrove ecosystems, as they often assume that these are unimportant compared to the influence of hydrodynamic parameters. 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 within the mangrove canopy. Thus, the physical parameters that operate within and upon mangrove swamps have been poorly studied, although Wolanski (1986 [4.1]), Kjerfve (1990), Wattayakorn et al. (1990 [4.2]), Mazda et al. (1990b [5.4]), Mederios and Kjerfve (1993), Ridd et al. (1997 [4.3]), Hollins and Ridd (1997), Ridd and Stieglitz (2002 [4.4]) and Wolanski (2007) suggested that they might be important in mangrove environments.

Wolanski (2007) examined the feature of wind blowing over the height of tree canopies. The author estimated the effect of such wind on the defoliation, snapping, and overturning of mangrove trees during typhoons and tsunamis. With reference to the study undertaken by Takle et al. (2006), Wolanski (2006) also discussed quantitatively the function of mangrove tree canopies in absorbing wind energy and intercepting the transport of salt spray to inland areas behind mangrove forests.

Based on observations at Klong Ngao, Thailand (I in Plate 1), and in Sawi Bay, Thailand (I in Plate 1), Wattayakorn et al. (1990 [4.2]) and Wattayakorn et al. (2000) emphasized the influence of river discharge, which varies with seasonal rainfall, on both water properties and biogeochemical processes that occur within mangrove estuaries. Wolanski and Cassagne (2000) stated that in the mangrove-fringed Konkoure River delta, Guinea (M in Plate 1) hypersalinity occurs due to large seasonal variation of river discharge so that these areas appear unsuitable for rice farming. According to this research, Wolanski (2006) stressed that the mangrove environment should be understood as a component of the total ecosystem that comprises the river basin, river, and estuarine and coastal waters, forming an ecohydrology system that should be considered using a holistic approach.
2.2.5. Feedback relation between physical and ecological processes

Physical processes, especially processes of water movement such as tidal flow and sea waves, are important in maintaining the mangrove ecosystem. Water circulation and the dispersion of material in mangrove swamps control biodiversity and maintain mangrove colonies (Wolanski, 1989; Mazda et al., 1990a [7.1]; Mazda et al., 1999 [9.2]; Wolanski et al., 2001; Bryce et al., 2003 [6.5]; Sato, 2003). Vertical density gradients within tidal creeks strongly influence the dispersion of mangrove seeds (Ridd et al., 1998 [1.4]; Stieglitz and Ridd, 2001; Kuwabara, 2002). Excess sedimentation at the mouths of tidal creeks can inhibit water exchange between mangrove areas and the adjacent open sea, resulting in the degradation of the mangrove ecosystem (Wolanski et al., 1980 [1.1]; Mazda et al., 1990b [5.4]). The structural and phenological variability of mangrove forests results from feedback processes or interactions between biology and hydraulics, including the frequency of tidal inundation, tidal prism volume, and the duration of inundation at long time scales (decades), as described in Chapter 5 (Bunt et al., 1985; Mazda et al., 1990b [5.4]; Mazda and Kamiyama, 2007 [2.4]).

Large numbers of tidal creeks help to supply various materials such as seawater, nutrients, dissolved oxygen, and fish eggs/larvae to the innermost area of the swamp. They also help to export anoxic water and humus soil to offshore areas. The network of these creeks in mangrove areas is similar in appearance to the capillary vessels in human bodies; that is, the network appears to sustain the natural mangrove ecosystem. Furthermore, this system appears to play a key role in the preservation of aquaculture farms established within mangrove forests (Mazda, unpublished data for Majagual in Esmeraldas, Ecuador (N in Plate 1), and for Thanh Phu, Vietnam (J in Plate 1)). These farms require significant water exchange between the farm pond and the open sea through tidal creeks (see Fig. 4.7; Hong and San, 1993). On the other hand, the development of the farm ponds tends to close the creek mouth, as described in Section 5.2 (Wolanski, 2006). A quantitative evaluation of the network of tidal creeks has yet to be undertaken.

2.3. Modeling-based studies of mangrove areas

Riverine-type mangrove forests comprise tidal creeks and mangrove-vegetated swamps. To assess the interaction between a tidal creek and fringing mangrove swamps, Wolanski et al. (1980 [1.1]) used linked 1-dimensional (for the tidal creek) and 2-dimensional (for the mangrove swamp) numerical models to simulate tidal flow distribution in a mangrove area around Coral Creek, Hinchinbrook Island, Australia (E in Plate 1). Applying the concept of material trapping in an embayment that has been proposed by Okubo (1973), Wolanski and Ridd (1986 [5.2]) and Ridd et al. (1990 [1.2]) demonstrated a simplified analytical model that material dispersion in R-type forests is controlled primarily by the tide-driven trapping within the swamps. As seen in Fig. 4 in [9.2] and Fig. 7 in [5.2], the tidal trapping is the process of temporary water storage in the swamp at rising tide when swift tidal currents prevail in the creek. 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 (see the lower right picture in Plate 2).

Mazda et al. (1995 [1.3]), Mazda et al. (2002 [9.5]) and Nihei et al. (2004) used horizontal 2-dimensional numerical mesh models to simulate the tidal-scale hydrodynamics of a creek–mangrove swamp system. To discuss the detailed flow in riverine-type mangrove areas with meandering tidal creeks, Nihei et al. (2004) applied a nesting procedure in the Fukido-Gawa mangrove area, Ishigaki Island, Japan (A in Plate 1). In the nesting model simulation the authors used three computational domains with different grid resolutions: large-, intermediate-, and small-scale domains. Furthermore, Nihei et al. (2001) developed a two-way nesting procedure that overcomes difficulties in the treatment of open boundary conditions.
Massel et al. (1999) proposed an analytical model for use in analyzing the dissipation of wave energy in mangrove forests. Furthermore, Mazda et al. (1997b [3.2]) and Mazda et al. (2006 [3.3]) parameterized the drag force against sea waves as a function of thick mangrove tree trunks, leaves, and emergent roots, based on their observations of a *Kandelia candel* forest and a *Sonneratia caseolaris* forest within the Tong King delta, Vietnam (B in Plate 1).

Mazda et al. (1990a [7.1]) and Susilo (2004) developed analytical models for groundwater flow in mangrove swamps on the assumption of homogeneous and isotropic soil. On the other hand, Heron and Ridd (2001 [7.3]) and Heron and Ridd (2003 [7.4]) analyzed the hydrodynamics of groundwater within animal burrows in mangrove swamps, based on a computational simulation model and a laboratory experiment, respectively. Further, from a practical viewpoint Susilo and Ridd (2005 [8.4]) proposed a simple mathematical model of animal burrows to measure the hydraulic conductivity of mangrove sediment.

The substrate of mangrove swamps commonly consists of cohesive sediment (mud). This sediment is periodically deposited and resuspended by tidal currents and sea wave currents in a process that is linked to turbulence generated by the interaction between the currents and vegetation. Thus, the swamp topography deforms as a result of these interactions. Furukawa and Wolanski (1996 [6.4]), Furukawa et al. (1997 [3.1]) and Sato (2004) discussed these relations; however, there are no models that consider the formation or deformation of the topography of mangrove areas. From a mathematical standpoint, Yagi et al. (2005) and Yagi et al. (2007) are trying to form a model for understanding the mechanism of formation of a remarkable fractal pattern due to networks of tidal creeks and their tributaries in mangrove forests. The authors intend to apply a general idea of the “self-organization”, in which the remarkable pattern must be formed by the feedback interactions among mangrove vegetation, soils and water flow (see Plate 2), and which has been developed in fields of physics and biology (e.g., Yagi et al., 2007). Furthermore, they state that in the study of forest kinematic model, the numerical simulations on the basis of suitable mathematical models are one of indispensable methods because the models naturally contain very strong nonlinear terms. Their mathematical approach is expected to explain the process of development of the mangrove geo-ecosystem, which forms the unique fractal pattern with numerous meandering tidal creeks, and to clarify the roles played by the quite different kinds of constituent elements, i.e., mangrove vegetation, soils and water flow.

Wattayakorn et al. (2000) used a multiple-box model to estimate the net fluxes of nutrients within a mangrove estuary at Sawi Bay, Thailand (I in Plate 1). Mazda et al. (1999 [9.2]) discussed the recovery and degradation of mangrove colonies after thinning or deforestation, based on a simplified model experiment that involved the dispersal of material due to the tidal trapping effect, which has been proposed by Wolanski and Ridd (1986 [5.2]). Chong et al. (1996) applied a horizontal two-dimensional diffusion model to explain the distribution of prawn larvae spawned at northern Klang Strait in Malaysia (I in Plate 1), in which the larvae were assumed to be passive and non-buoyant. The result showed that the distribution is due to principally tidal currents and lateral trapping in mangrove-fringed tidal creek. Wolanski et al. (1998) developed a hydrodynamics–sedimentation model for mangrove areas fringing Hinchinbrook Channel, Australia (E in Plate 1), and concluded that the mangroves play a significant role in trapping fine sediment, thereby building new land and sheltering adjoining waters and marine ecosystems, including seagrass, from excessive turbidity and sedimentation. Wolanski et al. (2006) proposed an ecohydrology model that combines the hydrodynamic model and the food-web model for mangrove estuaries. The authors applied the model to the ecosystem in Darwin Harbor, Australia (H in Plate 1), and demonstrated that the mangroves are essential in maintaining the local fisheries.
Chapter 3

Physical Factors that Shape Mangrove Environments

3.1. Classification of mangrove landforms

The landforms of mangrove areas are defined in various ways by different researchers, depending on their purposes (Lugo and Snedaker, 1974; Thom, 1982; Cintron and Novelli, 1984; Woodroffe, 1992). In this book, we use the scheme provided by Cintron and Novelli (1984), as this classification is convenient in discussing the hydraulics of mangrove areas.

Cintron and Novelli (1984) modified the classification scheme for mangrove landforms proposed by Lugo and Snedaker (1974) into three types based on topographic features: fringe forest, riverine forest, and basin forest, as shown schematically in Fig. 3.1.

a. RIVERINE FOREST (R-type; Fig. 3.1a): This type of landform is defined as floodplains alongside river drainage channels or tidal creeks, which are inundated by most high tides and exposed during low tides. As evident in Fig. 5.3(b) and Plate 1 (the upper right), most tidal creeks run perpendicular to the coastlines at the creek mouth, are highly sinuous, and intertwine with other creeks. Sea waves rarely propagate into the swamps because of the dissipation of wave energy along the long tidal creeks. Swamp water close to the tidal creek is dragged by tidal flow in the creek, thus flows parallel to the creek, whereas flow in the swamp is predominantly perpendicular to the creek due to the gradient in the water surface between the swamp and the creek (Kobashi and Mazda, 2005 [2.2]; Mazda et al., 2005 [2.3]).

b. FRINGE FOREST (F-type; Fig. 3.1b): This landform comprises swamps along shorelines that face the open sea and are directly exposed to the action of both tidal water and sea waves. Sea waves are mitigated in swamps because of the resistance of thick mangrove trees and emergent roots (Mazda et al., 1997b [3.2]; Massel et al., 1999; Mazda et al., 2006 [3.3]).

c. BASIN FOREST (B-type; Fig. 3.1c): This landform comprises partially impounded depressions that are seldom inundated by high tides during the dry season, but are inundated by spring high tides during the wet season (John and Lawson, 1990). During the dry season, the water level in the depressions continues to slowly fall because of groundwater flow to the open sea driven by the difference in water level between the depression and the open sea (see Fig. 5 in [7.1] and Fig. 5 in [5.4]). The groundwater that slowly leaves and enters the swamp with tidal action exchanges various materials between the swamp and the open sea and vertically mixes the bottom water in the depression (Mazda et al., 1999a [7.1]; Mazda et al., 1999b [5.4]).

The different forms of the three mangrove types mean that the dominant water movements are different between these systems, resulting in different influences within the different ecosystems.
3.2. Bottom conditions of mangrove swamps

As Wolanski et al. (1992a) show, the bottom slopes of mangrove swamps are very gentle (ca. 1/1000), although there are innumerable local depressions or small holes formed by bioturbation and water eddies that develop behind mangrove roots and trunks. Furthermore, mangrove trees and their roots occupy a large proportion of the bottom area of swamps (Plate 3), as mentioned in the next section. Underground, there are many macropores related to animal burrows and decayed roots. According to Stieglitz et al. (2000a [9.3]), approximately 10% of the total volume of the bottom sediment to a depth of ca. 1 m in a Rhizophora forest at Gordon Creek, Townsville, Australia (F in Plate 1), is composed of animal burrows that are intermingled but not interconnected (Susilo, 2004).

Soils within mangrove swamps are rich in organic clay and humus because of biotic action in the mangrove ecosystem. According to Mazda and Ikeda (2006 [7.6]), the particle size of sediment within the mangrove swamp that fringes the Maira-Gawa, Iriomote Island, Japan (A in plate 1), is an order of magnitude smaller than sediment at the adjacent open coast. According to
Susilo (2004), the soil from the surface layer to a depth of ca. 1 m within a mangrove swamp at Cocoa Creek, Cleveland Bay, Australia (F in Plate 1), is mainly composed of organic clay made up of particles smaller than 10 µm.

It is generally observed for R-type forests that after the tidal water above the substrate has ebbed away from the swamp to the creek, the substrate at sites near the creek dries rapidly, while at sites far from the creek, in F-type swamps and at the open coast outside the mangrove area, the substrate remains wet (Mazda and Ikeda, 2006 [7.6]).

3.3. Physical characteristics of mangrove vegetation

As is apparent in Plate 3, mangrove roots are very dense in swamps. They emerge vertically from the soil (Sonneratia, Avicennia, Laguncularia, Bruguiera, and Lumnitzera) or take the form of prop roots (Rhizophora). In addition, thickly vegetated mangrove canopies cover swamps. These vertical configurations perform a variety of roles: The canopies moderate atmospheric influences and the roots resist water flow, although mangroves are influenced physiologically by atmospheric and hydrological conditions such as sunlight, humidity, tidal flow, sea waves, and salinity (Snedaker, 1989).

The vegetation density is greater in the vicinity of the bottom substrate of the swamp, though each mangrove species has a unique configuration (see Plate 3). As shown in Fig. 3.2, the control volume in a mangrove swamp \( V \) (a hatched rectangular element) with a horizontal area \( S(\Delta x \Delta y) \) and a depth \( H \) is divided into two parts,

\[
V = V_M + V_W
\]  
(3.1)

where \( V_M \) is the total volume of obstacles, which is composed of submerged tree trunks and roots over the substrate, and \( V_W \) is the volume of water in \( V \). \( V_M \) is not very small compared to \( V_W \) and cannot be disregarded, particularly at small depth (Fig. 3.3a; Mazda et al., 1997a [2.1]). Mazda et al. (2005 [2.3]) modified a proposal of Wolanski et al. (1980 [1.1]) and defined the characteristics of the vertical configuration of mangroves by the representative length scale in mangroves \( L \):

\[
L = \frac{V_W}{A}
\]  
(3.2)
Figure 3.3. (a) Dependence of $V_M/V$ (Mazda et al., 1997a [2.1]) and (b) the representative length $L$ on the water depth (Mazda et al., 2005 [2.3]) for different mangrove species.

In 3.3a,

a: Coral Creek, Hinchinbrook Island, Australia (E in Plate 1; *Rhizophora* sp.)
b: Nakama-Gawa, Iriomote Island, Japan (A in Plate 1; *Bruguiera* sp.)
c: Nakama-Gawa, Iriomote Island, Japan (A in plate 1; *Rhizophora* sp.)

In 3.3b,

a: Coral Creek, Hinchinbrook Island, Australia (E in Plate 1; *Rhizophora* sp.)
b: Can-Gio, Ho-Chi-Minh, Vietnam (J in Plate 1; *Rhizophora* sp.)
c: Maira-Gawa, Iriomote Island, Japan (A in Plate 1; *Rhizophora* sp.)
d: Rio-Chone, Manabi, Ecuador (N in Plate 1; *Rhizophora* sp.)
e: Aira-Gawa, Iriomote Island, Japan (A in Plate 1; *Bruguiera* sp.)
f: Nakama-Gawa, Iriomote Island, Japan (A in Plate 1; *Bruguiera* sp.)
g: Maira-Gawa, Iriomote Island, Japan (A in Plate 1; *Bruguiera* sp.)

where $A$ is the total projected area of the obstacles (i.e., trees and roots) to the flow in the control volume $V$. $L$ has a dimension of length and includes information on the spacing between vegetations such as mangrove trunks and roots in the swamp. Mazda et al. (1997a [2.1]) suggested that $L$ varies significantly with vegetation species and tidal elevation. Several examples of $L$ that varies with tidal level are shown in Fig. 3.3b. The tidal hydrodynamics are strongly dependent on $L$ (Mazda et al., 1997a [2.1]; Mazda et al., 2005 [2.3]). Because $L$ is defined at the macroscopic scale, the application of $L$ for hydrodynamics is not valid for the analysis of small-scale water motions such as that due to sea waves (see Section 4.5).
From the viewpoint of land protection, Sato (1978) statistically analyzed the morphological characteristics of *Rhizophora mucronata* and discussed the relationship between its spatial distribution and sedimentation. The author inferred that the root system, which concentrates near the substrate, contributes to determining the particle size distribution of the bottom sediment in the marginal and central parts of swamps. Based on field observations within mangrove forests of *Rhizophora* spp., Furukawa and Wolanski (1996 [6.4]) and Furukawa et al. (1997 [3.1]) emphasized that sedimentation associated with short-period waves such as sea waves depends upon the detailed flow pattern around the root matrix.

Below-ground roots are generally confined to a thin layer below the substrate (Komiyama et al., 1989). The radial extent of these roots and their density are comparable to that of the above-ground roots and trunks (Komiyama et al., 2000). This also has important hydrodynamic applications. For example, when a tsunami wave encounters a mangrove forest, the wave can scour the soil and uproot or snap the mangrove trees. However, the energy of the tsunami is greatly reduced because of the substantial resistance provided by underground roots that are uprooted by the tsunami itself. The result of this is that mangroves form a sacrificial barrier that helps protect the land and human settlements located behind the mangrove fringe (Mazda et al., 2007 [3.4]).

For swell waves and from field observations of a forest dominated by *Sonneratia* sp., Mazda et al. (2006 [3.3]) quantified the role of the vegetation in reducing the wave energy as the wave propagates in mangroves. Mangrove branches and leaves in the canopy are generally located above the height of the water surface, even at spring high tide. However, when the water level at spring high tide is further raised by an increase in mean sea level during the rainy season or a typhoon accompanied by large sea waves, the leaves are submerged and contribute significantly to reducing sea waves by applying a drag force to the water flow.

The wind from offshore is decreased through the height of the tree canopy. This diminishes the momentum of the air exiting the canopy and thus shelters the area downstream by a wake effect. As a result, the airflow downwind of trees creates less turbulent zones, where the suspended salt particles deposit, resulted in the significant protection against salt spray (Wolanski, 2007). Additionally, the mangrove canopy decreases the wind inside the forest and solar radiation, as mentioned in Section 2.2.4.

### 3.4. Water properties in mangrove areas

The water in mangrove areas can be divided into two types: surface water above the substrate and groundwater. Compared to surface water, groundwater is generally ignored because of the small rate of groundwater flux. However, considering the water/material permeability through innumerable macropores such as crab burrows, the role of groundwater in maintaining mangrove ecosystems cannot be ignored (Wolanski and Gardiner, 1981 [5.1]; Wada and Takagi, 1988; Ridd, 1996 [7.2]; Hughes et al., 1998; Susilo, 2004).

The two types of water contain both salt water and freshwater that originate from offshore water and river discharge, respectively. The mixing rate of these waters depends on the magnitude of tides, sea waves, river discharge, and landforms such as R-, F- and B-types (Wolanski and Gardiner, 1981 [5.1]; Wolanski and Ridd, 1986 [5.2]; Mazda et al., 1990a [7.1]; Mazda et al., 1990b [5.4]; Wattayakorn et al., 1990 [4.2]; Wolanski et al., 1990 [5.3], Wolanski et al., 2001). These water properties are further modified by chemical and biological actions as well as physical processes such as evaporation and solar radiation during residence in mangrove areas. During tidal inundation, the dissolved oxygen is commonly consumed by the soil to produce anoxic conditions; this process is dependent on the magnitude of tidal flow and sea waves. In B-type forests, the bottom water becomes anoxic and eutrophic within several days of the cessation of water exchange (see Fig. 4 in [5.4]), although the time taken for the water to become anoxic depends on the magnitude of water stratification, groundwater flow and solar radiation (see...
Figs. 5 and 6 in [5.4]; Mazda et al., 1990a [7.1]; Mazda et al., 1990b [5.4]). In some tidal creeks within R-type forests, dry-season evaporation and evapotranspiration can remove more water than is brought in from upstream areas. Consequently, the creek becomes hypersaline, resulting in the formation of a salinity maximum zone (density maximum zone) in middle of the creek (see Figs. 3.6 and 3.7). This density maximum zone inhibits the mixing of nutrient-bearing riverine water and coastal seawater (Wolanski, 1986 [4.1]; Ridd and Stieglitz, 2002 [4.4]).

3.5. Behavior of water in mangrove areas

3.5.1. Surface water in mangrove swamps

Mangrove swamps are generally a wide flooded area because of the very gentle bottom slope of the swamp (Wolanski et al., 1992a). However, the tidally flooded volume depends on both the area of the swamp and vegetation conditions such as the vegetation density and species of vegetation that form drag and viscous forces. Generally, water begins to inundate a mangrove swamp at around mean tidal level. At ebb tide, the swamp water discharges and the soil dries until the subsequent flood tide covers the swamp. Figure 3.4 shows the schematic variations in the water surface for swamps with and without mangroves during a single tidal period. The drag force of mangrove trees and roots means that the water surface in the swamp (Fig. 3.4b) behaves very differently from that without mangroves (Fig. 3.4a), especially at shallow water depths. The asymmetric change in the water surface between flood and ebb tides for the case with mangroves should be noted in comparison with the case without mangroves.

At around high tide, the water level in the swamp coincides with the tidal level in the creek or open sea (see Fig. 5.1). This means that the water surface at high tide forms a horizontal surface throughout the area. During ebb tide, the water level in the swamp gradually deviates from that in the creek. This is because of the considerable flow resistance due to the prop roots and pneumatophores of mangroves (Mazda et al., 1997a [2.1]; Mazda and Kamiyama, 2007 [2.4]). This cycle is similar for F-type and B-type forests, except for periods when B-type forest becomes ponded with stagnant water during the long dry season or for several days at neap tides (Twilley, 1985; Twilley et al., 1986; Mazda et al., 1990a [7.1]). F-type forests are further affected by the action of sea waves. R-type forests are only weakly influenced by sea waves except near creek mouths adjacent to the open sea, as bottom friction means that sea waves are reduced in size when traveling up creeks (Mazda et al., 2005 [2.3]).

Water within R-type forests consists of swamp water that floods over creek banks and creek water that enters and exits the creek with each tidal period (see Fig. 4 in [9.2]). The swamp is inundated by brackish waters that consist of a mixture of fresh water discharged from the catchment area and offshore salt water that enters through the tidal creek. The tidal flow in the swamp near the creek is predominantly parallel to the creek (Wolanski et al., 1980 [1.1]; Kobashi and Mazda, 2005 [2.2]). In contrast, within parts of the swamp that are distant from the bank of the creek, water flows perpendicular to the creek (see Fig. 4.5); the hydrodynamic reasons for this flow pattern are discussed in Section 4.4. Consequently, in R-type swamps, water flow forms a horizontal circulation pattern with each tidal period, along with considerable dispersion due to turbulence generated around mangrove vegetation and local depressions within the swamp surface. Mazda et al. (1999 [9.2]) used a numerical simulation to investigate the dependence of horizontal tidal circulation and material dispersion on the vegetation density in R-type forests, which is described in detail in Section 5.3.1. Based on field observations, Furukawa and Wolanski (1996 [6.4]) and Furukawa et al. (1997 [3.1]) considered sediment transport into the swamp from the tidal creek (see Fig. 3 in [3.1]). However, difficulties involved in making direct measurements of flow patterns mean that we currently have little firm information on patterns of water circulation and sedimentation within mangrove swamps (Sato, 2003).
3.5.2. Water flow in tidal creeks

Water flow in tidal creeks fringed by mangroves (i.e., R-type systems) is very different from that in rivers without mangroves. It should be noted that creek water not only inundates the swamp with tidal periods, but it is also strongly influenced by the water returning from the swamp at ebb tide.

The flooded volume of a swamp results in a huge increase in water flux within the creek, particularly at the creek mouth, compared to the case of a similar creek without swamps (Fig. 3.5). In some locations, freshwater is pushed back laterally into the swamp during flood tides and trapped until ebb tide. At ebb tide, the freshwater returns to the creek after the saltwater (see Fig. 7 in [5.2]). Thus, at the beginning of ebb tide, a front forms between the freshwater and saltwater
near the bank of the creek. This front along the stream accumulates floating detritus such as mangrove pollen, leaves, and seeds (see the lower right picture in Plate 2; Wolanski, 1992 [5.5]). Concentrations of suspended sediment in the creek change dramatically with tidal stage, depending on the strength of the tidal current (Wolanski et al., 1992b [6.1]). Mazda et al. (2002 [9.5]) and Hang et al. (2003) studied the nature of coastal erosion (see Fig. 2 in [9.5]) caused directly and indirectly by this strong flow.

Many tidal creeks with wide mangrove swamps record a tidal flow asymmetry in which the peak current velocity is higher at ebb tide than at flood tide (see Fig. 6 in [5.3] and Table 1 in [1.3]). Wolanski et al. (1980 [1.1]) and Wolanski (2006) pointed out that this tidal asymmetry helps flush out coarse sediment from the creek, ensuring the maintenance of creek depth and material exchange between the mangrove area and the open sea.

Water flow in tidal creeks is accompanied by secondary circulation, which involves water movement in the lateral cross-section of the creek, depending on the existence of freshwater runoff from the upper stream and meanders of the creek (see Fig. 9 in [1.4]). This secondary circulation influences the dispersal of mangrove seeds (Ridd et al., 1998 [1.4]; Kuwabara, 2002).

During conditions of low runoff and high evaporation in the dry season, a salinity maximum zone can develop in the creek (Fig. 3.6 and Fig. 3.7). This isolates the upper reaches of the creek from coastal waters (Wolanski, 1986 [4.1]; Wolanski, 1992 [5.5]; Ridd and Stieglitz, 2002 [4.4]), or induces an inverse estuary circulation (Wolanski, 1989; Wattayakorn et al., 1990 [4.2]). The inverse estuary, or the negative estuary (e.g., Dyer, 1973), induces an unusual gravitational
circulation with upstream flow in the upper layer of creeks and downstream flow in the lower layer. Consequently, floating material that originated in the mangrove swamp (e.g., mangrove seeds) is unable to reach the open sea.

3.5.3. Groundwater processes in mangrove swamps

Once the soil surface of a mangrove swamp is exposed to the atmosphere, only groundwater flow is available for discharge to the mangrove creek or open sea. The descent speed of groundwater is very slow compared to that of surface water, as seen in Fig. 2 in [7.6]. However, the existence of numerous intricate animal burrows and sediment layers rich in mangrove humus acts to increase water permeability (Heron and Ridd, 2003 [7.4]; Susilo et al., 2005 [7.5]; Mazda and Ikeda, 2006 [7.6]). Susilo (2004) stated that 50% of the salt that accumulates around underground roots and that limits the growth of mangrove trees and can lead to fatal hypersaline conditions may be discharged to the creek via groundwater thanks to the large value of water permeability.

Observations of groundwater levels near a creek within an R-type forest at Maira-Gawa, Iriomote Island, Japan (A in Plate 1) undertaken by Mazda and Ikeda (2006 [7.6]) indicate that after tidal inundation of the swamp has ceased, groundwater tables descend by up to 15 cm in the time until the subsequent flood tide. In contrast, only minor changes occur in the groundwater table at sites far from the creek, including swamp within an F-type forest that neighbors the observational area and even at the open coast outside the mangrove forest (see Fig. 3 in [7.6]). These findings suggest that the behavior of groundwater varies significantly between R-type, F-type, and B-type forests.
Figure 3.7. Longitudinal salinity transects in (c) Crocodile Creek and (d) Cocoa Creek in Australia (F in Plate 1) shown in (a) and (b). In (c) a salinity maximum zone is seen at the middle reaches, and the salinity exceeds 55 psu. In (d) the estuary becomes completely hypersaline within 1 month after a rainfall event in late August 1998. □, 3 September 1998; ○, 10 September 1998; △, 16 September 1998; ▽, 14 October 1998 (after Ridd and Stieglitz, 2002 [4.4]).
3.6. Atmospheric processes

Mangrove environments are influenced by atmospheric elements such as sunlight (solar radiation), wind, rain, evaporation, evapotranspiration, air temperature, and humidity (Snedaker and Snedaker, 1984; Clough and Sim, 1989; Kjerfve, 1990).

The mangrove canopy provides considerable shading of the soil surface. According to Mazda (unpublished data from the Thanh Phu mangrove area, Vietnam; J in Plate 1), 10% of solar radiation reaches the soil beneath the canopy. This solar radiation plays a role in supplying oxygen to the water via the photosynthesis of algae on the soil surface and on the surface of the aerial roots of mangrove trees. This oxygen supply is significant in maintaining mangrove ecosystems, which otherwise tend to become anoxic (see Section 3.4; Fig. 4 in [5.4]); this topic is introduced in the following section.

Sea waves are rapidly attenuated in swamps because of the resistance of mangrove trees and roots (Mazda et al., 1997b [3.2]; Massel et al., 1999; Mazda et al., 2006 [3.3]), and the lack of wind beneath the canopy prevents the occurrence of surface waves within the swamp (Mazda et al., 1990b [5.4]).

In most studies, direct rainfall into mangrove swamps is usually neglected because it is a minor source of water compared to the huge amount of water that inundates the swamp on most high tides. However, in tropical mangrove regions the year is generally divided into two seasons, the wet and dry seasons, and variation in rainfall throughout a year is an important parameter. The difference between environmental conditions in the wet and dry seasons can be extreme (Ridd and Stieglitz, 2002 [4.4]). Plate 6 shows a destroyed coral reef covered with mud discharged from a mangrove swamp due to heavy rain. The effect of rain on water properties cannot be neglected, especially in the wet season (Wattayakorn et al., 1990 [4.2]; Wattayakorn et al., 2000). River discharge due to rainfall results in an increase in mean water levels in both creeks and adjacent coastal areas. Freshwater discharge during the wet season results in changes in both water properties and hydrodynamics, including density stratification and vertical water circulation in tidal creeks. These changes can have a marked influence on biotic activity (Uncles et al., 1990; Ong et al., 1991). In B-type forests, water exchange between the swamp and the open sea occurs mainly at high tide in the wet season when the sea level is high. During periods of low water in the wet season, freshwater derived from rainfall is generally the dominant influence in the swamp. Groundwater properties such as salinity and nutrient content are strongly influenced by rainfall (Susilo, 2004).

Evaporation and evapotranspiration in mangrove swamps result from the compound effects of solar radiation, air temperature, humidity, and wind (Medeiros and Kjerfve, 1993; Hollins and Ridd, 1997). Although evapotranspiration from mangrove leaves has been studied in the fields of biology and ecology, the physical properties of evaporation from mangrove swamps have only been considered by Wolanski (1986 [4.1]), Wattayakorn et al. (1990 [4.2]) and Hollins and Ridd (1997). Wolanski (1986 [4.1]) and Wattayakorn et al. (1990 [4.2]) stated that the increase of salinity (water density) in tidal creeks due to evaporation commonly interrupts the exchange of water and material between mangrove swamps and offshore waters (see Fig. 3.6), as mentioned in Section 3.5.2. Hollins and Ridd (1997) reported that in dry seasons with high evaporation rates, high values of salinity develop in both surface water and groundwater, forming salt flats that are devoid of mangrove vegetation. Ridd and Stieglitz (2002 [4.4]) presented the data shown Fig. 3.7, based on observations at Cocoa Creek and Crocodile Creek near Townsville, Australia (F in Plate 1). These data show the changes in salinity along the length of the creeks. Figure 3.7c shows a salinity maximum zone in Crocodile Creek, where salinity reaches a maximum of ca. 55 psu. Figure 3.7d shows data from Cocoa Creek that records changes in salinity following a rainfall event in late August, 1998. The estuary becomes completely inverse at this time, with salinity increasing to 55 psu within several months.
Mazda et al. (1990b [5.4]) considered changes in water properties within a B-type forest that resulted directly from atmospheric conditions. In this B-type forest, located at Bashita-Minato, Iriomote Island, Japan (A in Plate 1), a density interface was formed at intermediate water depths due to a combination of solar radiation and rain. Under these conditions, the heat accumulates day by day just below the density interface, and it stimulates biological activity that in turn leads to an increase in light absorptivity (see Figs. 5 and 6 in [5.4]). In the absence of light and with isolation from the atmosphere due to the high stability of the water column, the lower layer rapidly becomes anoxic within several days (see Fig. 4 in [5.4]).

Wind from offshore areas is reduced in speed over the tree canopy. This reduces the momentum of the air exciting the canopy and thus shelters the downstream area by virtue of the wake effect. Consequently, the airflow downwind of the trees creates zones of low turbulence where suspended salt particles are deposited, resulting in significant protection against salt spray (Wolanski, 2007).

3.7. Offshore processes

Mangrove areas are proximal to coastal systems such as coral reefs and seagrass meadows. Duke and Wolanski (2001) summarized the complex tropical ecosystem formed from interactions between coral reefs, sub-tidal seagrass meadows and mangroves that grow along the upper intertidal zone. As a typical example of this type of research, Mazda et al. (1990b [5.4]) analyzed the importance of water and material exchange processes between a mangrove swamp and a coral reef on Iriomote Island, Japan (A in Plate 1). The mangrove waters drain into a coral reef area that has concentration levels of dissolved oxygen (DO) that are completely different to those in the mangrove swamp. Figure 3.8 shows a time series plot of the solar radiation, swamp water level, and DO for the swamp and the neighboring coral reef area. The DO in the swamp rose sharply at the commencement of the flood tide and fell slowly thereafter until anoxic conditions were reached, irrespective of solar radiation. It is thus apparent that the main input of DO was generally from the incoming reef water rather than production within the swamp. The DO from the reef strongly influences that of the swamp, which in turn influences aquatic or benthic organisms within the swamp such as crabs and prawns. Figure 3.8 shows that fluctuations in DO levels at the coral reef are much larger than those usually recorded in offshore water. The DO at the reef has a dominant diurnal cycle, with a minimum value in the early morning and a maximum in the evening close to sunset. In shallow coral reefs, such a diurnal cycle of DO generally results from the biological activity of corals and algae, as oxygen is consumed at night due to respiration and accumulated after sunrise due to photosynthesis. This results in a DO maximum at sunset and a minimum just before sunrise. This behavior of DO is also usual in coastal areas that contain seagrass beds (Komatsu, 1989).

The transport of coral-reef water into the swamp depends on tidal action. In the case shown in Fig. 3.8, the flood tide occurred in the evening and early morning when DO in the reef was at maximum and minimum values, respectively. Consequently, the evening value of DO in the swamp was considerably larger than that in the early morning. However, as the timing of the high tide shifts by approximately 50 minutes every day because of astronomical movements (see Section 4.2.4), the timing of the flood tide (when the reef water is able to flow into the swamp) does not always coincide with the time at sunset when the reef water is saturated in DO, as it did in the case shown in Fig. 3.8. If the reef water flows into the swamp several hours before or after the occurrence of a maximum in DO, the swamp will not record such high values of DO. Hence, both oxygen production at the reef and tidal transport processes into the swamp control biotic activity within the ecosystem of the mangrove swamp.

Where mud flats are widely developed offshore, as with alluvial fans of the Mekong River and the Red River in Vietnam (J and B in Plate 1; Hong and San, 1993; Hong, 2004), sea waves
induced by typhoons and tsunami waves are mitigated due to bottom friction over the long distance of the mud flat (Mazda et al., 2006 [3.3]). Wide and shallow intertidal mud flats also have a considerable effect on the temperature of water that floods the mangroves, as shallow water is prone to rapid changes in temperature during the day. The mangrove swamps are inundated by the warmest water when the flood tide occurs in the afternoon or early evening, and colder water when the flood tide occurs in the morning. Heath (1977) noted the importance of the heat budget on tidal mud flats in terms of the interrelation between solar radiation, which has a diurnal period, and tidal motion, which has diurnal and semi-diurnal periods (see Section 4.2.4).

3.8. Terrestrial processes

Mangrove ecosystems are intimately connected with ecosystems of the surrounding areas. Por (1984) explained the basic concepts of both biotic relations and energy flows through terrestrial, mangrove and offshore areas. Based on observations in mangrove fringed estuaries in Babeldaob Island, Palau, Micronesia (C in Plate 1), Victor et al. (2004) stated that mangroves trap riverine sediment, and are important buffers protecting fringing coral reefs from excessive sedimentation, while in a pouring rain a coral reef is widely covered with mud discharged from a mangrove swamp, as seen in Plate 6.
Wolanski (2006) stressed the opinion that coastal ecosystems such as mangrove areas should be understood in terms of eco-hydrology, which is constructed from the interrelations between the hydrology of the coastal, offshore, and terrestrial areas. Physical processes and the influence of terrestrial hydrology on the mangrove environment should also be investigated, as only Kjerfve (1990), Wattayakorn et al. (1990 [4.2]) and Mederios and Kjerfve (1993) have investigated this topic.

3.9. Links between topography, physical processes and environmental consequences

Physical factors described in the above terms link with each other. Particularly, their links are different between the types of mangrove landform, i.e., R-type, F-type and B-type forests. Figures 3.9 and 3.10 show the links between topography, physical processes and environmental consequences in R-type and F-type forests, respectively.

R-type forests comprise mangrove swamps and tidal creeks. As seen in Fig. 3.9, the swamp and the creek strongly connect with each other for forming mangrove ecosystems through physical processes. For example, strong tidal flow depending on long channel length and deep channel depth forms strong dispersion of materials such as nutrients and mangrove seeds with the help of large tidal prism depending on wide-flat swamp area and strong friction depending on vegetation density, resulting in maintenance of mangrove colonies. On the other hand, for F-type forests without tidal creeks (Fig. 3.10), the ecosystem in the swamp depends directly on the physical actions of the open sea. Tables 3.1 and 3.2 show the existing studies for individual terms in Figs. 3.9 and 3.10, respectively. The studies analyzed hitherto concentrate on a few terms, as seen in the tables. Other terms that have not been studied hitherto should be addressed in future.

Figure 3.9. Links between topography, dynamic processes and environmental consequences in R-type mangrove swamps (after Wolanski et al., 1992a).
Unfortunately, the processes for B-type forests have not been studied adequately, because we have so far accumulated little information, notwithstanding the pioneer investigations of Twilley (1985), Twilley et al. (1986), Mazda et al. (1990b [5.4]) and Susilo and Ridd (2005 [8.4]).

In Figs. 3.9 and 3.10, one-way processes from topography to environmental consequences alone are represented. However, as described in Chapter 5, it must be stressed that these factors interact each other with feedback systems.

<table>
<thead>
<tr>
<th>Terms in Fig. 3.9</th>
<th>References</th>
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<tr>
<td>Strong tidal flow</td>
<td>Boto and Bunt (1981), Woodroffe (1985a, b), Mazda et al. (2002)</td>
</tr>
<tr>
<td>Depressing sea waves</td>
<td>Mazda et al. (2005)</td>
</tr>
<tr>
<td>Large tidal prism</td>
<td>Chong et al. (1996), Mazda et al. (2002)</td>
</tr>
<tr>
<td>Inundating at high tide</td>
<td>Mazda et al. (2006)</td>
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<tr>
<td>Strong friction</td>
<td>Mazda et al. (1997a), Kobashi and Mazda (2005), Mazda et al. (2005)</td>
</tr>
<tr>
<td>Vacating space in mud</td>
<td>Stieglitz et al. (2000a), Susilo (2004)</td>
</tr>
<tr>
<td>Depressing the wind</td>
<td>Wolanski (2007)</td>
</tr>
<tr>
<td>Strong dispersion</td>
<td>Ridd et al. (1990), Chong et al. (1996), Mazda et al. (1999)</td>
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<tr>
<td>Gravitational circulation</td>
<td>Ridd et al. (1998), Stieglitz and Ridd (2001)</td>
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<tr>
<td>Tidal deformation</td>
<td>Mazda and Kamiyama (2007)</td>
</tr>
<tr>
<td>Underground water flow</td>
<td>Ridd (1996), Stieglitz et al. (2000a), Heron and Ridd (2001), Heron and Ridd (2003), Susilo (2004), Susilo et al. (2005), Mazda and Ikeda (2006)</td>
</tr>
<tr>
<td>Shifts in evapotranspiration</td>
<td>Wolanski (1986), Hollins and Ridd (1997)</td>
</tr>
<tr>
<td>Maintaining channel depth</td>
<td>Wolanski et al. (1980), Wolanski (2006)</td>
</tr>
<tr>
<td>Supplying oxygen inside the swamp</td>
<td>Furukawa and Wolanski (1996), Furukawa et al. (1997), Wolanski et al. (1998), Brinkman et al. (2005)</td>
</tr>
<tr>
<td>Growth of algae</td>
<td></td>
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</table>
Part I: Outline of the Physical Processes within Mangrove Systems

Figure 3.10. Links between topography, dynamic processes and environmental consequences in F-type mangrove swamps.

Table 3.2 References for each term in Fig. 3.10.

<table>
<thead>
<tr>
<th>Terms in Fig. 3.10</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal inundation</td>
<td>Friedrichs et al. (1990), Miyagi (1998)</td>
</tr>
<tr>
<td>Wave inundation</td>
<td>Ellison (1993), Mazda et al. (1997b), Mazda et al. (2006a)</td>
</tr>
<tr>
<td>Strong friction</td>
<td>Mazda et al. (1997a), Hamzah et al. (1999), Kobashi and Mazda (2005), Mazda et al. (2005), Mazda et al. (2007)</td>
</tr>
<tr>
<td>Vacating space in mud</td>
<td>Kathiresan and Rajendran (2005), Wolanski (2006)</td>
</tr>
<tr>
<td>Depressing the wind</td>
<td>Wolanski (2006)</td>
</tr>
<tr>
<td>Scouring muddy bottom</td>
<td>Mazda et al. (2007)</td>
</tr>
<tr>
<td>Depressing sea waves</td>
<td>Mazda et al. (1997b), Mazda et al. (2006a)</td>
</tr>
<tr>
<td>Tidal deformation</td>
<td>Mazda and Kamiyama (2007)</td>
</tr>
<tr>
<td>Stagnating groundwater</td>
<td>Mazda et al. (1990a)</td>
</tr>
<tr>
<td>Shifts in evapotranspiration</td>
<td>Mazda and Kamiyama (2007)</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>Mazda and Kamiyama (2007)</td>
</tr>
<tr>
<td>Supplying oxygen</td>
<td>Mazda et al. (1990b)</td>
</tr>
<tr>
<td>Preventing erosion</td>
<td>Sato (1978), Mazda et al. (1997b), Sato (2003), Danielsen et al. (2005), Winterwerp et al. (2005), Mazda et al. (2006), Mazda et al. (2007)</td>
</tr>
<tr>
<td>Depletion of coastal ecosystems</td>
<td>Duke and Wolanski (2001)</td>
</tr>
<tr>
<td>Eutrophication inside the swamp</td>
<td>Mazda and Ikeda (2006)</td>
</tr>
<tr>
<td>Maintaining colonies</td>
<td>Mazda and Kamiyama (2007)</td>
</tr>
<tr>
<td>Maintaining mud properties</td>
<td>Wada and Takagi (1988)</td>
</tr>
<tr>
<td>Growth of algae</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 4

Hydrodynamics and Physics that Support the Mangrove Environment

4.1. Hydraulic features that are unique to mangrove areas

The behaviors of hydraulic factors such as tides, sea waves, and groundwater flows in mangrove areas are very different from those of temperate estuaries or coastal areas with which many scientists are familiar. It should be recognized that even though the physical mechanisms in these areas are basically the same as those in temperate areas, their behaviors cannot be estimated by extrapolation from those in temperate areas. One of reasons for this is that mangrove areas generally constitute a very wide intertidal area. In temperate areas, the presence of the intertidal zone is usually neglected when considering the behavior of water macroscopically. The volume of water in a creek-swamp system may change by an order of magnitude between high tide and low tide, and the total area of the swamps can be many times the area of the creek. Thus, the effects of dramatic changes in the extent of the flooded area and the volume of the estuary in mangrove areas must be taken into account, whereas in many temperate estuaries this is only a minor effect. Furthermore, mangrove swamps are aquatic areas at high tide and terrestrial areas at low tide. Thus, compared to the temperate estuaries, water movement in such an area cannot be treated as a continuous flow throughout the cycle of a tidal period. Another way in which mangrove estuaries are different from conventional estuaries is the large number of obstacles to water flow, including mangrove trees, prop roots and pneumatophores. Interaction between water flow and these obstacles forms eddies or turbulence with various spatial (horizontal and vertical) and temporal scales. In particular, for R-type forests that are composed of mangrove swamps and tidal creeks, water motions in the swamp and the tidal creek are always connected and strongly interact (see Fig. 3.9; Wolanski et al., 1992a), notwithstanding the contrasting topographies of the wide, flat swamps and the long, deep creeks.

To preserve and utilize the mangrove environment, it is necessary to quantitatively understand the unique hydrodynamics that constitute the mangrove environment and that support the mangrove ecosystem.

4.2. Scale of environmental change and driving forces

Natural phenomena comprise many elements with various spatial and temporal scales. As each spatial scale generally corresponds to the individual time scale, it is convenient to arrange the characteristics of these elements in order of time scale. In water areas, there are various horizontal and vertical water motions with different time scales, from changes in water level with a seasonal period to water turbulence at time scales of less than 1 sec (Fig. 4.1).
4.2.1. Seasonal changes

Mangrove ecosystems are influenced by seasonal changes in climate, even though they are within tropical to sub-tropical areas. Although seasonal variations in rainfall are well known, seasonal changes in sea level are often neglected. Generally speaking, seasonal changes in sea level result from a number of factors, including (a) variations in wind direction and speed (often monsoonal) upon the coastal ocean (Ridd et al., 1988), (b) changes in water temperature that bring about an expansion in water volume, (c) changes in atmospheric pressure, and (d) changes in river runoff due to rainfall (Kjerfve, 1990). For example, Mazda and Kamiyama (2007 [2.4]) presented the data reproduced in Fig. 4.2. At the Can-Gio coast, southern Vietnam (J in Plate 1), the annual range in mean sea level between the summertime low and the wintertime high is approximately 60 cm. At Ishigaki Harbor, southern Japan (A in Plate 1), the range between the springtime low and autumn high is ca. 40 cm, whereas the annual range at the mouth of the Chone River (Rio Chone), central Ecuador (N in Plate 1) is negligible. Thus, some mangrove swamps are dry for several months, and their ecosystems depend strongly on these seasonal changes (Snedaker, 1989; Kjerfve, 1990).

4.2.2. Fortnightly changes in tidal regime

Variations in tidal forcing lead to the spring–neap cycle, which is associated with the lunar cycle and often causes the tidal range to change significantly over fortnightly time scales (Fig. 4.2). The volume of water that enters and is trapped in a mangrove swamp changes markedly during the spring-neap cycle (Mazda et al., 1995 [1.3]). The magnitude of groundwater flux also varies markedly between the spring and neap tides (see Fig. 4 in [7.6]). Tidal inundation in the innermost parts of mangrove swamps is particularly affected by this cycle; the soil in these innermost parts may be exposed continuously for several days during neap tide, and this influences not only the growth of mangrove trees but also the lives of benthos in those areas.

4.2.3. Daily changes in atmospheric variables

The diurnal variation in solar radiation causes changes in air temperature and soil temperature, particularly in coastal tidal flats neighboring mangrove swamps. These variations result in daily
changes in the temperature of the water that inundates mangrove swamps. Dissolved oxygen in coastal water, which is transported to mangrove swamps by tidal action, also varies with the daily cycle in solar radiation and biotic activity such as photosynthesis and respiration, as mentioned in Section 3.7 (Fig. 3.8).

4.2.4. Diurnal and semi-diurnal tidal fluctuations

Tidal fluctuations can be partitioned into a sequence of sinusoidal tidal harmonic components. Those components with an approximately 24-hour period are termed the diurnal constituents, \( K_1, O_1, P_1, Q_1 \) and \( S_1 \), which have periods of 23.93, 25.82, 24.04, 26.87 and 24.00 hours, respectively.
Similarly, those components with an approximately 12-hour period are termed the semi-diurnal constituents ($M_2 = 12.42$ hours; $S_2 = 12.00$ hours; $N_2 = 12.66$ hours; $K_2 = 11.97$ hours). Among these components, $K_1$, $O_1$, $M_2$, and $S_2$ are termed the dominant tidal constituents. As mentioned above, the tidal range changes fortnightly with the progression of spring and neap tides. The amplitude and phase of each tidal component depend on the location of the observation site. Generally, the levels of high and low tides change daily, as does the interval between consecutive high tides; these fluctuations are known as tidal inequality. Differences in the periods of the dominant tidal components mean that the timing of high tide shifts by approximately 50 minutes each day (Ippen, 1966), as evident in Fig. 5.1a. The effect of this shift in the phase of tides from that of solar radiation by approximately 50 minutes every day is discussed in Section 3.7.

In mangrove areas, it is usual that the tide behaves like a solitary wave, as at low tide the bottom substrate is exposed. The water begins to inundate the swamp at around the middle of the flood tide period (mean sea level) and stagnates at high tidal level (Fig. 5.1b). Although tidal oscillations in offshore regions are almost symmetrical about flood and ebb tides, they become highly asymmetrical in mangrove swamps due to the effect of mangrove vegetation and local topography (Aucan and Ridd, 2000 [1.5]; Mazda and Kamiyama, 2007 [2.4]). The modification of the tidal signal is apparent at the time when the water begins to inundate the swamp, and is especially pronounced at around the time when the bottom substrate dries up at ebb tide (Fig. 5.1b).

S. C. Snedaker (personal communication) suspected that the structural variation and phenological variability of mangrove forests depend on the statistical characteristics of the tidal elevation over many decades. Perhaps the most important factors that affect mangrove forests are the frequency of tidal inundation, inundation volume (tidal prism) and inundation duration (Bunt et al., 1985).
4.2.5. Resonant oscillation

In many mangrove swamps, water oscillations with a period of 10–30 minutes are present in addition to the usual astronomical tidal oscillations (see Fig. 4.3). These are free oscillations with a period that is dependent on the horizontal dimensions and the water depth of the area. These water oscillations are termed a Seiche or a resonant oscillation (e.g., Ippen, 1966). The wavelength of this wave is of the same order of magnitude as the horizontal scale of the area. This water motion can transport floating leaves and suspended and bottom sediments between the swamp and the coastal area. Little quantitative work has been done on these phenomena in mangrove areas.

4.2.6. Sea waves

Sea waves that penetrate mangrove areas vary from short-period wind waves to longer-period swells or surges with periods of 1–30 sec that are induced by winds or tropical depressions in the open sea. In R-type forests, the waves are attenuated due to bottom friction along long tidal creeks before reaching the swamps; consequently, the swamp area has calm water surface. In F-type forests, however, sea waves intrude into the swamp directly and are attenuated due to the drag force of mangroves within the region of the swamp close to the boundary with the open coast. The rate of wave reduction depends on the vegetation conditions and the characteristics of the waves in the open sea (see Plate 4; Massel et al., 1999).

4.2.7. Water turbulence

Mangrove prop roots and pneumatophores are densely intertwined above the bottom substrate. Because of interaction between mangrove roots and tidal flows or sea waves, water turbulence or eddies with periods smaller than those of sea waves occurs primarily in the region of the swamp near the boundary of the open coast (see Fig. 7 in [6.4]). These turbulent interactions act to mix and diffuse water and materials, and contribute to form and maintain the distribution of material within the swamp (Wolanski et al., 1992b [6.1]; Wolanski, 1995 [6.2]; Wolanski et al., 1996 [6.3]; Furukawa and Wolanski, 1996 [6.4]; Furukawa et al., 1997 [3.1]). In particular, Wolanski et al. (1998) proposed that sedimentation related to water turbulence results in the formation of new land.

4.2.8. Damaging events

Tropical depressions or typhoons can result in an increase in water levels by several meters, and this effect can continue for several days in coastal areas (Dean and Dalrymple, 2002). Superposition of this elevated water level on high water at spring tide leads to destructive conditions in coastal areas. Generally speaking, sea waves move across deep water without any reduction in energy because the effect of bottom friction decreases with increasing water depth. Mazda et al. (2006 [3.3]) presented an actual example of this phenomenon from the Song Hong (Hong River) delta, northern Vietnam (B in Plate 1), where typhoons can generate an increase in sea level of more than 2 meters (Sundstrom and Emma, 2004). As shown in Fig. 4.4, an artificial dyke constructed to protect shrimp ponds was destroyed by sea waves in the early hours of 14 October, 1995, when the astronomical high tide occurred close to a spring tide and a typhoon passed close to the area. The fact that the height of the collapsed part of the dyke was 2 m above ground level suggests that the water depth increased by up to 2 m due to the concurrent effect of the typhoon and the astronomical high tide. Under these conditions, the wave forces caused by the typhoon maintained their large wave heights in the deep water and destroyed the upper part of the dyke. Mazda et al. (2006 [3.3]) suggested that under these conditions, mangrove vegetation with its vertical configuration and thick coverage of leaves effectively consumes the energy of severe waves and plays an important role in protecting the coast.

When tsunamis occur, the bores penetrate into mangrove swamps with a period of between 10 minutes and 1 hours. Although the Sumatra tsunami of 26 December, 2004 destroyed many
coastal areas along the Indian Ocean, mangrove-fringed coasts are thought to have buffered the coast from the destructive effects of the tsunami (Plate 5; Kathiresan and Rajendran, 2005; Danielsen et al., 2005; Mazda et al., 2007 [3.4]). However, considerably more work needs to be done to analyze the effect of tsunamis on mangroves and the influence of mangroves in terms of attenuating tsunamis (see Section 4.9 for more details).

Figure 4.4. Views of an artificial dyke in northern Vietnam (B in Plate 1), which was collapsed by the concurrent effect of the water level rise caused by the typhoon and the astronomical high tide (Mazda et al., 2006 [3.3]).
(a) A view of the top of the dyke.
(b) A part of the dyke slope facing the offshore. A part collapsed by severe sea waves is seen in the center.
(c) The opposite side of the collapsed part of the dyke, which was given first aid by sandbags.
In tidal creeks, wakes generated by boats and ships can produce waves with a period of several seconds. These waves erode sediment from the creek bottom and the creek bank made of the fine and often unconsolidated nature of mangrove sediments. Mazda et al. (2007 [3.4]) documented the effects of erosion caused by tourist boats, and found that the erosion exposed roots, causing trees to fall into the water.

The sea level may rise by approximately 50 cm over the next century due to global warming. As mentioned above, an increase in sea level means that sea waves will attack coastal areas without any reduction in their destructive energy. Many islands in the South Pacific region, which are generally at low elevations, have healthy mangrove ecosystems (Sugi, 1992); however, it is not easy to estimate the response of these ecosystems to an increase in sea level (Ellison, 1993; Kikuchi, 1995; Miyagi, 1998). More research is required to understand the influence of this long-term increase in sea level on the mangrove environment.

4.2.9. Residence time of water and materials

The concept of the age of water or dissolved materials resident within a mangrove area is important and useful in evaluating mangrove ecosystems. As noted by Bolin and Rodhe (1973) and Mazda (1984a), various concepts and parameters such as transit time, turn-over time, averaged age, and residence time have been used for aging the water and dissolved materials within a reservoir, although these terms do tend to become confused. These parameters are interrelated, and depend on the spatial scale of the area, the intensity of diffusion, and the distribution of water flow in and around the area (Wolanski et al., 1990 [5.3]; Wolanski, 1992 [5.5]; Wolanski et al., 2001).

The residence time is defined as the time required to replace 63% of the water within a reservoir with water from the open sea (Mazda, 1983). The initial water in the reservoir is exchanged with water of the open sea through the mouth of the reservoir with each passing tide. The water that enters the reservoir through the mouth during flood tide is mixed with the initial water before a fraction of this mixed water is discharged through the mouth at ebb tide. In other words, the water discharged at ebb tide is composed of the initial water in the reservoir and a fraction of the water that entered the reservoir during the preceding flood phase. Thus, the amount of initial water in the reservoir is reduced asymptotically and in a logarithmic manner with each tide rather than in a linear manner (see Fig. 5 in [5.3]). Wolanski et al. (2001) estimated a residence time of 10 days for the Klong Ngao mangrove area in Thailand (I in Plate 1), which has a 5 km tidal creek, and a time of 50 days for the Hinchinbrook Channel in Australia (E in Plate 1), which is 45 km long and fringed by thickly vegetated mangroves.

4.2.10. Interaction between mechanisms with different time scales

As stated previously, Watson (1928) proposed a simplified classification model to explain the fact that the growth of mangrove vegetation and their colonies is strongly dependent on hydrological conditions, i.e., the tidal condition and land elevation. This model is based on the concept that mangrove vegetation or mangrove colonies were established by interaction or feedback between the physiology of mangrove vegetation itself, topography, tidal regime, etc, over many decades, as described in detail in Section 5. Furthermore, S. C. Snedaker (personal communication) has stated that the important parameters for the growth of mangroves and their colonization are the flooding frequency, duration of inundation, and height of inundation. As mentioned in Sections 4.2.1, 4.2.2, and 4.2.4, the water level in mangrove systems changes across a wide range of scales from seasonal to semi-diurnal. The growth of mangrove vegetation is influenced by these changes in water level that are basically repeated from year to year. However, given that the amount of water that inundates mangrove swamps depends on the vegetation density and related flow resistance (see Fig. 3.4), we conclude that the present tidal elevation in a swamp
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(e.g., Fig. 5.1) was established under the influence not only of the tide in the open sea but also the
mangroves themselves, i.e., the feedback processes between the physiology of mangrove vegetation
and the tidal motion over many decades.

It should be noted that in addition to mangrove vegetation, other organisms such as benthos
and mangrove topography formed by the deposition and erosion of soil sediment have been
established from similar feedback systems with individual time scales. The succession of the
physiology and ecology of biota occurs at time scales of several decades. In contrast, the tidal
regime has diurnal or semi-diurnal periods that repeat with a period of 1 year in a statistical sense,
as mentioned above. Mazda and Kamiyama (2007 [2.4]) described the nonlinear interaction or
feedback between these biota and tidal regimes with different time scales; biota in mangrove areas
are unable to respond instantly to a tidal regime with diurnal or semi-diurnal periods, but follow
the statistical tidal inundation characteristics. As a result, the transition of biota physiologies and
ecologies related to the feedback system is generally gradual, occurs over many decades, is
asymptotic, and occurs in a logarithmic manner (Mazda, 1984b) rather than being linear (see
Section 4.2.9).

4.3. Forces of resistance to water movement

It is well known in a qualitative sense that water movement in mangrove swamps is restricted
by the presence of mangrove vegetation. The resistance to flow results from four factors: drag
forces due to submerged mangrove vegetation, viscous forces (eddy viscosity) due to water
turbulence associated with interaction between water flow and densely distributed vegetation,
bottom friction due to the uneven muddy bottom, and wind stress upon the water surface (see
Fig. 1 in [2.3]). The magnitudes of the drag force and eddy viscosity are strongly dependent on
the vertical configuration of mangrove vegetation (Mazda et al., 2005 [2.3]). Wind stress can
generally be neglected in mangrove swamps relative to other terms because mangrove canopies
inhibit wind within the swamps. The three significant terms behave differently depending on time
scale of individual phenomena, as described below.

4.4. Hydrodynamics at the tidal scale

According to Mazda et al. (2005 [2.3]), tidal-scale hydrodynamics in mangrove swamps are
controlled by the drag force and eddy viscosity, as the bottom friction is negligible compared to
these terms (see Fig. 4.5). Both the drag coefficient and the coefficient of eddy viscosity, which
characterize the magnitudes of the drag force and the eddy viscosity, respectively, decrease with
increasing values of the representative length of vegetation \( L \) defined in Eq. (3.2). The
representative length of vegetation \( L \) varies greatly with vegetation species, vegetation density
and tidal elevation (Fig. 3.3b). For low value of the representative length \( L \), both of these
coefficients reach much higher values than those typical of vegetation-poor estuaries and rivers
(see Figs. 4 and 6 in [2.3]). Consequently, the tidal flow within mangrove swamps depends to a
large degree upon the submerged vegetation density that varies with the tidal stage. Because of
the energy consumed by the drag force and eddy viscosity, the tidal flow decreases markedly
within mangrove swamps.

In particular, within R-type mangrove swamps the tidal flow in a part of the swamp close to
the creek is predominantly parallel to the creek, as it is dragged by tidal flow within the creek. In
parts of the swamp far from the bank of the creek, the water flow direction is perpendicular to the
creek, as determined by the gradient of water surface between the swamp and the creek (Fig. 4.5).
4.5. Hydrodynamics at the scale of sea waves

In R-type forests, water flow at tidal periods is dominant because sea waves are attenuated in tidal creeks. In contrast, for F-type forests, in places within mangrove swamps that are located close to the boundary facing the open sea, the effect of sea waves cannot be ignored. The hydrodynamics of sea waves, which have at most a period of 30 sec during a typhoon or cyclone, is very different from tidal-scale hydrodynamics with a diurnal or semi-diurnal period. Thus, in F-type areas, the hydrodynamics of sea waves needs to be superposed on that of tidal-scale hydrodynamics described above (Mazda et al., 2006 [3.3]).

Based on field observations, Mazda et al. (1997b [3.2]) estimated the effect of mangroves on wave amplitude. The authors found, for example, that on the coast of Thui Hai, northern Vietnam (B in Plate 1), where mangroves were planted in a strip of 1.5 km wide and 3 km long (along the shore), a wave height of 1 m in the open sea is reduced to 0.05 m at the coast, whereas without the sheltering effect of mangroves the waves would arrive at the coast with a height of 0.75 m (Plate 4). The study by Hong and Dao (2003) confirmed these earlier findings as that when a typhoon struck this area in 1996, the embankments enclosing the shrimp and crab ponds were well protected by mangroves located seaward of the embankments, while embankments in a nearby coastal area where mangroves had been deforested were strongly eroded and broken.

As mentioned in Section 4.2.8, in shallow water the bottom friction is effective in reducing wave height; however, the bottom effect decreases with increasing water depth. In contrast, the effect of mangrove vegetation (with its vertical configuration) on wave energy doesn’t decrease with increasing water depth (Mazda et al., 1997b [3.2] and Mazda et al., 2006 [3.3] showed the characteristics of the rate of wave reduction and the drag coefficient due to mangrove vegetation). In many cases where typhoons or tropical depressions have encountered coastlines, the mean sea level in coastal areas increases primarily from the effect of onshore winds. Furthermore, the sea
level may rise by 0.5 m within the next century due to global warming. Even in such examples of increased water depths, the high density of mangrove vegetation distributed throughout the entire water column will still work effectively in reducing wave energy and protecting coastal areas from wave-induced erosion.

Mazda et al. (1997b [3.2]), Massel et al. (1999) and Mazda et al. (2006 [3.3]) reported that the reduction in sea waves, i.e., the ratio of wave reduction and the drag coefficient, is strongly dependent on the mangrove species because of considerable variation in the physical form of different species (see Plate 3). Wave reduction also depends upon vegetation density and growth level, water depth (which changes with tidal stage) and the spectral characteristics of incident waves, including wave height and period (e.g., Fig. 7 in [3.3]).

4.6. Turbulence-scale hydrodynamics

A portion of the kinetic energy of tidal flow or sea waves that penetrate mangrove swamps disperses to small eddies or turbulence due to the presence of mangrove vegetation that is intertwined both horizontally and vertically (see Figs. 7 and 8 in [6.4]). This three-dimensional turbulence contributes to the formation of the mud substrate of mangrove swamps and helps to maintain the biological environment (Wolanski, 1995 [6.2]; Wolanski et al., 1996 [6.3]; Furukawa and Wolanski, 1996 [6.4]; Furukawa et al., 1997 [3.1]). Wolanski et al. (1992b [6.1]) analyzed the mechanism and role of turbulence in the settling of mud flocs, based on laboratory experiments and field observations. Wolanski (2001) suggested that wave energy is dissipated in small eddies at the scale of the vegetation (several centimeters) as a result of wave-induced reversing flows around the vegetation. Furukawa and Wolanski (1996 [6.4]) and Furukawa et al. (1997 [3.1]) stated as follows. The intensity of turbulence around densely vegetated mangroves is 2–3 times greater than the mean current velocity (Fig. 8 in [6.4]). At flood tide, flocs of fine cohesive sediment enter mangrove swamps, and sedimentation occurs when turbulence diminishes near slack high tide. The settled sediment is not re-entrained into the water at ebb tide because the high density of vegetation inhibits currents, which are too sluggish to erode the sediment (Fig. 3 in [3.1]). As a result, mangroves actively pump fine cohesive sediment from coastal waters. Mangrove swamps are thus an important sink for fine sediment from coastal waters or tidal creeks. In turn, the removal of mangrove trees may increase water turbidity at ebb tide and hence lead to a reduction in the primary productivity of planktonic algae in coastal waters and tidal creeks (Furukawa and Wolanski, 1996 [6.4]).

4.7. Hydrodynamics within tidal creeks

In R-type forests, various materials such as water, nutrients, dissolved oxygen, fish eggs, larva, sediment, and mangrove seeds are transported between mangrove swamps and offshore waters through the tidal creek. In other words, the flow mechanism in the creek controls the magnitude of the material exchange between mangrove swamps and offshore waters. Dyer (1973) proposed a mathematical method that solves quantitatively the mechanisms of material transport at river mouths (see Section 6.2). Applying this method to the Sungai Merbok mangrove estuary, Malaysia (K in Plate 1), Dyer et al. (1992) discussed the mechanisms of material flux and noted that the roles of river discharge, tidal oscillation, and cross-sectional vertical circulation (secondary circulation) in controlling material transport and material dispersion change with varying hydraulic conditions such as river runoff, tidal range, and vertical density stratification. Furthermore, Ridd et al. (1998 [1.4]) stated that secondary circulation sometimes develops in large creeks due to an interaction between the along-river salinity (density) gradient and the cross river velocity shear. This produces a zone of sinking water in the middle of the creek on flood tides which trap floating materials in mid stream (see Fig. 9 in [1.4]). The secondary circulation is also modified
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We generally observe (e.g., Wolanski et al., 1988) that during the dry season, the water column in tidal creeks fringed by mangroves are vertically uniform in terms of salinity and temperature. However, in some creeks, while the vertical gradient in suspended sediment concentration is small at flood tides, for most of ebb tide a lutocline separates a clear upper layer from an extremely turbid bottom layer, both layers being of comparable thickness. Wolanski et al. (1988) and Wolanski et al. (1992b [6.1]) stated that this sediment-induced buoyancy effect inhibits vertical mixing, and the presence of a lutocline may aid in the formation of mud banks on the inner side of a meander. However, based on observations at the Normanby River estuary, northern Australia (D in Plate 1), Ridd et al. (1998 [1.4]) reported that it was unable to quantitatively confirm the effect of secondary circulation on sediment transport toward the inner side of a meander.

The peak ebb tidal-currents in many tidal creeks fringed by wide mangrove areas are often 20 to 50% higher than the peak flood tidal-currents (see Fig. 6 in [5.3] and Table 1 in [1.3]; Wolanski et al., 1980 [1.1]; Woodroffe, 1985a, b), notwithstanding the fact that river runoff can be negligible. This result is the opposite to that observed in many estuaries without mangroves (Aubrey, 1986; Friedlichs et al., 1990). Wolanski et al. (1992a) considered that this ebb-flood asymmetry is caused by the tidal phase difference between the mouth and the head of the creek, which in turn results from bottom friction within the creek. Furthermore, based on the results of numerical analyses, Mazda et al. (1995 [1.3]) suggested that the asymmetry is dependent on the tidal phase difference between the creek and the swamp; this difference results from the drag force associated with mangrove roots in the swamp. This tidal flow asymmetry influences various environmental conditions in mangrove areas (see Section 5.2).

In many mangrove creeks, sedimentation leads to the formation of a sill-like bottom topography at the creek mouth, facing the open sea. Mazda (1985) proposed a hydraulic mechanism resulting from gravitational tidal trapping, which in turn results from interaction between the sill bathymetry, oscillatory tidal flow, and the density difference between the creek water and offshore water (Fig. 4.6). At flood tide, the offshore water passes through the sill and intrudes below the less dense creek water as a density flow, but at ebb tide the sill prevents the return of the water offshore, resulting in the entrapment of offshore water within the lower layer below the sill level. This mechanism not only influences the nature of material exchange between mangrove areas and offshore waters, which determines the residence time of the area (see Section 4.2.9), thus it also controls the life-cycle of benthos such as mud crabs and shrimps in R-type mangrove areas.
Mangrove forests generally have many tidal creeks and therefore connect to the open sea at several mouths, as shown in Fig. 4.7. Offshore waters enter these mouths at flood tides and move up the creeks into the tributaries. Within the forests, water masses encounter the waters that entered the forest through the different creek mouths. At this meeting point, the water becomes stagnant, although the water rises up to the high water level and floods the mangrove swamps. At ebb tide, this water returns toward the open sea, but the water at the meeting point cannot reach the open sea, then at the next flood tide, the water returns to the same point. As a result, the water properties within the stagnant area deteriorate with each passing tide. For example, if a prawn farm pond has been developed close to such a meeting point, the water supplied from the tidal creek through a sluice gate at flood tide is the same water that was discharged from the same pond at the previous ebb tide. Furthermore, given that generally the creek water intrudes the pond as the density flow (Fig. 4.8; Y. Mazda, unpublished data from Thanh Phu, southern Vietnam; J in Plate 1), the water exchange between the pond and the creek may not be effective, because the water density of the pond is much the same as that of the creek adjacent to the sluice gate. Unfortunately, we have little knowledge of the network flow systems that operate in tidal creeks within mangrove areas.
4.8. Hydrodynamics of groundwater

Groundwater moves according to pressure gradients caused by the slope of the water table. However, the velocity of groundwater flow and material flux such as nutrients discharged to the open sea via groundwater flow depend on the hydraulic conductivity, which is a parameter that
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Figure 4.9. Schematic cross-section perpendicular to the creek, showing the tide table, the groundwater flow \( (u_x) \) and the groundwater flux \( (F_x) \) (after Mazda and Ikeda, 2006 [7.6]).

represents groundwater permeability and is controlled by soil conditions such as grain-size and porosity. According to Darcy’s law, the following relationship accounts for groundwater flow (Fig. 4.9).

\[
u_x = \frac{dh}{dx}
\]

where \( u_x \) is the velocity of the groundwater flow passing through a vertical section at a horizontal co-ordinate \( x \) along the flow direction, \( h \) is the elevation of the groundwater table above an impermeable level surface, and \( k \) is the hydraulic conductivity. As shown in Fig. 4.8, the slope of the tide table of groundwater depends on the local landforms, i.e., the interrelation between the swamp and the creek. In other words, Eq. (4.1) contains two factors that determine the magnitude of groundwater flux, i.e., the hydraulic conductivity, which depends on soil properties, and the pressure gradient, which depends on local landforms such as the creek–swamp system and the history of tidal inundation.

The hydraulic conductivity of mangrove swamps is one to two orders of magnitude larger than that of normal sediment because of the presence of large-scale crab burrows, laminar mangrove humus, and other macropores within the soil (Susilo and Ridd, 2005 [8.4]; Mazda and Ikeda, 2006 [7.6]).

For R-type forests, the volume flux of groundwater discharged to the creek from the swamp depends linearly on the tidal range (see Fig. 4 in [7.6]). This suggests that the spring tide not only dilutes the salinity and other nutrients in the soil that were concentrated within the inner portion of the swamp during the preceding neap tide, but it also contributes to flushing the nutrients to the
B-type forests are rarely inundated by seawater during the dry season or neap tides. Furthermore, the presence of a mangrove canopy means that the wind is inhibited within the basin. Accordingly, water mixing associated with the flow of groundwater into the basin is relatively important in controlling and maintaining the water properties of the basin, even though the volume flux of this groundwater is small and the offshore water is unable to reach the basin directly during some tidal periods because of the slow speed of groundwater flow (Mazda et al., 1990a [7.1]; Ridd, 1996 [7.2]).

4.9. Hydrodynamics of tsunamis in mangrove areas

The Sumatra tsunami of 26 December, 2004 destroyed many coastal areas along the Indian Ocean; however, coastal mangrove forests are considered to have protected the coast from the tsunami (Plate 5; Mazda et al., 2007 [3.4]). Danielsen et al. (2005) reported the results of research undertaken in Cuddalore District, Tamil Nadu, India (L in Plate 1), immediately after the Sumatra tsunami struck the coast. A number of hamlets located behind mangrove forests fringing the coast survived the tsunami, even though the waves damaged those areas that were not shielded by vegetation. Kathiresan and Rajendran (2005) investigated the damage resulting from this tsunami in 18 hamlets located along the south-east coast of India. According to their report, there was no loss of life in three of the hamlets situated behind mangrove forests, and a low death toll was reported for a further four of the hamlets behind mangroves.

Many studies have investigated the hydraulic behavior of tsunami waves (e.g., Iida and Iwasaki, 1983; Hebenstreit, 1997; Satake, 2005). Imai and Matsutomi (2005) noted the importance of the inertial force of the bore-like wave front, as well as the drag force due to vegetation. Harada and Imamura (2005) summarized the effectiveness of forest width, vegetation density, and wave period on the mitigation of tsunamis, and proposed criteria that can be used to quantitatively identify the relation between the intensity of the tsunami wave and resulting damage. These criteria can be used as a quantitative standard in designing coastal forests to act as a tsunami countermeasure. These studies, however, did not specifically focus on mangrove areas, except the works of Hamzah et al. (1999) and Hiraishi and Harada (2003) who investigated the behavior of the drag force while taking into account the vertical configuration of mangroves.

Mangrove areas are commonly located adjacent to wide tidal flats that can extend offshore for 5–10 km or more. The bottom substrates of mangrove trees are generally very loose clay. Given these conditions, a tsunami may behave with peculiar characteristics compared to those of a tsunami in coastal areas of Japan, which are more familiar in the field of tsunami engineering (Satake, 2005). However, we have little information regarding the effect of mangrove forests on tsunami mitigation. Although the effects of mangrove vegetation in mitigating sea waves were discussed in Section 4.5, these data are restricted to short-period waves of less than 30 sec. The effect of the drag force of mangrove trees and roots on tides, which are waves with periods of 12 and 24 hours, was considered in Section 4.4; however, bearing in mind that the period of a tsunami, which is between 10 minutes and 1 hours, is in stark contrast to that of both sea waves and tides (see Fig. 4.1), the hydraulic characteristics of tsunamis may be very different from those of both sea waves and tidal waves. As noted by Imai and Matsutomi (2005), the crucial difference between sea waves/tides and tsunamis is that a tsunami propagates as a bore, which is far more destructive than sea waves and tides. The bore is formed when the tsunami wave breaks at shallow water depths, and its momentum accumulates and increases with movement upstream within shallow waters. Tidal waves barely break, even within shallow waters, as they behave as quasi-steady waves due to their long periods. Sea waves disperse their momentum because of their short period. Thus, as suggested by Kathiresan and Rajendran (2005), the hydrodynamic influence of tsunamis...
on mangrove forests should not be estimated by interpolation between the characteristics of sea waves and tidal waves.

Tsunamis first break within offshore areas of shallow water, then advance as a bore with strong flow. A part of the tsunami energy is absorbed by muddy substrate through long distance (Wang et al., 1998). Upon arriving at mangrove swamps, the bore scours the loose muddy bottom around mangrove roots to a depth of approximately 1 m beneath the bottom substrate (see Section 3.3); the mangrove trees then fall into the water. Wolanski (2007) discussed the threshold conditions at which tree trunks break and buried roots are uprooted, based on the findings of Niklas (2000) and Bowles (1988), respectively. The volume of intricate mangrove roots within the bottom substrate is comparable to the total volume of mangroves above the substrate (Komiyama et al., 1989). Considering these conditions, the great volume of roots, including those exposed in the water, and thick vegetated leaves of fallen trees acts to dissipate the kinetic energy of the tsunami, whereas if mangrove trees remain standing, both the underground roots and leaves in the air have no effect as obstacles to the flow.

During the Sumatra tsunami, a number of coastal villages within a bay upon Katchall Island within the Nicobar Islands, Indian Ocean (K in Plate 1), were protected by the sacrificial effect of mangrove trees that were felled by the tsunami (Plate 5). In other words, although the natural mangrove environments in this area were destroyed by the tsunami, their sacrifice protected human lives in inland areas. Unfortunately, we have little quantitative information on the influence of mangroves in terms of coastal protection from tsunamis. As mentioned above, the exception is the work of Hamzah et al. (1999) and Hiraishi and Harada (2003), whose studies were limited to laboratory model experiments using a simplified vertical configuration of mangroves. It would be useful to develop mathematical models that are able to assess whether and how mangroves might be instrumental in mitigating the destructive effects of tsunamis at any particular site. In this context, Mazda et al. (2007) proposed the procedure of the future study for the tsunamis in mangrove areas, and the Food and Agriculture Organization of UNESCO is studying in detail the effects of tsunamis on mangrove areas (J. B. Burnett, personal communication).
Chapter 5

Feedback Processes that Maintain the Mangrove Environment

5.1. Interactions between biota, landforms, water flow, and the atmosphere

Within individual sections of this book, various physical mechanisms have been introduced on the basis that the feedbacks between biotic, topographic, and physical processes play important roles in forming and preserving the natural mangrove environment. Here, we consider the details of the individual factors that comprise these feedback processes, even though the topics mentioned previously may be repeated to some degree.

Plate 2 shows schematically the feedback relations in the mangrove environment. There are various feedback cycles among biota, landforms, water flow, and the atmosphere. For example, 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, accumulate their decayed leaves around their bottom substrate as sediments, which leads to the establishment of landforms (bio-geomorphology). The landform or topography feeds back to modify the water flow by the drag force of the mangrove trees and roots.

Feedback effects not only occur for all four of the factors listed above, but also for pairs of factors, as described below.

5.1.1. Interrelations between biota and landforms

Woodroffe (1992) reported that mangrove ecosystems demonstrate close links between vegetation assemblages and geomorphologically defined habitats. In other words, biota depends on mangrove landforms, and inversely landforms depend on biota. For example, the lives of biota in mangrove areas such as mangrove trees, fishes, fish larvae/eggs, crabs, shellfishes, and algae depend on the landform or mangrove topography in the following manner. Mangrove trees need the bottom substrate upon which they grow. Crabs and shellfishes are able to construct their residences within and upon the topography formed of loose soil (Watson, 1928; Lugo and Snedaker, 1974; Vannucci, 1989). In return, the mangrove topography is influenced by the action of biota in the following manner. Fine sediment, mangrove litter, dead bodies of organisms and other materials form the bottom soil. Mangrove prop roots and pneumatophores densely intertwine with each other to protect these soils from the effects of waves and tidal currents and help to maintain the landforms of the mangrove swamp, i.e., bio-geomorphology (see Section 4.6) (Furukawa and Wolanski, 1996 [6.4]; Furukawa et al., 1997 [3.1]).

Small animals such as crabs and mud lobsters (see the upper left picture in Plate 2) dig intermingled burrows within about 1 m of the soil surface and form mounds varying in size from several millimeters to one meter (Komiyama et al., 1989; Mazda and Ikeda, 2006 [7.6]). Stieglitz
et al. (2000a [9.3]) found that the fraction of the bottom area occupied by these animal burrows is approximately 10% in a Rhizophora forest at Gordon Creek, Townsville, Australia (F in Plate 1). The animal burrows enable the passage of water deep into the mangrove soil and influence the soil properties by removing salt that accumulates around the mangrove roots (Heron and Ridd, 2001 [7.3]; Susilo et al., 2005 [7.5]).

5.1.2. Interrelations between biota and water flow

Biota depends on water flow, and in return the water depends on the biota. Mangrove trees, shellfish, and algae receive water, nutrients and dissolved oxygen from tidal inundation and sea waves, as mentioned in Sections 3.7 and 4.7 (Mazda et al., 1990b [5.4]). Fish enter and leave the swamps with the tidal water. The dispersal of mangrove seeds, which preserves and expands their colonies, is controlled by the water flow distribution, as mentioned in Section 5.3.1 (Mazda et al., 1999 [9.2]; Stieglitz and Ridd, 2001). Watson (1928), Snedaker (1989) and Lewis (2005) noted the importance of statistical tidal information in understanding the growth of mangrove forests, including the frequency of tidal inundation, the tidal prism volume, the duration of inundation, and salinity intrusion with the tidal flow. In return, the magnitude and direction of water flow is restricted by the drag force caused by mangrove trees and their roots, as mentioned in Sections 4.4 and 4.5 (Mazda et al., 1997a [2.1]; Mazda et al., 2005 [2.3]; Mazda et al., 2006 [3.3]). The tidal level in mangrove swamps departs greatly from that in the adjacent open sea (Fig. 5.1), and the magnitude of this discrepancy is related the vegetation conditions, including vegetation density and species, as well as the distance from the creek bank and the water depth at high tide (Mazda and Kamiyama, 2007 [2.4]).
Furthermore, as mentioned above, the high density of animal burrows enhances the transport of water and material (Stieglitz et al., 2000a [9.3]; Heron and Ridd, 2001 [7.3]; Susilo et al., 2005 [7.5]).

5.1.3. Interrelations between biota and the atmosphere

The biota within mangrove swamps is strongly influenced by atmospheric forcing factors such as rainfall, wind and humidity, and is also influenced by insolation, as mentioned in Section 3.6 (Clough and Sim, 1989). In return, the mangrove canopy influences the micro-climate within the forest by providing a protected and shaded region where relative humidity is elevated, wind is negligible, and sunlight is restricted.

The interrelation between wind outside the swamps and the tree canopy also plays an important role in determining the natural environment, as mentioned in Section 2.2.4 (Wolanski, 2006); however, these factors are not considered in this book, as we focus mainly on the hydrodynamics of mangrove forests.

5.1.4. Interrelations between water flow and landforms

Water movement in mangrove swamps is controlled by the topography of the swamp and creeks and by bottom friction associated with animal mounds and burrows, as mentioned in Sections 3.1, 3.5, 4.7, 4.8, and 5.3 (Mazda et al., 1990a [7.1]; Mazda et al., 1997a [2.1]; Kobashi and Mazda, 2005 [2.2]; Mazda et al., 2005 [2.3]; Mazda and Ikeda, 2006 [7.6]). In return, topography is modified by water flows that transport and disperse bottom sediments, as mentioned in Sections 3.5.2, 4.6, 4.7, 5.2, and 5.3 (Wolanski et al., 1980 [1.1]; Larcombe and Ridd, 1995; Wolanski, 1995 [6.2]; Mazda et al., 2002 [9.5]; Bryce et al., 2003 [6.5]; Hang et al., 2003).

5.1.5. Interrelations between landforms and the atmosphere

The soil surface and the atmosphere exchange heat, water vapor, and gasses. For example, the surface of the soil is saturated with oxygen supplied from the atmosphere when the swamp dries up, but becomes anoxic during long periods of inundation (Mazda; unpublished data from the Maira-Gawa, Iriomote Island, Japan (A in Plate 1)). Rainfall acts to reduce the salinity of the soil, although in the dry season the soil can become hypersaline (Ridd et al., 1997 [4.3]; Hollins and Ridd, 1997; Ridd and Stieglitz, 2002 [4.4]). In return, humidity within mangrove swamps is influenced by evapotranspiration from the soil surface, as described in Section 3.6 (Medeiros and Kjerfve, 1993).

5.1.6. Interrelations between the atmosphere and water flow

The atmosphere and water surface also exchange heat, water vapor, and oxygen. For example, Wolanski (1986 [4.1]), Wattayakorn et al. (1990 [4.2]), Wolanski (1992 [5.5]) and Ridd and Stieglitz (2002 [4.4]) reported that evaporation can lead to the formation of a salinity (density) maximum zone in mangrove creeks that can inhibit material exchange between mangrove areas and the open sea (see Section 3.6 and Figs. 3.6 and 3.7). During the wet season, rainwater dilutes the concentrations of various components within water and leads to an increase in water levels in coastal areas. In return, humidity within mangrove swamps is influenced by evaporation from the water surface within creeks.

We emphasize that the interrelations between each pair of factors described above are not independent of other interrelations: the individual interrelations combine to define the total feedback system. In conclusion, mangrove areas have established their own topographies (biogeomorphology) and preserved their sensitive ecosystems through various long- and short-term feedback processes between biotic activity, water flow, landforms, and the atmosphere in and around mangrove forests (see Plate 2), although these ecosystems are also strongly dependent on
changes in global sea level such as eustacy (Fujimoto et al., 1996; Miyagi, 1998). Therefore, it must be recognized that any impact of human activity on topography, water flow, or biotic activity in mangrove areas, including minor impacts, has the potential to alter the feedback chains and thereby lead to the degradation of natural mangrove ecosystems.

5.2. Bio-geomorphology formed by the mangrove ecosystem itself to ensure survival

Mangrove areas have two topographic peculiarities (see Section 4.1): (1) Wide areas of mangroves are flooded with each tide, grossly changing the flooded area and volume of the system, and (2) mangrove trees, prop roots, and pneumatophores interact with water flow to form eddies or turbulence at various spatial (horizontal and vertical) and temporal scales. In addition, R-type forests comprise mangrove swamps and tidal creeks. Notwithstanding the drastic difference in topography between wide-flat swamps and long-deep creeks, water motions in the swamp and tidal creek are always connected and influence each other (see Fig. 7 in [5.2]). As evident in Fig. 3.9, these topographic characteristics play important roles to maintain a natural and healthy mangrove ecosystem. These unique topographic characteristics have developed over many decades through the feedback processes described in Section 5.1. In other words, to maintain a healthy environment for its survival, the mangrove ecosystem has created its own topography (i.e., bio-geomorphology) via a number of important feedback processes. The following examples illustrate this idea.

As mentioned in Section 4.7, the ebb–flood tidal asymmetry in creeks (see Fig. 6 in [5.3]) is caused by interaction between the flow in tidal creeks and flooding water within the wide mangrove swamp. This tidal asymmetry is crucial in the maintenance of the geometry of the mangrove/creek system. The larger ebb current tends to export bottom sediments of the creek to the open sea and maintains the deep tidal creek. Reducing the size of the swamp or increasing the vegetation density acts to reduce the ebb tidal currents, i.e., the tidal asymmetry, and the creek rapidly accumulates silt, thereby resulting in the isolation of the mangrove ecosystem from the open sea. It appears that in order to maintain the creek depth required for survival, natural and healthy mangrove forests have exerted a control on their own vegetation extent and density via the feedback processes described above.

Offshore waters are able to reach the innermost parts of mangrove swamps via tidal action through numerous creeks and intertwining tributaries (see Figs. 4.7, 5.3b and the upper right picture in Plate 1). Without these tidal creeks and tributaries, biota such as mangrove vegetation and benthos living in the innermost parts of mangrove swamps would be unable to receive organic/inorganic materials such as nutrients and oxygen from the open sea, as tidal water is unable to travel long distances directly through mangrove swamps because of the strong drag force in such environments. The network of these tidal creeks and tributaries play a role that is similar to that of the vascular system in humans. Material transport through ‘capillary vessels’ supports biotic activities in the mangrove environment. In a sense, it can be considered that in order to maintain the ecosystem, the ecosystem itself has created the creeks and tributaries, or capillary vessels, via the feedback processes.

Aquaculture farms developed in such areas have unknowingly utilized these natural mechanisms (Fig. 4.7); however, increased siltation at creek mouths and reduced navigability (to the point where the creek can dry up totally at low tide) is a common occurrence in Southeast Asia in areas where prawn farms have been constructed within mangrove forests (Wolanski, 2006). Hong and San (1993) stressed that one of main reasons for low production of cultured shrimps in traditional shrimp pond system in Vietnam is the difficulty of water exchange between the pond and the tidal creek due to unsuitable pond location. As mentioned in Section 4.7, the siting of the farm ponds requires much more care than at present.
5.3. Response of nature to human activities

5.3.1. Thinning of mangrove forests: destruction or recovery?

Dissolved, floating or suspended particles in/on water such as mangrove seeds, fish eggs, prawn larvae, nutrients and fine sediments are dispersed within mangrove areas, and may then be flushed out to the adjacent coastal sea due to tidal and wave action. This dispersion is important for sustaining mangrove colonies and their ecosystems (Boto and Bunt, 1981).

In order to demonstrate that the material dispersion in an R-type forest depends on vegetation density (or the drag force due to mangrove vegetation), Mazda et al. (1999 [9.2]) used numerical experiments, based on the tidal trapping model that is introduced in Section 2.3 (e.g., Wolanski and Ridd, 1986 [5.2]), resulting in Fig. 5.2. The dashed line \((a)\) in the figure indicates the magnitude of material dispersion caused by a decrease in the inundation of water volume from the creek into the swamp with increasing vegetation density (volume effect). The dashed line \((b)\) indicates the effect of an increase in the delay time of water discharging to the creek at ebb tide with increasing vegetation density (delay effect). The solid line \((a \cdot b)\) is the combined effect due to the volume effect \((a)\) and the delay effect \((b)\), which shows the nonlinear relationship between vegetation density and material dispersion. The solid line records a minimum level of dispersion at Point A and a maximum level at Point B.

Considering the above nonlinear relationship between vegetation density and material dispersion, Mazda et al. (1999 [9.2]) proposed the following basic guideline regarding deforestation or thinning within mangrove areas. In natural forests, the vegetation density is maintained by the balance between the decay of trees, production of seeds, decay of the seeds, and dispersion of the seeds from generation to generation. Artificial thinning disturbs this natural balance. Thinning not only leads to a reduction in vegetation density, which is accompanied by a reduction in the production of seeds (propagules), but also a change in the dispersion of seeds seen in Fig. 5.2. When the vegetation density after thinning lies within the range to the left of Point A in Fig. 5.2 or in the range to the right of Point B, the dispersion of seeds is enhanced compared with that before thinning. In contrast, when the vegetation density after thinning lies within the range between...
Point A and Point B, a reduction in seed dispersion occurs. These considerations suggest that the question of whether the mangrove colony will progressively degenerate from generation to generation following thinning or whether it will recover to the pre-thinning vegetation density depends not only on the vegetation density at thinning but also on the dispersion characteristics of seeds following thinning. Mangrove trees shed thousands of seeds to the surrounding area; however, the fact that it is difficult to locate these seeds within the forest after a period of time is an indication of the effectiveness of the above dispersion. Thus, when thinning is planned, the characteristics of seed dispersion should be taken into consideration. Unfortunately, however, Fig. 5.2 is just a schematic representation based on a simple model simulation, and the above discussion is purely conceptual. The actual positions of Points A and B for a real forest are unknown, because although the relationship between vegetation density and the drag force is presumed to depend on the species of mangrove, the details of the relationship have yet to be investigated.

The above experiment is based on well-mixed flow conditions. Other processes of material dispersion can occur in density (salinity) stratified flows (Turell and Simpson, 1988). Furthermore, Kuwabara (2002) emphasized the importance of physical characteristics for seed dispersion in tidal creeks, including the position of the centroid of floating seeds and the density of seeds relative to the surrounding water. These processes merit further study in the field, laboratory, and via numerical experiments in view of their importance to mangrove ecology and their implications for environmental management.

5.3.2. Coastal erosion resulting from deforestation

It is well known that F-type mangrove coasts that have been partially deforested are susceptible to severe erosion by sea waves. The hydrodynamic characteristics of F-type forests that prevent coastal erosion from sea waves have been analyzed by Mazda et al. (1997b [3.2]), Furukawa et al. (1997 [3.1]), Massel et al. (1999) and Mazda et al. (2006 [3.3]). Here, we also discuss an example of coastal erosion caused by tidal action that occurred as a natural response to human activities within R-type forests (Mazda et al., 2002 [9.5]). The coast at Long Hoa village, southern Vietnam (J in Plate 1; Fig. 5.3b), has been eroded continuously by approximately 50 m/year since the early 20th century, and the rate of erosion does not appear to be abating (Fig. 5.3a). As evident in Fig. 5.3b, the coast borders the mouth of a tidal river (Mui Nai) that is fringed by wide mangrove forests. The erosion results from long-term changes in vegetation density within the mangrove swamps, even though the eroded coast is not in direct contact with the mangrove swamps (R-type).

The progress of coastal erosion over many decades, as seen along the Long Hoa coast, requires two prerequisite conditions. First, the current flow has to be strong enough to move bottom sediment. Second, the flow should not be in a steady state over this long term; otherwise, erosion is balanced by sedimentation, and no net erosion occurs. The existence of wide R-type mangrove swamps leads to strong tidal currents at the mouth of the creek (see Fig. 3.5). These strong tidal currents are able to move bottom sediments along the coastline of Long Hoa adjacent to the creek mouth. Accordingly, the first necessary condition for coastal erosion is well satisfied in this area. In addition, human-induced changes in the density of mangrove vegetation since the late 19th century (see the bottom in Fig. 5.3a) probably prevented the amplitude of tidal flow from achieving a steady state; this satisfies the second condition. The persistence of these two conditions means that long-term transitional coastal erosion continues in this area. However, it is not simply a matter of whether the coastal erosion is caused by deforestation or afforestation, as both erosion and sedimentation depend on various subtle changes in the topography of the sea floor. Hang et al. (2003) reported similar events, in which some coastal zones were eroded and the neighboring zones were accumulated with 20 m/year (maximum).
It should be noted that it is not only the deforestation of F-type forests that leads to coastal erosion, as the deforestation of R-type forests, which do not have contact with the open sea, can also lead to coastal erosion. This suggests that to prevent coastal erosion, it is important to intensively manage human activities throughout the entire estuary system, including inland areas.

5.3.3. Paradox between preservation and utilization of mangroves

Along coastlines in tropical areas worldwide, earnest efforts have been made to plant mangroves over extensive areas. To promote effective plantings, preserve the environment of the planted forests, and utilize the ecosystem that develops in such an environment, it is necessary to obtain a quantitative understanding of the key physical and hydraulic processes in such a setting (Wolanski, 2006).

As mentioned in Section 4.5, the reduction in wave amplitude in mangrove forests results from the energy loss throughout the entire width of vegetation (Mazda et al., 1997b [3.2]). Therefore, both vegetation density and vegetation width are important factors for consideration at the time of planting. The mitigation of wave energy transforms the mangrove forest facing the open sea into a comfortable nursery for aquatic life; however, excessive planting, i.e., excessive vegetation density and/or excessive width of the vegetation area, will act to suppress water movement at the forest head and prevent the exchange of water and organic/inorganic materials.
between the forest and the open sea. This in turn will result in the degradation of water/sediment quality and consequently damage to the forest ecosystem. This afforestation paradox should be noted.

Another example for the paradox is as follows. Chong et al. (1996 [9.1]) observed that one of R-type mangrove estuaries, Klang Strait in Malaysia (I in Plate 1) shelters about 65 billion penaeid prawn larvae annually. Based on a numerical simulation (see Section 2.3), the authors suggested that the tidal currents in the narrow mangrove-fringed creeks have a strong cross-shore component (e.g., Wolanski et al., 1990 [5.3]), and prawn larvae remain trapped in the mangrove swamps by the lateral trapping effect. In other words, mangrove swamps are a storage area or a nursery ground of prawn larvae when they are inundated. This explains that if the mangroves were destroyed for development of prawn farm, prawn larvae may be advected into the open sea from the spawning grounds. The loss rate of these larvae thereafter may double. This should measurably decrease the value of the prawn fishery itself.

To avoid these paradoxes, the functioning of the ecosystem and hydrology at the site should be understood quantitatively before allowing any human impacts, as argued by Lewis (2000). Unfortunately, however, we have insufficient knowledge of the relevant processes.
Chapter 6

Research Technology

Snedaker and Snedaker (1984) published a book on methodological procedures for studying mangroves from a viewpoint of biology, ecology, geomorphology, and phenology, while Kjerfve (1990) presented a manual, written from a physical viewpoint, for mangrove researchers who are working with field observations. Kjerfve’s manual describes a number of salient features of the hydrological processes that affect mangrove ecosystems and outlines a basic physical methodology to use in studying hydrological processes within mangrove environment. With reference to these results and our own experiences in various mangrove fields, we make the following recommendations in terms of mangrove research technology.

6.1. Field observations

As the natural environment in mangrove areas is basically controlled by tidal inundation, we emphasize that observations undertaken from an ecological viewpoint should be carried out by interdisciplinary collaboration with consideration of the temporal changes in water movement and water properties particularly at the tidal time scale, even though the ecology may change over much longer time scales. The concentration of material such as nutrients, fish eggs and larvae, and their fluxes, generally change with tidal stage. Thus, for example, the concentration of material collected at high tide cannot be considered to be representative of the concentration of material throughout a tidal cycle (e.g., Fig. 3.8). To obtain a representative value, e.g., the mean value for a tidal period, measurements should be taken with at most 3-hour intervals for a semi-diurnal tidal cycle, as this includes information for low, flood, high and ebb tidal stages; the resulting data should then be dealt with quantitatively under a proper system of evaluation. For more accurate data analyses Kjerfve (1990) recommended 1-hour or 1.5-hour intervals.

It should also be remembered that tidal conditions, for example, tidal amplitude and mean tidal level, are not constant throughout the year, but change fortnightly and seasonally (see Section 4.2). In particular, when evaluating the material budget through a complete tidal cycle, i.e., the net transport of material between mangrove areas and the open sea, the phenomenon of tidal inequality (Section 4.2.4) should not be neglected. Under the condition of tidal inequality, in which the water-mass transported during flood tide is not equal to that transported during ebb tide, it is meaningless to compare the magnitude of material transported by these different water masses during flood and ebb tides (Mazda, 1984a).

Considering the potential for spatial variability in water currents within swamps and creeks, particular care needs to be taken in selecting sites for measuring current velocities (see Figs. 7 and 8 in [6.4]). In contrast, water levels and water properties are generally similar over a wide area (Woodroffe, 1985a). As current velocity can be estimated from changes in water level, Woodroffe (1985a) recommended that to understand the average characteristics of water flow in mangrove
swamps it is easiest to measure time series plots of water elevation rather than directly measuring current velocity, based on quantitative measurements from Tuff Crater in New Zealand (G in Plate 1).

In mangrove swamps with shallow water depths water properties are vertically uniform because of mixing related to water turbulence. Thus, to determine a representative value it is sufficient to measure just one layer within water column. However, this approach is not valid for creeks: the water properties in many creeks show strong vertical stratification during ebb tide, although they tend to become uniform during flood tide (see Section 4.7).

As mentioned previously, water movement and material distribution within mangrove soils play an important role in the development of mangrove ecosystems. The spatial distribution of macropores such as animal burrows and void spaces formed from rotten leaves and roots within the soil is very irregular. Thus, particular care should be taken when measuring the hydraulic conductivity, which is an important factor in controlling the soil condition (see Sections 3.3 and 4.8). In terms of the methodology to be used for quantitative underground observations, Ridd (1996 [7.2]), Ridd and Sam (1996 [8.1]), Ridd et al. (1997 [4.3]), Stieglitz et al. (2000b [8.3]), Hollins et al. (2000) and Susilo and Ridd (2005 [8.4]) describe various simple methods that can be used to detect groundwater levels, salinity, electric conductivity, and hydraulic conductivity. These methods are based on electrical conductivity probes that use a similar principle to geophysical resistivity arrays that are commonly used in geophysical prospecting. A small current is injected into the soil across two electrodes and the voltage is measured across another electrode pair. The ratio of current to voltage gives a measure of electrical conductivity of the soil. The probes can be made very small, down to a few millimeters in diameter and have a variety of uses. The probes can be used to measure the salinity of the groundwater, and can detect the presence of crab burrows, as crab burrows filled with water have a very high conductivity relative to the surrounding soil. Burrows filled with air give a very low conductivity reading when the probe passes through them.

6.2. Data analyses

Generalizing the many physical mechanisms that occur within mangrove swamps requires the accumulation of field data, which depend on many parameters such as mangrove landforms, mangrove species, vegetation densities, and seasonal, tidal, and atmospheric conditions.

In R-type forests, materials that are exchanged between mangrove swamps and the adjacent open sea pass through the creek mouth. Thus, it is convenient to analyze temporal changes in material distributed on a cross-section at the mouth (Dyer, 1973; Mazda, 1983; Mazda, 1984a; Mazda, 1985). Dyer (1973) proposed a method of distinguishing the different physical processes of material transport through the mouths of bays or estuaries. Water flow velocity and flux of materials transported by the water flow are composed of a constant term caused by river runoff, a tidally oscillating term, and a turbulent term. Furthermore, each term comprises a cross-sectional average and a deviation from the average. This deviation can be separated into a transverse deviation and a vertical deviation. Analyzing observational results via this method, Dyer et al. (1992) found that river discharge that depends on rainfall, and gravitational (density-induced vertical) circulation, which depends on the tidal range, play important roles in the material exchange between mangroves and offshore waters.

The residence time or flushing time, which is introduced in Section 4.2.9, is a useful parameter in evaluating the potential of preservation of the ecological environment within individual enclosed areas (Mazda, 1983; Wolanski et al., 1990 [5.3]; Wolanski, 1992 [5.5]; Wolanski et al., 2001; Heron and Ridd, 2001 [7.3]; Wolanski, 2006).

As mangrove swamps are intertidal areas with no water during low tide, time-series plots of observational values such as water level, current velocity, salinity, and other water properties are
discontinuous between flood and ebb periods (e.g., Fig. 3.8 and Fig. 2 in [7.6]). Accordingly, in this case it is not appropriate to use the method of harmonic analyses, which is convenient for the analysis of continuous phenomena with sinusoidal time series.

Altimetry measurements in mangrove forests are not easy because of the thick vegetation and muddy bottom substrate. To determine a horizontal surface (i.e., datum line) in the forest, it is accurate and convenient to simply measure the water level at various sites. This method is based on the principle that the water surface is horizontal at high tide, when tidal flow ceases in swamps (see Section 3.5.1). However, our field experience suggests that this method should not be used when the water depth is less than around 10 cm. In such shallow water depths, the high tide in the recesses of the forest lags behind that in coastal areas due to the drag force of mangrove roots, which strengthens with decreasing water depth (see Fig. 3.4b).

### 6.3. Laboratory experiments

Mangrove trees are a complex combination of trunks, prop roots, pneumatophores, branches, and leaves. The vertical configuration of these elements restricts water flow due to drag forces and viscous forces. Furthermore, both the drag and viscous forces vary with tidal level because of the vertical profile of mangroves. As it is difficult to reduce the scale of these vertical configurations for laboratory experiments (rule of hydrodynamic similarity), little experimentation has been undertaken to understanding the detailed hydrodynamics of mangrove areas. Notable exceptions are the work of Hamzah et al. (1999) and Hiraishi and Harada (2003) for tsunamis in mangrove areas, as described in Section 4.9, and the work of Heron and Ridd (2003) for underground flow through animal burrows. Heron and Ridd (2003) using a combination of computational fluid dynamic models and laboratory studies found that the flushing of burrows is inhibited by highly saline water which may sometimes fill burrows. Highly saline waters can accumulate in burrows due to salt exclusion at the mangrove root. Because highly saline waters have higher density, they can form a stable water mass within burrows. It is speculated that the presence of buttress roots and other obstacles to surface water flow generate larger pressure gradients across animal burrows which can help to flush the highly saline burrow water. When executing laboratory experiments, these peculiarities in mangrove swamps need to be considered.

### 6.4. Numerical experiments

The hydrodynamics of mangrove areas is not easy to model numerically because mangrove areas comprise compound intertidal areas. At low tide, mangrove swamps are exposed, changing to submerged areas at high tide. Thus, it is not easy to simulate this condition continuously. Wolanski et al. (1980 [1.1]) computed the pattern of tidal flow within a tidal creek–mangrove swamp system, i.e., an R-type forest, with combined two cell models, a swamp model and a creek model, in which both the tidal creek and the swamp were separately divided into many cells. Wolanski and Ridd (1986 [5.2]) and Ridd et al. (1990 [1.2]) studied flow mechanisms in tidal creeks using simple mathematical models and simplified morphologies. Mazda et al. (1995 [1.3]) and Mazda et al. (1999 [9.2]) studied tidal flow mechanisms in R-type forests using numerical mesh models with simple morphologies. Nihei et al. (2004) developed a nesting procedure to numerically simulate tidal currents in mangrove swamps. Uchiyama (2004) developed a numerical model (WD-POM model) that incorporates a wetting and drying scheme into the Princeton Ocean Model (POM model; Blumberg and Mellor, 1983). Uchiyama (2005) adapted this model for San Francisco Bay, which has extensive intertidal area including mudflats and deeper channels, though there is no mangrove. The model demonstrated that cohesive sediments are suspended dominantly in the deeper channels while being transported and deposited on intertidal areas; this result supports the observation in Hinchinbrook Cannel in Australia (E in Plate 1) by Wolanski.
et al. (1998), which is mentioned in Section 2.2.3.

These numerical experiments were performed under the assumption of constant coefficients of drag force and viscous force, except Wolanski et al. (1980 [1.1]). As mentioned above, vertical variations in the obstructions that mangroves present to water flow must be considered. Based on the idea of Wolanski et al. (1980 [1.1]), Mazda et al. (1997a [2.1]) simply modified these vertical configurations and parameterized them in terms of the representative length scale \( L \); see Eq. (3.2)), which varies with water depth. Furukawa et al. (1997 [3.1]) studied flow patterns on the basis of the simplified horizontal distribution of mangrove vegetation. In terms of understanding the physical characteristics of the prop roots that support mangrove ecology, Sato (1978) statistically determined the vertical distribution of the prop roots of \textit{Rhizophora mucronata}.

Mazda et al. (1997a [2.1]), Kobashi and Mazda (2005 [2.2]) and Mazda et al. (2005 [2.3]) analyzed the behavior of the drag and viscous forces due to mangrove vegetation within a tidal time scale, however, with the exception of \textit{Rhizophora} spp. and \textit{Bruguiera} spp. The mechanisms of the drag and viscous forces associated with mangrove vegetation with vertical configurations have yet to be formulated.

Once quantitative formulae for the drag and viscous forces of mangrove vegetation are established, the combined model of the nesting model proposed by Nihei et al. (2004) with the WD-POM model by Uchiyama (2004) will be able to accurately simulate flow and formation of topography within mangrove swamps with meandering creeks and intricate numerous tributaries. These developments are needed as basic information when maintaining and utilizing mangrove environments.

Numerical simulations of smaller-scale phenomena such as animal burrows intertwined within the soil substrate are less common. Heron and Ridd (2001 [7.3]) succeeded to simulate tidally induced flow in multi-opening animal burrows within mangrove swamps.
Chapter 7

Modeling of Mangrove Systems

To preserve and utilize the natural environment over a long time period, it is necessary to consult appropriate models that quantitatively assess whether the natural environment, i.e., the mangrove ecosystem, is able to survive the impact of human activities.

Considering the peculiarities of mangrove areas, the following models are required to enable sound management practices, particularly from a hydraulic viewpoint.

1) Water flow models that take into account the peculiarities of mangrove areas: Since the nature of water flow within mangrove areas depends on the time scale, it is necessary to develop separate hydrodynamic models of tidal flow, sea waves, groundwater, and tsunamis.

2) Models of material transport: Models of dissolved material should take into account the peculiarities of the dispersion coefficient, which depends on the unique topography and spatial characteristics of vegetation density (see Section 5.3.1). Models of suspended material are also important because suspended material derived from mangrove litter coagulates and contributes to the formation of bottom topography. Furthermore, models of bottom-sediment transport are also important because bottom sediment is readily transported with flowing water, resulting in deformation of the topography and the destruction of mangrove colonies.

3) Ecosystem models: As mentioned previously, the mangrove ecosystem is maintained via strong feedback between biotic action, landforms, water flow, and the atmosphere (Plate 2). Each of these elements operates at different time scales. The total ecosystem is established by nonlinear interactions between these elements with contrasting time scales.

Until now, assessments of temperate coastal environments have been performed according to a one-way process described in the following two steps.

Step 1: According to the chosen hydrodynamic model, water flow, which transports and disperses chemical/biological materials, is simulated within a fixed topography.

Step 2: Using the chosen ecosystem model that composed of the flows of biomass and energies in food-webs, the dynamics of chemical/biological materials and their distributions in the area are simulated, linking the water flow calculated in the above hydrodynamic model.

Compared with temperate environments, mangrove environments and ecosystems are sustained via strong feedback processes between biotic action surrounding mangrove trees, landforms (three-dimensional topographies), water flow with twice inundations a day, and the atmosphere (Plate 2). For example, as noted in Chapter 5, the tide within mangrove swamps is significantly deformed compared to that in offshore areas. In other words, the present tidal elevation in mangrove swamps was established under the influence not only of the tide in the open sea but also the activity of the mangroves themselves (Mazda and Kamiyama, 2007 [2.4]). Accordingly, the
physiology of mangrove vegetation, the tidal motion in mangrove swamps and the bottom
topography develop via the above feedback processes over many decades. Once the bottom
topography changes as a result of natural or human-induced factors, this change leads directly to
subsequent changes in the intensity/pattern of water flow, the transport processes of materials
such as mangrove seeds/nutrients, and the distribution of mangrove trees/benthos; these changes
in turn feedback to additional changes in the bottom topography. Conclusively, the mangrove
ecosystem is a system for which feedback processes cannot be neglected.

Considering these processes, modeling should be performed as follows. First, models of the
elements listed in Plate 2, i.e., biotic action, water flow, landforms, and the atmosphere, need to
be developed independently. Next, the nature of interaction between the individual models needs
to be quantified, and the individual models need to be modified. Lastly, the total ecosystem model
should be established via the connections or feedbacks between these modified individual models.
In this sense, each of the different models developed previously, which are described in Section
2.3, should be arranged as a combined model. As these models currently lack quantitative
mechanisms, they should be modified according to the findings of future studies.
Chapter 8

Future Studies in the Context of the Preservation and Utilization of Mangroves

The rapid degradation and destruction of mangrove forests in tropical countries calls for conservation based on a sound scientific understanding of mangrove ecosystems. Sixteen years ago, Kjerfve (1990), who is a pioneer and a distinguished leader in the field of mangrove physics, made the following comment. “Lugo and Snedaker (1974) stressed that both physiognomy and formation of mangrove forests are controlled largely by local tidal patterns and terrestrial surface drainage. Hydrological differences from site to site may be the dominant factor in controlling structure and productivity of coastal mangrove zones. However, at present this is only a hypothesis, and the data base to allow testing of this hypothesis does not yet exist.”

Since that time, many physical factors have been identified that are unique to mangrove areas, and their behavior and mechanisms have been analyzed, as summarized in this book. It has also been recognized that many physical processes play important roles in mangrove ecosystems; however, a quantitative understanding of this link between physical processes and the ecosystem is inadequate. It is quantitatively unclear as to how biological and chemical phenomena in mangrove swamps are related to those physical mechanisms and/or hydrodynamics, and how mangrove ecosystems are affected by changes in physical and/or hydrodynamic properties (Wolanski, 2001).

We propose that in the future, the study of mangroves should be advanced in a systematic manner according to the following list.

1) **Data collection from different areas and under different conditions:** Major studies in mangrove areas have been undertaken from physiological and ecological standpoints. It is only a short time since the first studies considered the physical processes that are active in mangrove areas. Since Wolanski *et al.* (1980 [1.1]) first studied the role of tidal flow in the formation of mangrove environments, physical processes, especially hydrodynamics in mangrove areas, have been studied by Wolanski and Ridd (1986 [5.2]), Kjerfve (1990), Mazda *et al.* (1995 [1.3]), Furukawa *et al.* (1997 [3.1]), Massel *et al.* (1999), Susilo and Ridd (2005 [8.4]), etc. However, most studies are case studies that focus on particular locations and are not yet generalized. There is a clear need for more data from different locations to enable generalizations to be made, and it is hoped that researchers, particularly young researchers or students interested in mangrove physics, will be encouraged to take on this challenge.

2) **Generalizing physical processes and formulating mechanisms:** To preserve and utilize mangrove environments and ecosystems, it is necessary to generalize and quantitatively formulate physical processes and their mechanisms within mangrove areas.

3) **Investigating the roles of the above physical processes within mangrove ecosystems:** To understand the important roles of physical processes on mangrove ecosystems, it is necessary...
4) **Formulating the relationships between physical processes and mangrove ecosystems:**

Formulating the relationships between physical processes and mangrove ecosystems is the ultimate goal of mangrove physics. We will be unable to successfully preserve and utilize mangrove ecosystems until we have quantitatively formulated the relevant physical processes and mechanisms and their relationships to the ecosystem (Wolanski, 2006).

As Wolanski (2006) stated, the mangrove ecosystem is established in the context of ecohydrology, which involves interactions and feedback between terrestrial, estuarine, coastal, and offshore areas. Furthermore, taken from contrasting viewpoints, the mangrove ecosystem evolves via intertwining nonlinear interactions among biological, chemical, and physical factors, each of which has unique individual temporal and spatial scales. To understand the mangrove ecosystem as a whole, and to preserve it and ensure that human activity is in harmony with it, interdisciplinary studies, including various study fields, should be undertaken by researchers with an interest in mangrove coastal areas. To solve the nonlinear interaction among biological, chemical, and physical factors, it is necessary to undertake joint studies involving researchers with different areas of expertise, especially simultaneous studies at a common site. To quantify and confirm the importance of mangrove ecosystems as a natural sink for atmospheric CO$_2$, interdisciplinary research has been undertaken in the past by multiple researchers with different specialties, focusing on targeted field sites, Hinchinbrook Channel in northeastern Australia (E in Plate 1) from 1995 to 1997 (Ayukai, 1998), and Sawi Bay in southern Thailand (I in Plate 1) from 1998 to 1999 (Brown and Limpsaichol, 2000), sponsored by the Kansai Electric Power Co. Inc, the Kansai Environmental Engineering Center Co. Ltd., and the Australian Institute of Marine Science. Furthermore, an interdisciplinary study undertaken by physicists, chemists, biologists, ecologists, hydrologists, pedologists, dendrologists, entomologists, and geneticists has been organized and developed under the sponsorship of the Research Institute for Subtropics from 2000 to 2003 (Research Institute for Subtropics, 2003). Additional such interdisciplinary studies should continue to be organized at an international level in the future, especially in the field of mangrove ecosystems where important controls are exerted by strong feedback processes between many different factors.
REFERENCES


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References


