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## Coastal development through mangrove creek catchments



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singapore-delft water alliance

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## Summary

Mangroves are woody plants with distinctive root structures that grow at the land-sea interface, such as bays, estuaries, lagoons and backwaters, in low latitude regions (i.e. the tropics). They are subject to periodic inundation in saline conditions due to tidal variations at these land-sea interfaces. The distinctive root structures help the mangroves to obtain enough oxygen to survive. The term mangrove is more commonly used to indicate the entire mangrove ecosystem with all of its associated organisms. The definition of mangroves then becomes a tidal forest ecosystem in a sheltered saline to brackish environment.

Mangroves have the ability to accrete the substrate on which they grow and can therefore be used as measures opposing the negative impacts of sea-level rise. This form of using nature as engineering solutions is called eco-engineering. The hydrodynamics and morphodynamics within a mangrove ecosystem are studied in this master thesis. Knowledge on these processes is of importance for possible use of mangroves as engineering solutions in flood protection.

Shoreline development is normally based on the morphological cycle of hydrodynamics, sediment dynamics and morphology. With the presence of mangrove vegetation, a fourth factor can be added to this cycle, creating a morphological diamond. The mangrove vegetation causes obstruction in the currents during tidal inundation and wave activity, meaning that it directly influences hydrodynamics and sediment dynamics. In the past, research has been performed already into the influence of mangrove vegetation on hydrodynamics and sediment dynamics. This research focused on riverine and fringing mangroves, with a special interest on how the vegetation influenced hydrodynamics, such as current velocities and wave heights, and morphodynamics, such as the magnitude of sediment transport and sediment deposition. However, how sediments were supplied into the mangroves was of minor importance. It is known that sediments are transported over the fringe and through the tidal creeks, but how most sediments are transported deep into a mangrove forest is still unknown. This research focuses on the importance of tidal creeks in the supply of sediments into a mangrove forest and on sediment circulation through a mangrove forest, together with the spatial distribution of deposited sediments. With this focus, knowledge is obtained on how a mangrove forest accretes and how it could oppose the impacts of sea level rise by linking all three aspects of the morphological cycle in relation to the influence of mangrove vegetation.

To quantify the influence of tidal creeks on the supply and spatial distribution of sediments through the mangrove forest, field data was collected in a mangrove creek catchment in Southern Thailand. This field site was chosen for its extensive creek influence and a direct interaction with the estuary of the Kantang River. Also river influences were present from this river, which likely results in supply of sediment to the estuary and consequently to the creek catchment.

For the field measuring campaign the creek catchment bathymetry and vegetation characteristics were surveyed as boundary conditions for the hydrodynamic and morphodynamic processes. To investigate the hydrodynamic processes three Vectors (Acoustic Doppler Velocimeters, ADV) were deployed on a spatial grid during multiple spring-neap tidal cycles. These ADV's measured current velocities, current directions, suspended sediment concentrations and water depths, to obtain hydrodynamic and sediment dynamics data over one spring tidal cycle. During spring tide the

catchment is most active and therefore dynamics during spring tide are of most interest. For changing morphology, the sediment deposition was measured using sediment traps of own design. These traps consisted of tiles with a roughened topside to mimic a rough forest floor.

Results of the hydrodynamic measurements showed different current velocity ranges for the tidal creeks and for the inner area of the mangrove creek catchment. The current velocities in the tidal creeks were one order of magnitude larger than those in the creeks, with a maximum current velocity in the tidal creeks of 0.3 m/s and a maximum current velocity in the creek catchment of 0.07 m/s. This difference is caused by the increased bottom friction, due to the smaller water depths and the expected increased friction by the dense vegetation cover. Also a difference in the velocity profile over one spring tide is observed, with an ebb-dominated tidal asymmetry for the tidal creeks and a flood-dominated tidal asymmetry for the creek catchment. The current direction measurements indicate an inundation pattern that starts in the creeks, where water is supplied deeper into the creek catchment via a creek arm that extends into the center of the creek catchment. Once the entire creek catchment is inundated, the current directions become perpendicular to the forest fringe and water from the estuary flows directly into the forest over the forest fringe. Vegetation does not seem to directly influence the current directions. For this the bathymetry is more important. However, the magnitude of the current velocities seems to be affected by both the vegetation and the bathymetry.

For the sediment dynamics ADV measurements were taken of the suspended sediment concentrations. The absolute values of the suspended sediment concentrations seem to be too small to be valid data. However, the suspended sediment profile over one spring tidal cycle shows good coherence in the current velocity profiles at the same measuring points. So the trends of suspended sediment concentrations are still useful for interpretation. The large current velocities in the creeks cause large suspended sediment concentrations to be carried into the creek catchment. Also over the fringe much larger suspended sediment concentrations are present than within the creek catchment. In the creek catchment relatively large suspended sediment concentrations are present during flood tide and smaller suspended sediment concentrations during ebb tide. This results in settling of sediments to the bed that cannot be entrained again by ebb currents. This could be caused either by lower ebb current velocities and by flocculation of sediments during settling. The settling of the sediment leads to little outflow of sediments over the forest fringe. The creeks however show large suspended sediment concentrations during the large ebb current velocities. These sediments are most likely entrained from the creek bed itself and this causes the self scouring of the creek bed.

The measured sediment deposition rates ranged from 27 to 209 g/m<sup>2</sup>, which corresponds to an estimated accretion rate for clay dominated soil of 0.013 to 0.10 mm over one spring tidal cycle. These deposition rates are quite variable. The largest deposition rates are found in the center of the creek catchment and at the forest fringe. At the forest fringe large amounts of sediments are carried into the creek catchment from the estuary. Because of the large drop in current velocities and the dense vegetation at the fringe, the sediments are deposited at the bed of the forest fringe. Large amounts of sediments are carried into the creek catchment sediments are carried into the creek catchment through the tidal creeks extending into the center. The sediments transported through the creeks are also deposited in the forest due to the reduction in current velocities when the water enters higher elevated areas, resulting in the high sediment deposition rates within the creek catchment. An indicative calculation of the accretion

rates extrapolated to an annual accretion compared with forecasted annual sea level rise shows that a mangrove forest can keep up with sea level rise. This makes a mangrove forest a very interesting ecological engineering solution for flood protection.

In conclusion, the tidal creeks seem to play an important role in the supply of sediments to the mangrove creek catchment. Tidal inundation of the creek catchment starts with the tidal creeks, very high suspended sediment concentration rates in these creeks and high sediment deposition rates in the center of the creek catchment. The high deposition rates at the forest fringe in combination with low deposition rates just behind the fringe indicate that the high deposition rates in the center of the creek catchment originate from sediment supplied by the tidal creeks. The comparison of the collected field data in combination with the research area characteristics to collected field data in literature gives confidence in the validity of the results. Because the scale of the research creek catchment was smaller than in most literature, smaller hydrodynamic and morphodynamic data can be expected. The outcomes of this research prove that mangroves are a good engineering solution to adapt coasts to sea-level rise.

### Preface

Eco-engineering is a topic in civil engineering that has been of great interest in recent years. The ability to use nature for engineering solutions is very appealing. By using nature instead of hard technological engineering solutions a more durable long-term situation can be obtained, because nature is more capable of adapting to changing conditions. I personally strongly believe that nature is more capable of protecting us against more extreme events than technological solutions. Hard technological solutions require constant upgrading to keep up with the changing conditions, because they are designed for specific events. With this research I hope to have contributed to the possibility to use mangroves as an eco-engineering solution in the future.

I would like to thank my supervisors Erik Horstman and Marjolein Dohmen-Janssen for their help and assistance during my research. Special thanks go out to Erik, in first for my wonderful stay in Singapore and Thailand and our stay together during this period of time. Second, for your guidance and support during our close cooperation under tough working conditions in Thailand. I would just like to say: "Erik, we did it!". Also special thanks to Niels-Jasper van den Berg for our nice cooperation and stay in Thailand during your 3 months of living in Thailand. Also I would very much like to thank my parents for their big support from the Netherlands during my stay in Singapore and Thailand, and later on during the writing of my report here in the Netherlands.

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## 1. Introduction

This master thesis describes a study into hydro- and morphodynamics of mangroves and consequently the opportunity for the application of mangroves in the battle against sea-level rise. The application of mangroves against the impacts of sea-level rise is a form of ecological engineering that uses nature to protect coastal regions. In case of uncertain scenarios related to sea-level rise, ecological engineering solutions may be used to postpone destructive and irreversible engineering measures for coastal protection. Ecological engineering solutions for sediment trapping, which can be a future application of mangroves, may be applied to counteract sea-level rise by accretion of coastlines. Ecosystem engineering solutions have a more adaptive nature in coastal protection than hard engineering solutions and measures can therefore be less over-dimensioned. The smaller dimensioned solution in turn leads to reduced costs (Borsje et al., 2011).

In this introductory chapter, first a system description of mangroves is given, to get a better understanding of the mangrove ecosystem. Consequently, the interaction between mangrove vegetation and hydrodynamic and morphodynamic processes is described from present knowledge in literature based on a morphological framework that will be presented. From these descriptions of the entire system, a research objective is derived with corresponding research questions. The last section of this chapter gives a brief overview of the set-up of this research and the remainder of this report.

#### 1.1. The mangrove ecosystem

Mangroves comprise an entire ecosystem and not just a type of vegetation. A good perception of what mangroves exactly are and where they grow, is essential in the understanding of the interactions between mangroves and the physical processes and for their possible implementation in coastal engineering.

#### 1.1.1. Defining mangroves

To give a definition on mangroves is not straightforward, because the term mangrove is used in two ways. First, the word 'mangrove' can be used to indicate a single tree, with specific characteristics and a restricted living environment. Secondly, the term 'mangrove' can be used to indicate a forest of mangrove trees. So a clear definition of both meanings of the term mangrove will help understand the use in certain contexts.

An individual mangrove tree is a woody plant that grows in low latitude regions (i.e. tropics) along sheltered land-sea interfaces, like bays, estuaries, lagoons and backwaters (Kathiresan, 2005). The individual mangrove tree consists of various species with different appearances and preferred living conditions. A full list of mangrove trees is presented in appendix 3. Such an individual mangrove tree has a very distinct root structure, as described in appendix 1, which is able to obtain enough oxygen to survive during periodic inundation. This distinct root structure interacts with hydrodynamics and morphodynamics during the periodic inundation. The individual mangrove tree is capable of growing in these areas, because it is tolerant to saline conditions and actually needs these saline conditions, along with a tidal regime and low energy wave environment, to survive. These individual trees and their associated organisms (microbes, fungi, other plants and animals), constitute the 'mangrove

forest community' or 'mangal'. The mangal and its associated abiotic factors constitute the mangrove ecosystem, as has been illustrated by Figure 1.



Figure 1 Physical and biological components of mangrove ecosystems (Kathiresan, 2005)

The main use of the term mangroves is to indicate the mangrove ecosystem. In that case, the definition of 'mangroves' is a tidal forest ecosystem in a sheltered saline to brackish environment (Augustinus, 1995). Because mangroves grow at the land-sea interface, they form the transition between terrestrial ecosystems and marine ecosystems, and are considered the low latitude equivalent of salt marshes. Mangrove presence is restricted to low latitudes, because of mainly climatic factors. A more in depth description of mangrove distribution and the factors influencing mangrove presence are presented in appendix 2.

#### 1.1.2. Mangrove settings and classifications

The presence of mangroves in low latitude regions can have different appearances, with different species compositions and multiple landscapes, where different physical processes play a more dominant role in a mangrove ecosystem. To get a quick understanding of the important processes and characteristics in a specific mangrove ecosystem; a functional classification can be made from physiological characteristics of the mangrove forest in combination with an understanding of the environmental setting. These environmental settings are based on geomorphological landforms affecting the physical processes for sediment transport and deposition (Woodroffe, 1992). Five types of environmental settings can be described according to Woodroffe (1992):

- 1. River-dominated
- 2. Tide-dominated
- 3. Wave-dominated barrier lagoon
- 4. Composite river and wave-dominated
- 5. Drowned bedrock valley

These five environmental settings are displayed in Figure 2. The figure shows the physical setting of the landforms and the places of mangrove establishment, with a cross-sectional display of the substrates common in these types of settings. For a more in-depth description of the environmental settings, the reader is directed to appendix 4.



Figure 2 Environmental settings of Mangroves (Woodroffe, 1992)

The functional classification of mangroves gives a more ecosystem specific assessment of the forest characteristics and appearances in different locations within each of the environmental settings. The classification gives more insight in what hydrodynamic processes are dominant in a local forest community and how these processes occur around the mangrove ecosystems. The discrimination between different mangrove forest types, as a functional mangrove classification, based on physiological characteristics of mangroves, consists of six different classes (Lugo et al., 1974):

- 1. Overwash mangroves; generally composed of Rhizophora, completely overwashed by high tides and often underlain by mangrove peat.
- 2. Fringe mangroves; dominated by Rhizophora, inundating daily by tides. Bordering directly on the estuary or open sea
- 3. Riverine mangroves; tall and productive Rhizophora dominated mangrove stands alongside a river channel and frequently flushed with fresh water. Mangrove areas penetrated by tidal creeks that inundate the forest during high water.
- 4. Basin mangroves; mostly mixed or Avicennia dominated mangroves that are characteristic of the interior of mangrove forests. Mangrove areas also penetrated by tidal creeks that inundate the forest during high water.
- 5. Scrub mangroves; a dwarfed stand of mangroves, usually of Rhizophora, in a nutrient poor environment.
- 6. Hammock mangroves; a special form of basin mangroves that are found in the everglades, where it consists of small islands of mangroves over a mangrove derived peat which infills a depression in the underlying limestone.

The six classifications of mangroves are illustrated in Figure 3. A more detailed description of the different functional mangrove classes is presented in appendix 5.



Figure 3 Functional mangrove forest classification (Lugo and Snedaker, 1974)

The different classes of mangroves all have their characteristic hydrodynamic influences along the land-sea interface. Depending on different hydrodynamic and morphodynamic factors such as local wave climate, climate change, tidal prism and sediment supply, a mangrove ecosystem can be either eroding, accreting or stable as a long-term development. How this long-term development is established is described in appendix 6.

#### 1.2. Physical processes in mangroves

With mangroves existing at the land-sea interface and being subject to regular inundation, physical processes related to hydrodynamics and morphodynamics shape the mangrove environment. The physical processes work at different time scales. In the past, research has been conducted into these physical processes of importance in mangrove forests. The available knowledge on these physical processes that are of importance in a mangrove ecosystem and some gaps in the existing knowledge are described in this section.

#### 1.2.1. Biophysical interactions

The stability of mangrove covered shorelines depends on local hydrodynamic and morphodynamic processes. In the absence of vegetation on the local scale, a loop will be present in the hydrodynamic and morphodynamic processes, which can be seen in Figure 4. Changing hydrodynamics (i.e. current velocity changes and current direction changes) consequently influence the magnitude and direction of sediment transport. With a change in sediment dynamics, the sediment deposition is altered as well, leading to morphological changes in bed topography. A changing morphology in turn changes the hydrodynamic processes. With the presence of vegetation another factor is introduced in the loop that influences hydrodynamics and sediment dynamics. Vegetation will be an obstruction in the water flow, changing hydrodynamics and sediment dynamics. Thus the loop from Figure 4 can be extended into a morphological diamond presented in Figure 5.





Figure 5 Morphological diamond

The biophysical interactions in the morphological diamond determine whether a coastline is stable, accreting or eroding. As explained in the previous paragraph the interactions of sediment availability, hydrodynamics and the influence of vegetation on the hydrodynamics and sediment dynamics can reinforce each other. The vegetation influences the hydrodynamics in such a way that sediment transport is affected so that more sediment is deposited, creating a better environment for vegetation to thrive. This loop is called a positive feedback, as described by (Van de Koppel et al., 2005). However in Van de Koppel et al. (2005) a critical state is reached for the positive feedback where vegetation collapses in the end. This is not necessarily obtained in mangrove vegetation. Also a negative feedback loop can develop where one of the factors in the diamond has a negative impact on substrate accretion or vegetation development leading to an eroding coastline.

Sediment dynamics in a mangrove ecosystem react instantaneously to changes in hydrodynamics. However it takes much longer for changes in morphology to be noticeable. For a changing morphology, the trend of hydrodynamic changes over a longer period of time is important. For vegetation changes in the morphological diamond also longer periods of time will pass, since vegetation needs time to settle and develop. So the positive feedback loop is relevant for long-term development of the ecosystem.

Figure 6 shows the time scales of the different physical processes. For instance both tides and sediment deposition or erosion have a daily time scale, whereas tree growth and surface level change on the time scales of decades. The initiation of surface level change however lies in the sediment deposition or erosion. So to know whether surface level changes are favorable for long term development against sea level rise, which has a time scale of centuries, first the small timescales of (less than) one day need to be investigated to know if a trend of accreting shorelines can be recognized. The physical processes of interest for daily timescales are:

- Waves and turbulence
- Tidal currents
- Sediment transport
- Sediment deposition and erosion

Because of their larger characteristic time scales, surface elevation changes and vegetation development are not variable on a daily time scale and will not be considered in this study.



Figure 6 Time scales of physical processes (Friess et al., Submitted)

#### 1.2.2. Hydrodynamics

#### Tidal inundation

Mangrove forests are all inundated for a period of time, due to tides. The frequency and duration of these inundations depend on the tidal amplitudes in the spring-neap tidal cycle. Research shows that the inundation of mangrove forests, can be divided into two distinct routings (Mazda et al., 2007; Alongi, 2009). These two routings are the water supply directly from the sea, estuary or river into the adjoining mangrove forest over the forest fringe and the supply of water into the mangrove through a system of tidal creeks. The tidal creeks can be mostly found in riverine forests and basin forests. During a flood, water is flowing into the tidal creek systems and via the banks the adjoining mangrove swamp is inundated. The fringe, overwash and scrub forests are mostly directly inundated across the forest fringe.

#### Tidal flow in mangroves

The importance of tidal creeks during tidal inundation of mangrove forests has been acknowledged in literature (Mazda et al., 2007) and knowledge on the hydrodynamics of the tidal creeks has been obtained. The uniqueness of a mangrove ecosystem is the fact that two different tidal asymmetries are present in one environment. The ecosystem experiences an ebb-dominated tidal asymmetry during overbank tidal flow inundating the forest, whereas a flood-dominated tidal asymmetry occurs when no overbank tides are observed (Bryce et al., 2003). Specific research into the hydrodynamics of the tidal creeks shows that tidal currents in the creeks can exceed 1 m/s, with a tidal asymmetry of stronger ebb tidal currents relative to flood tidal currents (Wolanski, 1992). The asymmetry between the tidal currents is a result of the phase lag between the head and the mouth of the creek. During

the flood, the water level is rising equally over the entire creek and inundating the forest. When water in the mangrove forest starts to fall at ebb tide, the water level in the mouth of the creek is falling while water in the forest is held back due to the vegetation. This means that the same amount of water needs to be transported out of the system in less time with higher gradients in water level, leading to higher tidal currents at ebb tide (Wolanski, 1992).

In addition to research into the hydrodynamics of the tidal creeks, the hydrodynamics in the mangrove forest have also been investigated. The available knowledge on hydrodynamics of a mangrove forest focuses on the impediment of the flow during inundation of the forest, from the creek into the forest or from the sea over the fringe. Tidal current velocities in mangroves are in general much lower than in the tidal creeks or in the waters fronting the mangrove forest and have a maximum of around 0,2 m/s (Furukawa et al., 1997; Anthony, 2004). The lower velocities are mainly caused by the woody structures of the mangroves (roots, stems, branches and even canopy) in densely vegetated areas, which form extra resistance for water flowing into and out of the forest at flood and ebb tide respectively. The extra resistance is the result of turbulence behind the roots that are in the water flow. The extra turbulence creates a drag force that has a much larger impact on the reduction of current velocities than the bottom friction (Mazda et al., 1997; Struve et al., 2003; Mazda et al., 2005). The magnitude of the drag force created by the vegetation, is related to the density of roots and canopies. A densely vegetated forest will reduce current velocities further than less dense forests. In forests with less dense root structures flow is directed around the roots into the lEast obstructed pathways (Struve et al., 2003). This is also why the drag force will be lower with increasing water depths. The increasing water depth means that the root structures will be completely inundated and the stems of the trees now penetrating the water surface are much less dense than roots. However, information on how currents are directed through a mangrove forest with different vegetation densities is still unknown. Little information on circulation of water and sediments through a mangrove forest is present (Sato, 2003).

#### Waves in mangroves

Mangrove forests are located in estuaries and river deltas and therefore parts of the forest are directly exposed to the sea. During inundation of a mangrove forest therefore wave activity is important in the mangrove hydrodynamics. The magnitude of wave activity however is very much dependent on the wave climate. For calm wave climates, waves are of no importance to mangrove hydrodynamics, which is mostly the case for riverine and basin mangroves (Woodroffe, 1992).

In coastal areas without vegetation, sea waves propagating towards the shore are influenced by the bottom, because of a reduction in water depth. The reduction of water depth increases the bottom friction working on the propagating waves, causing them to lose energy and shoal. The increasing wave height and increasing steepness of the wave front will eventually cause the waves to break and lose much more energy. Studies in mangrove forests fringing at open sea have shown that vegetation reduces wave energy further by adding more friction (Brinkman et al., 2005; Massel et al., 1999). Rates of wave height reduction in mangrove forests can be up to 20% per 100 meters of mangrove forest (Mazda et al., 2007). The wave attenuation by the mangrove root structures is caused by the obstruction of the roots for incoming waves. The roots cause large drag forces induced by the flow around them resulting in a loss of wave energy density and consequently wave height (Quartel et al., 2007; Vo-Luong et al., 2008). The water depth is important for the influence of the bottom friction on

wave attenuation, which is also the case for mangroves. For bottom friction, an increase in water depth results in a decrease of bottom friction and a decrease in wave attenuation. In mangroves the relation between water depth and wave attenuation is more complex. The amount of wave attenuation differs for different mangrove species, because of different root structures, such as pneumatophores, stilt roots and knee roots (Mazda et al., 2006). A large density of the root structure results in the most wave attenuation.

#### 1.2.3. Morphodynamics

#### Sediment transport due to tides

In recent studies the sediment transport to and from a mangrove forest has been investigated extensively. During a tidal cycle, peak flood currents and peak ebb currents are rarely of equal magnitude, causing the effect that is called tidal pumping. During flood currents, the sediment is entrained into the flowing water and transported landward. When the tide is turning, flow velocities are slowed down to zero and the flow finally turns around. When the velocities reduce to zero, the sediment settles at the bed. When ebb currents start subsequently, flow velocity increases again and sediment is again entrained into the flow but is now transported seaward.

The circulation of these sediments once transported into the forest is however still unknown. Some knowledge is available on the amounts of sediment transported into the mangrove forest, but the sediment pathways are largely unknown. It is known that due to the change in flow direction at ebb tide (Wolanski, 1995) and due to the trapping effect caused by stagnation zones around mangrove vegetation (Furukawa et al., 1997), less sediment is transported seaward again. A large part of the sediment, mainly the larger flocs, settles down on the bed. The settling of the flocs occurs mainly in the wakes of the roots of mangroves and around very dense root structures that are avoided by the currents (Furukawa et al., 1997). Only the smallest particles can usually stay in suspension in a mangrove forest, because of the low flow velocities. The smallest particles are expected to be transported to the most upward regions of the forest and given enough time they will settle at the bed (Anthony, 2004). The finest clay particles are therefore mainly found deep into the mangrove forests. However, tidal creeks penetrate deep into the mangrove forests and are able to carry large amounts of sediments, due to high flow velocities and might therefore be able to carry larger particles deeper into the mangrove forest.

Sediment transport in the creeks has been researched more extensively and the behavior of sediment transport for tidal creeks is better known than the behavior of sediment transport in the mangrove forest. For the ebb-dominated tidal asymmetry in the tidal creeks, the sediments will have a net displacement seaward. The ebb-dominated tidal asymmetry in the creeks causes the creeks to have only a small amount of fine sediments (Van Santen et al., 2007; Bryce et al., 2003), because sediment is being left behind in the forest after turning of the tide. These asymmetrical sediment concentrations between ebb and flood will prevent the creeks from silting up, by entraining fine sediments. This effect is called the self scouring of the tidal creeks (Mazda et al., 2007).

#### Sediment transport due to waves

In addition to tidal currents, waves rolling into the forest may be responsible for sediment transport in a mangrove forest. The orbital velocities, due to the waves, are able to entrain sediments in the near-shore region, because they protrude downward to the seabed in the decreasing water depths towards the coastline. With sediment particles entrained underneath the waves, the sediments are transported into the forest as the waves roll into the mangrove forest (Brinkman et al., 2005; Vo-Luong et al., 2006), because orbital velocities have slightly higher velocities directed onshore. On the other hand, when sediments at the fringe of a mangrove forest are put into suspension during storm waves due to the high energy impact of these waves, this sediment will be pulled out to sea because it stays in suspension under these turbulent conditions and will not settle to the bed and is consequently pulled out to sea. This results in a net flow velocity directed offshore. Sediments transported offshore during a storm, are then settling offshore during calmer conditions. During very calm conditions wave activity is so minor that sediment transport due to waves is expected to be negligible compared to transport by the higher tidal flow velocities.

#### Morphological dynamics

The sediment transport processes in past research show that mangrove forests are a large sink for fine sediments, leading to a more rapid accretion of sediments in the forest. The root structures are very important in trapping sediments in the forests and cause large accretion rates (Adame et al., 2010). Although mangrove forests are commonly a large sink of sediments, they can also act as a source of sediment. The erosion of sediments from mangrove forests is the consequence of large wind waves (e.g. hurricanes) that in calmer conditions actually induce the sedimentation (Van Santen et al., 2007).

Similar to intertidal flats and salt marshes, mangrove forests can be in a dynamic equilibrium in which both sedimentation and erosion occurs at some point in time. During the dynamic equilibrium of the mangrove forest, erosion and sedimentation are in balance. A disturbance in this balance can lead to the net erosion or net sedimentation in a mangrove forest and thus causes an evolution of the shoreline. The factors influencing and maintaining the dynamic equilibrium are the fine sediment supply, river flows, tidal currents and wave action, that can also induce long-shore currents distributing the fine sediments along the shore (Vo-Luong and Massel, 2006).

The effect of these sedimentation and erosion processes is the expansion or shrinking of a mangrove forest. It is observed that mangrove forests do not directly expand the shoreline seaward, but instead increase the elevation level in the forest (Anthony, 2004). This heightening of the bed level is observed through deposition measurements in mangrove forests. The distribution of the deposition in a mangrove in relation to the sediment transport and hydrodynamics has not been linked so far. So it is still unknown where most accretion takes place in a mangrove forest and why more accretion takes place at certain locations in the mangrove forest.

The actual expansion of the forest seaward occurs when mudflats are formed in front of a mangrove forest and this mudflat is then colonized by seedlings of mangroves. Once a mudflat is colonized, the accelerated accretion starts and the mudflat is less susceptible to erosion, leading to stabilization of the shoreline. The shrinkage of mangrove forests is the direct consequence of erosion by natural disturbances such as severe storms which will remove large parts of soil around the mangrove trees causing them to become unstable and to fall over (Alongi, 2008).

#### 1.3. Research objective

In the past, extensive research into the hydrodynamics and morphodynamics in mangrove forests has been carried out. Two types of mangroves have been of particular interest, namely the fringing mangroves and the riverine mangroves. These types of mangrove forests are most common and most extensively researched. Most mangroves are present on shorelines and in estuaries with either rivers or large tidal creeks. When implementing mangroves for coastal protection the shorelines facing sea and estuaries have the main focus because people most commonly settle in these areas at the land-sea interface.

For fringing mangroves, research mainly focused on the impact of nearshore processes, mainly wave activity. For riverine mangroves, interest was also extended into some riverine processes. For riverine mangroves, past research showed that tidal creeks play a role in the tidal inundation of the mangroves and the supply of sediment to the mangrove forest. However, no extensive study has been performed into the importance of these tidal creeks in mangrove forests for coastal development. Neither has the flow routing and sediment circulation through a mangrove forest been thoroughly investigated yet. This is important knowledge, because knowledge on long-term development is required for using mangroves in coastal protection and development and developed mangrove forests all show the presence of a tidal creek system.

The knowledge on the flow routing and sediment circulation through a mangrove forest is lacking at the moment. At the moment no field data is present on the flow routing of water, circulation of sediments and spatial distribution of sediments in a mangrove forest during a tidal cycle. Only transect measurements have been performed either along a transect from a creek extending into the forest or a transect from the sea (or estuary) into the forest. No spatial grid of measuring points has been used to investigate the inundation flow patterns during a tidal cycle. Thus the importance of tidal creeks in this respect has not been found yet. Also the relation between the hydrodynamic processes and the morphodynamic processes is limited. With knowledge on flow routing also the main supply route of sediment and the spatial distribution of sediments through a mangrove forest can be explained with possible influences of vegetation. So, important questions such as 'how will a mangrove forest accrete or erode' and 'how is most sediment supplied to a mangrove forest' and 'why is sediment deposited at certain locations in a mangrove forest', still need to be answered with supporting field data.

To answer these questions, a field site needs to be located that has tidal creek influences and a link to an estuary, in order to find the importance of tidal creeks in comparison to the forest fringe for sediment supply. Also it needs to have a dense vegetation cover, so that the influence of mangrove vegetation is most likely present in the hydrodynamic and morphodynamic processes.

Therefore the main goal of this research is:

To collect field data on hydrodynamics, sediment dynamics and vegetation characteristics in a creek catchment of a mangrove forest in order to quantify the influence of tidal creeks for supply and spatial distribution of sediments in mangrove forests.

#### 1.4. Research questions

This section describes the research questions that need to be answered. The answers on the research questions will enable the achievement of the research objective.

- 1. How to study hydrodynamics, morphodynamics and vegetation characteristics in a mangrove forest?
  - What is a suitable field site for this study and why?
  - How can vegetation characteristics be measured in a mangrove forest?
  - How can hydrodynamics, sediment dynamics and sediment deposition be measured at this field site and where and when should these parameters be measured?
- 2. What is the flow routing in the mangrove creek forest over a tidal cycle?
  - What are the magnitudes and directions of the currents over a tidal cycle?
  - What are the magnitudes of currents entering the forest from the forest fringe and through the creeks?
  - What is the influence of vegetation on the magnitudes and directions of the currents in a mangrove forest?
  - What is the influence of elevation on the magnitudes and directions of the currents in a mangrove forest?
- 3. What is the magnitude of sediment concentrations on both a temporal and spatial scale through a mangrove forest during a tidal cycle?
  - $\circ$   $\;$  What are the sediment concentrations in a mangrove forest over a tidal cycle?
  - How do the sediment concentrations change in relation to the hydrodynamics over a tidal cycle?
- 4. Is there net accretion or erosion in a mangrove forest and what is the spatial distribution of this net accretion/erosion?
  - What are the sediment depositions rates throughout the mangrove creek catchment?
  - Is there net accretion or erosion in a mangrove creek catchment?
  - What is the spatial patterning of sediment deposition/erosion and can this be linked to hydrodynamic, elevation or vegetation characteristics?
- 5. What is the importance of tidal creeks in the supply of sediments to a mangrove forest?
  - What are the relative magnitudes of sediment transport through the creeks and over the forest fringe?
  - How is the sediment that is transported through the creeks distributed over the mangrove forest?

#### 1.5. Research methodology

The research methodology for answering the individual research questions is shown in the scheme of Figure 7. To realize the research objective of clarifying the importance of tidal creeks, empirical evidence has been gathered through an extensive field campaign. The field campaign was conducted

in a creek catchment in a mangrove forest in Southern Thailand during a period of five months. Exact research locations will be described in the next chapter. During the field campaign, current velocities, current directions, sediment concentrations, sediment deposition rates, vegetation characteristics and elevation data were gathered to answer the research questions. Data analysis is performed in the Netherlands to find relevant relations between mangrove vegetation and the physical processes of hydrodynamics and morphodynamics.

Important in this study is the morphological cycle that is expanded into the morphological diamond. The three main components, hydrodynamics, sediment dynamics and morphology, originating from the morphological cycle are the basis of the measuring campaign. How this measuring campaign was performed to obtain the necessary data is described in chapter 2. The consequent three chapters discuss the results of the measuring campaign. The elevation survey and the vegetation survey are important for analyzing every main component and its relating research questions. Analysis of the elevation survey and vegetation survey is discussed in chapter 3. Results of the hydrodynamic measurements are discussed and analyzed in chapter 4. In chapter 5 the results of the sediment dynamics measurements are discussed and analyzed. The final results chapter is chapter 6 with the analysis and discussion on the results of sediment deposition. A discussion on the entire morphological diamond and all results of the measuring campaign in relation to earlier studies into mangroves is presented in chapter 7. Finally in chapter 8 conclusions from the obtained and analyzed data are presented.



Figure 7 Research methodology

## 2. Field sites and measuring techniques

For this research into hydro- and morphodynamics in a mangrove creek catchment, a field campaign has been executed. The field campaign took place in Thailand during the months of January-May of this year. The methods and exact location of the field campaign will be described in this chapter. First a description and choice of the research area is made. Secondly, the methods for measuring hydrodynamic and morphodynamic variables are depicted, including an explanation of the applied measuring equipment and measuring grids.

#### 2.2. Description of the research area

The field campaign in a mangrove creek catchment was situated at the West coast of Southern Thailand in Trang Province. The chosen creek catchment for this research was situated in the estuary of the Kantang River along the Western bank of this estuary, about 6 km inland from the actual coastline (7o19'18''N 99o29'45''E). The exact location of the creek catchment is indicated in Figure 8. The location in the estuary means that the creek catchment of interest is subject to tidal influences and river influences. The research area can therefore be classified as a combination of riverine and fringing mangroves, which is exactly what is preferred for answering the research questions as described in section 1.4. Within the study area waves turn out to be negligible, with approximate wave heights of a few centimeters observed in the field, and will therefore not be considered in this study.

The creek catchment shows some distinctive features, as can be seen in Figure 9. The fringe of the catchment (bordering the East of the study area, facing the estuary) has a small cliff of about 1.5 meters high. In the North of the catchment a large main creek is present with a bifurcation in the West of the chosen catchment area that extends in Southern direction into the creek catchment. In the South of the creek catchment another small creek is present. The Northern creek is the largest in magnitude with a depth of approximately 3 meters and a width of approximately 10 meters. Dimensions of the West creek are approximately 2 meters in depth and a width of approximately 6 meters. Dimensions of the small creek at the South are an approximate depth of 1.5 meters and a width of approximately 4 meters.

Vegetation in the creek catchment seems to have a variety of mangrove species, with notable recognition of Rhizophora at the fringe of the catchment, where a very dense root structure is encountered. Further to the back the vegetation seems to be getting less dense and different types of mangrove vegetation are present that will be discussed in chapter 3.



Figure 8 Location of the creek catchment in the Kantang River estuary



Figure 9 Schematization of creek catchment

#### 2.3. Topography measurement techniques

During the field campaign a field survey was executed to obtain a detailed elevation profile of the creek catchment. The elevation profile is a key component in the analysis of hydro- and morphodynamic processes. For the field survey the equipment of choice was a Trimble Total Station as displayed in Figure 10. The elevation profile was created by taking close to 4400 measuring points during the survey. The points were measured relative to two manually created reference points. The first reference point was a random point in the forest for which an elevation of 10 meters was set. All other elevation points in the forest are relative to this manually set reference level. The second reference point was manually measured straight North from the first and the elevation difference was also determined manually. The two reference points are needed, so that the Total Station is calibrated for directions. So only the gradients through the creek catchment were obtained and not the absolute height relative to mean sea level.





#### Figure 10 Trimble Total Station

Combined with the topographic survey, a vegetation survey has been performed. The combination of the two surveys gives an overall description of the topography of the creek catchment. To survey the vegetation, first the vegetation has been classified into different zones each with a distinctive vegetation pattern (i.e. a combination of species and densities). Measuring plots of 15x15 meters were set out in each zone to specify the following vegetation characteristics:

- Type of vegetation
- Vegetation density

The type of vegetation was determined by identification of the trees, counting the number of trees of a certain type and taking pictures of the different types of trees, to analyze them later. The vegetation density consisted of counting the number of trees (per species) in each plot.

#### 2.4. Hydrodynamic measurement techniques

The analysis of hydrodynamics requires information on velocities and directions of currents as stated in the research questions. To measure these variables three Acoustic Doppler Velocimeter (ADV), called Vectors, were used simultaneously in biweekly measuring campaigns. The principle of an ADV measuring current velocities and directions is based on the Doppler effect. The Vector uses the Doppler effect to measure the current velocity by transmitting short pairs of sound pulses, listening to their echoes and, ultimately, measuring the change in pitch or frequency of the returned sound. However, sound does not reflect from the water itself, but rather from particles suspended in the water. These particles are typically zooplankton or suspended sediment. Long experience has shown that these small particles move with the same average speed as the water, so the velocity it measures is consequently the velocity of the water (Nortek AS, 2005). The ADV transmits sound through a single probe and receives the sound back via three probes displaced off to the side. Figure 11 shows how the beams intersect each other at 157 mm from the transmitter. The measurement volume is defined by this intersection. The transmit transducer sends a short pulse that covers only about 4 mm vertically, and the receivers listen to an echo that corresponds to about 14 mm vertically. Since the Vector uses three receivers, all focused on the same volume, it obtains three velocity components from that very volume (Nortek AS, 2005).



Figure 11 ADV probe, with transmitting and receiving beam (Nortek AS, 2005)

Because the measuring volume of the ADV is located at approximately 16 cm from the center of the transducer, the mounting height of an ADV probe needs to be 16 cm higher than the measuring height. The measuring height during the field campaign was set at 7 cm above the bed, leading to a mounting height for the ADV probe of 23 cm. The canister of the ADV's, containing the computer and memory of the ADV, also contains a pressure sensor. The canisters have been deployed so to measure at a depth of 7 cm, equal to the measuring height of the ADV probes (Figure 12).



Figure 12 Deployment of an ADV

The settings of the ADV at deployment are chosen to complete a measuring campaign of two weeks, so that an entire spring-neap tidal cycle is captured. Due to the limited battery capacity and memory of the ADV's, measurement settings were constrained to a certain frequency and time interval. Measuring settings of the ADV's were as summarized in Table 1:

Head frequency	6 MHZ
Sampling rate	16 Hz
Burst interval	1500 sec
Nominal velocity range	0.30 m/s
Samples per burst	4096
Sampling volume	14.9 mm
Sound speed	MEASURED
Salinity	35.0 ppt
Geography	Surf zone

Table 1 ADV measuring settings

With a sampling rate of 16 Hertz, sixteen samples are taken every second. In total 4096 samples are taken during every measuring burst, leading to a total measuring time per burst of 256 seconds (i.e. 4:16 min). Such a burst is taken every 1500 seconds (25 minutes) during the two week measuring campaign.

As mentioned, three Vectors are available for simultaneous measuring in the creek catchment. In total nine measuring points in the creek catchment are assigned as ADV measuring points. At every point an ADV was deployed for at least one entire spring-neap tidal cycle. The measuring grid (Figure 13) and deployment sequence are chosen so that transects into the creek catchment can show a

relation in hydrodynamic characteristics along these transects. The schedule for the measuring campaign is given in Table 2.

Table 2 Deployment schedule ADV's

Dates of deployment	<b>Grid points</b>
24 January – 6 February	K3, L3, N3
7 February – 20 February	N0, N1, N3
21 February – 6 March	N3, N4, O3
21 March – 2 April	K3, P1, N5

The first deployment sequence of grid points K3, L3, and N3 is chosen to investigate the influence of the main creek on the creek catchment hydrodynamics during tidal inundation. The second deployment sequence with grid points N0, N1, and N3 investigates the hydrodynamic influence of the fringe on the creek catchment. In the back of the forest, grid points N3, N4, and O3 were chosen during the third deployment sequence to investigate the hydrodynamics in the heart of the creek catchment. The final measuring sequence is executed at grid points K3, P1, and N5, to investigate the hydrodynamics in the individual creeks that can be linked to the creek catchment measurements.



Figure 13 Measurement grid Hydrodynamics ADV and suspended sediment concentrations

#### 2.5. Sediment transport measurement techniques

As part of the morphodynamics in the mangrove creek catchment, sediment transport through the creek catchment is of interest. To obtain relevant sediment transport data in the creek catchment, also ADV's were used.

To analyze sediment transport, suspended sediment concentrations at multiple locations in the creek catchment need to be measured. The ADV can be used because of the acoustic signal reflecting on particles in the water column. The concentration of sediment suspended in the water column is related to the backscatter strength (Ha et al., 2009). The more sediment present in the water column means that there is more material for sound to bounce back leading to a stronger return signal for the ADV. A stronger reflection leads to a higher Signal-to-Noise Ratio (SNR) measured by the ADV's. To relate the SNR to suspended sediment concentrations, a calibration of such an ADV has to be done. This is done by recording the SNR for a number of known suspended sediment concentrations. Next, the SNR is plotted against the sediment concentration to determine a calibration coefficient. This calibration is done at NIOO-KNAW in Yerseke after the field campaign. The calibration results will be discussed with the data processing in chapter 5.

Suspended sediment concentrations were also measured using a second method. For this method, 500 mL bottles were deployed to capture sediments present in the water column over two subsequent high waters at spring tide, at the same measuring grid as for the sediment deposition measurements (Figure 16). The results of this measuring technique are somewhat questionable however, so they are not further analyzed in this study. The processing of the bottle contents to determine the suspended sediment concentrations was done in the same way as for sediment deposition analysis, as will be described in the next section.

The sediment concentration measurements were executed according to the same deployment schedule as for the hydrodynamic measurements (Figure 13). The suspended sediment concentrations are measured simultaneously, because they are derived from the ADV signal.

Dates of deployment	<b>Grid points</b>
24 January – 6 February	K3, L3, N3
7 February – 20 February	N0, N1, N3
21 February – 6 March	N3, N4, O3
21 March – 2 April	K3, P1, N5

#### Table 3 Deployment schedule ADV's

For the first deployment sequence suspended sediment concentrations are analyzed through the main creek, over the creek bank to the center of the catchment at grid points N0, N1, N3. At the second deployment the suspended sediment concentrations over the forest fringe are investigated. During deployment sequence three, measurements were performed in the center of the catchment. In the final deployment sequence the suspended sediment concentrations within the creeks are investigated.

#### 2.6. Sediment deposition measurement techniques

To unveil sediment deposition patterns within the creek catchment, sediment trapping was executed during spring tides. The opted method for sediment trapping was the use of tiles, with a slightly rough topside. The tiles had dimensions of 20x25 cm and the rough topside was created by applying a smooth mortar layer. The tiles were placed on the bed with the roughened topside facing upward. The advantage of this method is that no sediments attach to the smooth surface of the tile that rests on the bed. The rougher mortar covered topside mimics the (rougher) forest bed, to capture deposited sediments. Such a tile, placed at the forest bed, is shown in Figure 14.



Figure 14 Sediment trapping tile

The analysis of sediment deposition rates is performed by deploying the tiles over two subsequent high waters during spring tide. At retrieval of the tiles the backside of the tile, facing the forest bed, is rinsed of any residual sediment, since this is irrelevant for sediment deposition. Transport of the complete tile from the forest to the laboratory is done in zip-loc bags. The analysis of the tiles is done by first rinsing the sediment of the tile with distilled water. The second step is to filter and further rinse the suspended sediments with distilled water to flush out the salts from the samples, because they are retrieved in saline conditions. For this process, 0.7 µm glass fiber filters (Whatman) have been applied. Third step in the process is to dry the filtered sediments in an oven at 105° Celsius for twenty-four hours. Finally, the dry weight of the sediments is determined using scales (dry weights of the sediments have been weighed before). The method of rinsing and filtering of the sediment samples is shown in Figure 15.



Figure 15 Filtering arrangement

This analysis method for sediment deposition in the creek catchment was performed during four spring tides with deployments at 24 January, 7 February, 21 February, and 21 March (each time at the first day of ADV deployment). There is a difference between the four measuring dates in the size of the measuring grid. During the first two spring tides a sixteen point measurement grid was used whereas for the last two spring tides the measurement grid was expanded to twenty points. The measurement grid is depicted in Figure 16. The measuring points Q1, Q2, Q3, and Q4 were added to the grid later on, because the influence of a creek in the Southern part of the creek catchment was not fully taken into account for sedimentation patterns with the smaller measuring grid.

The measuring grid for the sediment deposition is larger than for the ADV measurements for hydrodynamic and suspended sediment measurements (Figure 16). The larger grid helps in better analyzing the spatial patterning of sediment deposition rates, since the grid points are more evenly spread and they are located at more positions with different distances from the creek and forest fringe.



Figure 16 Measuring grid for sediment deposition

## 3. Creek catchment characteristics

To investigate the hydrodynamic and morphodynamic processes in the mangrove creek catchment some boundary conditions need to be known first. For the timescales of this research the vegetation and morphology can be assumed as boundary conditions in the morphological diamond (Figure 17). These static characteristics of the study area will be discussed in this chapter. For hydrodynamic analysis it is essential to have bathymetry data of the creek catchment, which were obtained as described in section 2.1 and will be presented in this chapter. In order to know how vegetation influences the hydrodynamics and consequently the morphodynamics, an assessment of the characteristics of the mangrove vegetation was made. First the elevation characteristics are presented and finally some relations between the vegetation and elevation characteristics are discussed.



Figure 17 Boundary conditions in the morphological diamond

#### 3.1. Elevation profile

Elevation data of the study area has been obtained as described in chapter 2.1. In total, the 4400 data points have been mapped and plotted in ArcGIS. An elevation map has been obtained by kriging interpolation. The resulting elevation map of the study area is shown in Figure 18. In the elevation map the estuary of the Kantang River can be observed on the right hand side and in the North of the figure the main creek is clearly visible. A tributary of the main creek extends South, bordering the West side of the study area. The main creek itself extends to the North, but due to limited resources it was impossible to map and study the entire catchment of this creek. Also the mud lobster mounds throughout the catchment are clearly visible in the elevation map. So a detailed profile of the creek catchment is obtained. The elevation map of the study area shows some distinct features. Most important are the gradients in elevation for the creek catchment and the gradients at the end of the creek in the center of the catchment area.



#### Figure 18 Elevation profile creek catchment

From the elevation profile, a very distinctive feature of a creek system in the catchment can be observed. The main creek penetrating into the creek catchment is getting shallower while penetrating deeper into the catchment, especially after the bifurcation in the West of the catchment area of interest. The creek extends into the forest and swings back towards the center of the catchment where the thalweg of the creek becomes increasingly more elevated until the creek is leveled to the catchment floor. Furthermore, a small creek at the South of the catchment extending into the forest is observed. Further into the forest this creek also becomes shallower until it is leveled with the catchment floor.

At the forest fringe in the East a positive gradient is observed up to about 30 meters into the forest at which a bank is encountered. This bank extends North to the main creek. Parallel to the main creek an even higher bank than behind the forest fringe is observed. This creek bank also extends along the bifurcated creek in the West of the creek catchment. The creek system extending from the main creek at the North of the catchment ends in the center of the catchment, within a lower lying area of the catchment (Figure 18). The center of the creek catchment is in fact lower than the banks near the main creek and the forest fringe. This lower lying area is enclosed by the banks at the forest fringe and along the main and West creek. Distinctive elevation features in the low lying center of the creek catchment are the mud lobster mounds (Figure 19). The mud lobster eats mud and lives underground. Its digging loosens the mud and allows air and oxygenated water to penetrate the otherwise oxygen-poor ground. All this digging and depositing eventually results in a distinctive volcano-shaped mound that can reach impressive proportions of about one meter height and several meters in diameter (wildsingapore, 2008).



Figure 19 Mud lobster mound

#### 3.2. Vegetation zones

In the creek catchment, vegetation cover is very diverse. No uniform mangrove species is present. Instead, a number of zones have been distinguished with multiple mangrove species and different vegetation densities. The mangrove vegetation in the creek catchment consisted of six different species. These species are:

- Rhizophora
- Avicennia
- Bruguiera

- Xylocarpus
- Acanthus
- Acrostichum









Figure 20 Mangrove species present in creek catchment. A: Rhizophora B: Avicennia C: Bruguiera D: Xylocarpus E: Acanthus F: Acrostichum

Four different vegetation zones are distinguished based on observed vegetation patterns. To distinguish the different vegetation zones, a couple of principles were employed. First the type of vegetation was judged, whether it was uniform or mixed. Furthermore the density of the vegetation and the spatial positioning in the creek catchment were used as criteria to distinguish the zones. The distribution of the vegetation zones is shown in Figure 21. The classification of the four vegetation zones is:

- Acanthus dominated vegetation zone
- Mud mounds and Rhizophora vegetation
- Dense Rhizophora vegetation
- Sparse distributed mixed vegetation



Figure 21 Vegetation zones in creek catchment

The Acanthus dominated vegetation zone is situated on the creek banks at the North and West. The zone is composed of a mix of Rhizophora, Avicennia, Sonneratia, Bruguiera, and Xylocarpus, with a dense understory of Acanthus shrubs. The tree density in this zone is about 37 trees per plot of 225  $m^2$ , disregarding the Acanthus shrubs, which are abundant at the catchment floor.

In the center of the creek catchment, Rhizophora vegetation is dominant, with a tree density of 16 trees per plot of 225 m<sup>2</sup>. The Rhizophora trees are already old with large tree heights. Some sporadic other species such as Avicennia and Xylocarpus are found, but these are negligible. The reduced vegetation density is combined with the presence of mud lobster mounds as described in the previous section. These mud lobster mounds are sometimes overgrown with Acrostichum shrubs.

At the fringe of the creek catchment also Rhizophora vegetation is dominant, but the difference with the center of the creek catchment is the higher density of the vegetation and the absence of mud mounds. The tree density at the fringe is 44 trees per plot of 225 m<sup>2</sup>. Moreover, the trees at the

fringe are younger with lower tree heights and more compact root systems than the trees in the center of the creek catchment, which are older and taller.

The vegetation zone behind the fringe is very distinct from other vegetation zones, because a rather mixed vegetation is present. The species encountered in this zone are Rhizophora, Avicennia, Sonneratia, Bruguiera and Xylocarpus, with the trees being of different ages and varying in size. The density of trees in this zone is a little less dense than at the fringe with 42 trees per plot of 225 m<sup>2</sup>, but the main difference is the smaller number of Rhizophora trees. This plot contains 7 Rhizophora trees only, in comparison to 14 Rhizophora trees in the plot on the fringe, resulting in a far less dense root system in this zone.

#### 3.3. Combined vegetation and elevation characteristics

Some relations between the elevation characteristics and the vegetation characteristics in the creek catchment can be identified. These relationships are analyzed by combining the elevation chart with the vegetation cover chart, resulting in Figure 22.

Most notable in the relation between vegetation cover and elevation differences is the presence of Acanthus vegetation on the higher elevated areas of the creek banks. On the entire creek bank, starting in the North along the main creek and extending alongside the West creek, Acanthus shrubs are present. In other areas of the creek catchment the Acanthus is absent. At lower areas in the creek catchment, the center and the fringe, mainly Rhizophora trees are present with different densities. Mainly at the fringe, vegetation is most dense with a high number of densely rooted Rhizophora trees. In the center of the creek catchment at the lower lying areas, Rhizophora is most dominant with a small density in number of trees, but the root structures still give a dense vegetation cover. The largest mix of vegetation is found at the higher elevated parts of the creek catchment. So some relations between vegetation cover and the bathymetry of the creek catchment are present.

The relation between the vegetation cover and the bathymetry is most easily explained by the inundation period of the creek catchment. The lower lying center and fringe of the mangrove forest have longer and more frequent inundation periods than the higher areas on the creek banks and the bank behind the fringe. The large stilt roots of the Rhizophora are able to cope with longer inundation periods than for example Xylocarpus and Bruguiera. The species least able to cope with long inundation periods are Acanthus and Acrostichum. This is particularly noticeable, since Acanthus and Acrostichum are present mostly on mud lobster mounds and in the highest elevated areas in the creek catchment with very little and short inundation periods.


Figure 22 Combined chart of elevation profile and vegetation zones in creek catchment

## 4. Hydrodynamics in a mangrove creek catchment

In the introduction chapter interactions between physical processes and mangrove vegetation are discussed, based on the concept of the morphological diamond (Figure 23). This chapter will focus on the starting point of the morphological diamond, namely the hydrodynamics in the mangrove creek catchment. Hydrodynamics are the starting point in the morphological diamond, since these processes have the smallest time scale and are therefore most variable. Furthermore the hydrodynamics trigger sediment dynamics and are directly influenced by vegetation and morphology.



Figure 23 Hydrodynamics within morphological diamond

In the field campaign, hydrodynamic characteristics of the creek catchment such as water levels, current velocities and current directions were collected at nine grid points within the study area. How this obtained data was processed into hydrodynamic information is discussed in the first section. The results of the field campaign on hydrodynamic characteristics are presented in the second section, after which the results are analyzed in the third section. Some preliminary conclusions on the hydrodynamics of the creek catchment are drawn in the third section as well.

### 4.1. Data processing

Hydrodynamic measurements were taken during a complete spring neap tidal cycle. The focus of this study lies within the hydrodynamics of a mangrove creek catchment during spring tides. The limitation for hydrodynamics during spring tide is related to inundation frequency of the creek catchment and is further explained in section 4.2.1. Therefore the data collected during biweekly field measurements was filtered to obtain only the spring tidal signal from the entire dataset. Matlab scripts to obtain the current velocities and current directions from the ADV output are presented in appendix 7.1 and appendix 7.2. The ADV output consists of three velocity components of which only the components in the horizontal plane are of interest. The velocity component in vertical direction is in general one order of magnitude smaller than the x-y components of the horizontal plane and therefore of little interest. Also the general trends of sediment distribution over the creek catchment are more of interest and this information lies within the x-y components. In principle the current velocities are plotted so that positive current velocities are directed landward (West during flood) and negative current velocities are directed seaward (East during ebb). Only for measurements at grid points N5 the orientation is different. This grid point is located in a creek with a North-South orientation, so the current directed landward (flood) has a Southern orientation, therefore positive current velocities are taken in Southern direction, for inundating the catchment.

### 4.2. Results hydrodynamic measurements

The results for the water levels, current velocities and current orientations are presented in this section. The water levels are plotted to obtain insight in the inundation periods of the creek catchment. The current velocities are plotted against water levels in order to observe the variation of current velocities through the creek catchment over one tidal cycle. For the current orientation, compass plots within the creek catchment are presented to visualize the direction of the currents through the creek catchment over one spring tidal cycle. The vectors drawn in the compass plots represent the direction in which the currents are directed, with their size representing the magnitude of the velocities. The change of the velocity orientation over a tidal cycle is observed in this manner.

#### 4.2.1. Water levels creek catchment

From the hydrodynamic measurements in the mangrove creek catchment, insight can be obtained into the inundation cycle. In Figure 24 the water levels as measured in the main creek at the North of the creek catchment are presented. The water levels show the expected fluctuation over a spring-neap tidal cycle. After around five days into the measurements neap tide occurs and water levels do not exceed 9.3 meters and do not fall below 8.6 meters. The tidal amplitude is then 0.7 meters only. Spring tide occurs after about 10 days into the measurements and the water level reaches about 10.5 meters. Minimum water level at spring tide is not known, since the ADV is not inundated during low water at spring tide. But the tidal amplitude will exceed 2.5 meters and is expected to even exceed 3 meters (Chansang et al., 1994).

During neap tide the water level does not rise high enough to inundate the mangrove creek catchment. During spring tide the water levels are high enough to inundate the mangrove creek catchment. The difference in tidal amplitudes between spring and neap tide results in periodic inundation of the mangrove creek catchment. The mangrove creek catchment starts to inundate at around 9.5 meters water level and is expected to reach full inundation at 10 meters water level, as indicated between the red lines in Figure 24. As observed in Figure 24, the creek catchment is not inundated for every tidal cycle, but during spring tide certain inundation will occur. Therefore the focus in this study is on the hydrodynamics and morphodynamics during spring tide, because data acquisition is certain in this tidal cycle.



Figure 24 Water levels creek catchment during a spring-neap tidal cycle

#### 4.2.2. Creek current velocities

The results for the creek hydrodynamics show some distinct patterns in the current velocities over a spring tidal cycle. Some general trends can be observed for the current velocities in the creeks. All three graphs for the three individual creeks have a similar mushroom-like shape. During flood, with the rise of the water levels, current velocities in all three creeks increase gradually. However, when a water level of about 9.5 meters is reached an acceleration of the current velocities is observed in all three creeks. This can be explained by the sudden increase of the tidal prism (Mazda et al., 2007), because the water level reaches the level of the forest floor and the forest starts to be inundated, as will be further explained in section 4.3. The current velocity ranges for the different creeks are different however. The magnitude of the range is related to the size of the creeks, with the largest and deepest creek having the largest velocity range, since bottom friction is less dominant with increasing water depths. Another distinctive characteristic for the creeks is the higher ebb current velocities and the longer duration of these high ebb current velocities, which have been mentioned in the introduction already.



Figure 25 Current velocities - Main Creek (North, K3) - Spring tide



Figure 26 Current velocities - South creek (P1) - Spring tide



Figure 27 Current velocities - West creek (N5) - Spring tide

In Figure 25 the current velocities at grid point K3 in the main creek are plotted over one spring tidal cycle. The current velocities range between 0.05-0.3 m/s during flood and between 0.08-0.3 m/s during ebb. At ebb tide, high current velocities are maintained during the fall of the water level from approximately 10.5 meters to 9.5 meters, whereas during flood only one peak flow velocity at 10.2 meters is identified. At ebb tide, higher current velocities are present during lower water levels, as observed in Figure 25. Water level fluctuation during one spring tide is approximately 2.1 meters in the main creek.

In Figure 26 the magnitude of the current velocities in the small creek in the South of the creek catchment (P1) are displayed. The creek is the smallest of the three creeks encountered in the catchment area. The range of the velocities over the spring tidal cycle is 0.02-0.15 m/s during flood and during ebb their range is 0.02-0.16 m/s. Similar to the main creek, higher current velocities are encountered for lower water levels at ebb than at flood. The water levels in the small creek vary between 9.2-10.8 meters, with the creek falling dry at a water level of about 9 meters.

In size, the Western creek at measuring point N5 falls between the main creek and the small creek. This can be traced back in the magnitude of the current velocities, for which velocity ranges are in between the ranges at K3 and P1. The current velocity range during incoming tide is 0.05-0.2 m/s and a range of 0.05-0.31 m/s is observed during outgoing tide. Again, the ebb current velocities are higher than the flood current velocities and also occur with lower water levels. A peculiarity in Figure 27 is the bulge at the top of the graph. Water levels show a sudden increase and drop at high water levels. From field observations this can be explained by the presence of a blocking trunk, which is shown in Figure 28. The tree is obstructing the flow during certain water levels and causes an artificial low water level behind the tree equal to the lowest part of the obstruction. Once the water level rises above the blocking stem a sudden increase of the water level is encountered in the velocity profile. Without this obstructing tree the profile would have been similar to that of the other creeks.



Figure 28 Blocking tree trunk

#### 4.2.3. Fringe current velocities

With the results of measuring points N0 and N1 an analysis into the hydrodynamics across the mangrove fringe can be made. At measuring point N0 the hydrodynamics in front of the mangrove forest (i.e. in the estuary) are investigated and at measuring point N1 the hydrodynamics in the forest fringe are investigated. In general, the velocity ranges for the estuary and the forest fringe have a large difference in magnitude. Also the orientation of the currents is different, with directions in the estuary having a North-South orientation and currents over the forest fringe having an East-West orientation, because the estuary is oriented in a North-South direction. The Kantang River discharges into the Andaman Sea in Southern direction and thus the tide has a North-South orientation as well.



Figure 29 Current velocities - Estuary (NO) - Spring tide



Figure 30 Current velocities - Forest fringe (N1) - Spring tide

In the estuary, current velocities range from 0.05-0.21 m/s at incoming tide, with a large acceleration towards the peak current velocity at a water level of 9.7 meter. At this water level the mangrove forest inundates as was also observed for the creeks. However, in contrast to the creeks, the current velocities in the estuary are larger during the flood cycle than during the ebb cycle. This can be explained by the absence of a lag effect, created by the mangrove forest and explained in the introduction, in the estuary. The current velocity range at ebb is 0-0.12 m/s. A notable observation in the current velocities of the estuary is the increasing magnitude of the velocities for lower water levels, which can be explained by the discharging river. The river maintains a constant flow of water resulting in accelerating velocities at decreasing water levels with outgoing tides.

Once the water level has risen enough during flood, the forest gets inundated with water flowing from the estuary over the forest fringe into the mangrove forest. The current velocities over the forest fringe are shown in Figure 30. The velocity range of the currents across the forest fringe during flood is 0.01-0.04 m/s and during ebb 0.02-0.065 m/s. So during ebb the current velocities are of a larger magnitude than during flood, because of retaining ability of the vegetation that causes a larger gradient in water level over the forest fringe. Furthermore, a somewhat symmetrical profile of the velocities is observed. Towards the turning of the tide, current velocities decrease at incoming tide and after the tide has turned current velocities increase again. This profile is the representation of the back and forth motion of the tidal cycle over the forest fringe.

#### 4.2.4. Catchment current velocities

Within the catchment, hydrodynamics are of interest, because it can indicate how the catchment is inundated and emptied during a tidal cycle. The current velocities as measured within the creek catchment at the grid points N3, N4, and O3 are displayed in this paragraph. These measuring points are located at the center, the Western part, and the Southern part of the creek catchment and thus give an impression of the hydrodynamics in the heart of the mangrove forest. The general impression reveals that the current velocities are of a small magnitude compared to the creek current velocities, as was observed with current velocities over the forest fringe.



Figure 31 Current velocities - Center of catchment (N3) - Spring tide



Figure 32 Current velocities - South catchment (O3) - Spring tide



Figure 33 Current velocities - West catchment (N4) - Spring tide

The current velocities at the center of the creek catchment (N3) have an erratic profile over one tidal cycle. The current velocities plotted against water depth do not show a consistent change in velocity directions at the turning of the tide. At the rise of the water levels during flood the current velocities start negative and change quickly to positive indicating a change in directions. For lowering of the water levels during ebb the current velocities change from negative to positive again. The negative and positive values for current velocities only indicate a Western or Eastern directed current respectively, since velocity directions are one dimensional in these graphs and these directions are obtained as a resultant of two velocity components and plotted with an East-West orientation. So to analyze the underlying cause of the negative velocities during flood and the positive velocities during ebb a more detailed current direction analysis will be performed in a later paragraph. The current velocities as measured at N3 have a range of 0.01-0.06 m/s during flood and a range of 0.01-0.06 m/s at ebb tide.

In the South of the catchment (O3) the current velocities show expected results for a tidal cycle with positive current velocities during flood and negative velocities during ebb tide. However, similar to the results at measuring point N3, further analysis of the current directions is necessary to know whether or not flow patterns in the creek catchment are not more complex. The ranges of current velocities at flood are 0.01-0.04 m/s and 0.01-0.065 m/s during ebb.

For the results at grid point N4 in the West of the creek catchment a similar shape of the current velocities to water levels is observed. The positive velocities during flood and negative velocities during ebb indicate an East-West orientation for a flood-ebb cycle. The magnitude of the current velocities during a spring tidal cycle varies from 0.01-0.07 m/s for flood and it varies between 0.01-0.02 m/s during ebb.

#### 4.2.5. Current directions

The current directions throughout the mangrove creek catchment are plotted in the elevation chart in Figure 34. The compass plot for every measuring point is displayed at the corresponding grid point. The compass plots with current velocities and directions add in the analysis of the hydrodynamics of the creek catchment.

At the measuring points in the creeks (K3, N5, P1) no special observations on the current directions can be made. During flood, all currents are directed away from the estuary and into the catchment, meaning that water is transported into the catchment, as is to be expected. Also during ebb the currents are directed towards the estuary following the creek, resulting in the draining of the catchment and the transportation of water towards the estuary. For measuring point K3 this means that all currents at flood are directed in a Western direction and in Eastern direction during ebb parallel to the creek orientation. At measuring point N5 at the West creek, currents are orientated differently due to the North-South orientation of the creek itself. The currents are orientated along the creek, with a Southward direction during flood and a Northern direction during ebb. For measuring point P1 the orientation is mostly Southwest-Northeast, which shows in the current directions plotted in Figure 34. The flood current directions are orientated to the Southwest into the catchment and orientated to the Northeast during ebb towards the estuary.

At the mangrove fringe most currents are directed in Western direction during flood and in Eastern direction during ebb. Only one velocity arrow is directed in Southern direction and has a very small length, meaning a small current velocity. This small current velocity indicates that briefly at the start of ebb, the mangrove fringe flows together with the estuary. In the estuary, directly in front of the fringe, the currents are all directed in Northern direction during flood (land inward) and in Southern direction during ebb (seaward). It is very clear from the compass plots that the forest is at least in part inundated over the forest fringe, because the currents over the fringe make an angle of about 90 degrees with the currents in the estuary. So water is diverted from the estuary into the forest.

The current directions within the catchment itself are more complex than in the creeks or at the forest fringe. Especially in the center of the catchment at measuring point N3 currents are not symmetrical in direction over a tidal cycle. During flood the directions at N3 are mostly directed in Northwestern direction, while at ebb the directions are mostly directed in Northeastern direction. However, also some velocity arrows in more Southwestern and Northern directions are found. During the start of the tidal inundation, current velocity is directed in a more Northern direction, while at the end of the tidal cycle the velocity component is directed in the opposite direction and has a more Southern orientation (Figure 56 in appendix 8.3). For current orientations at the measuring points O3 and N4, no erratic direction changes in the currents are observed. The currents are very symmetrical over one tidal cycle, with a West orientation during flood and an East orientation during ebb at both points in the creek catchment.



Figure 34 Current velocity directions in mangrove creek catchment

### 4.3. Analysis of mangrove hydrodynamics

In section 4.2 the hydrodynamic results for the measuring campaign in the mangrove creek catchment were presented, with current velocity ranges and current orientations through the mangrove creek catchment. From these data, some insight in the hydrodynamic processes of a mangrove creek catchment can be obtained. Notable are the importance of the creeks in catchment inundation and a hysteresis effect induced by the vegetation for inundating and emptying of the catchment area.

The shape of the creek current velocity plots resembles a mushroom-like shape. The acceleration of current velocities is the result of overbank flow. At this water level, the catchment starts to inundate and a larger volume of water needs to be transported through the creeks, resulting in increased current velocities. This acceleration of creek current velocities during overbank flow is similar to creek current velocities of salt marsh creeks, where the larger volume demand with marsh inundation also results in higher current velocities (Temmerman et al., 2005; Wolanski, 1992). The asymmetry in the current velocity plots for ebb and flood is the result of a time lag in the lowering of the water level during ebb in a tidal cycle. The time lag results in much higher current velocities during ebb and also in the higher current velocities during ebb for the same water levels as during flood. Vegetation in the catchment has an inhibitory effect during outgoing tide and retains the water a bit longer in the catchment. Because water levels in the estuary are dropping faster than water levels in the vegetated areas, a larger gradient originates in the creeks during ebb than during flood, leading to the higher current velocities with a longer duration (Mazda et al., 2007).

The effect of overbank flow on the current velocity versus water level profiles for the creeks indicates that the creeks play a significant role in the inundation of the creek catchment. This is further supported by the results of the hydrodynamic measurements within the creek catchment and over the fringe. As can be clearly seen from measuring point N1, part of the catchment is inundated over the fringe, since very consistent current velocities perpendicular to the forest fringe are present. So with full inundation of the creek catchment, the fringe currents will always influence hydrodynamics in the creek catchment. However, throughout the catchment current velocities are not as symmetrical in flow direction, and flow velocities are a result of the bathymetry in the catchment. This indicates that creeks also play an important role in the catchment hydrodynamics. At measuring point L3 an ADV was deployed that did not measure any currents due to the small inundation depths, so the creek bank only inundates for very high water levels. This results in a large transport of water through the creek system into the back of the catchment from the Western edge of the catchment.

The large contribution of the creeks to the inundation of the catchment is further corroborated by the current velocity orientations at especially measuring point N3, but also N4 and O3. During the start of inundation of the creek catchment water is transported through the main creek and West creek into the center of the catchment, because the first velocity component at measuring point N3 is shown to have a Northeastern orientation; in line with the bathymetry of the ending creek. Once again during the end of the tidal cycle, at ebb, the current orientation is related to the creek orientation, visible from the Southwestern orientation. At the intermediary period of the tidal cycle the overbank flow over the fringe seems to be of greater importance, as the orientation of the currents has a dominant Western orientation. However the influence of the creek is still present at

higher water levels. Flow velocities are namely not directed in perpendicular direction to the fringe during flood and ebb. During flood tide the velocity components are directed a bit Northerly as it is composed of the Northeastern flow direction from the creek end and a Western orientated fringe flow. At ebb, currents are directed in a Northeastern direction that is related to the low lying passage towards the fringe in this location. The negative water level gradient towards the fringe will cause the currents to be more directed towards the fringe during this period of ebb.

Also at the location of measuring point N4 the influence of the creek is visible in the hydrodynamics. The large current velocities during flood are all directed in Western direction, which at first glance seems unlikely as it is situated in close vicinity of the Western creek. However, in relation with the bathymetry, the arrows can be explained. The center of the creek catchment will inundate first and, as a result of the high creek banks in the West and North of the catchment, supply to the Western part of the catchment is dependent on the creek, leading to the Western directed currents. Maximum flow velocities are reached, since the fringe flow in Western direction at full inundation of the catchment will reinforce these currents. At ebb tide, the current velocities are very low, which is somewhat inexplicable. The Eastern orientation of the current direction seems logical with the Western directed flood currents. However, the magnitude is very small and a possible explanation is the water level gradient towards the creek in the West and a second water level gradient towards the center of the forest. Water levels in the creek will be lower at ebb tide, attracting water towards the creek, but at the same time water levels in the center of the catchment will also drop due to the more direct connection to the creek and fringe. With current components directed in two directions the resulting current is directed towards the creek to where a slightly larger gradient is present. At the end of the tidal cycle a larger velocity component is expected to be present towards the center of the catchment, because the creek bank in the West will fall dry and all water will be transported through the creek to empty the catchment. Supporting hydrodynamic data are lacking however due to the time interval in the measurements.

The reinforcement of the creek currents with the fringe currents at measuring point N4 is turned around at measuring point O3, where current velocities at flood tide are somewhat low and higher ebb flow velocities are encountered. The lower flood current velocities can be explained by the faster inundation of the location by the Southern creek. Water has to travel a shorter distance during the inundation through the Southern creek in comparison to the Western creek, leading to Western orientated flood currents. Bathymetry analysis would suggest Eastern directed currents, at least at the start of the tidal cycle, but due to the lag in the inundation of the creek, currents start in Western direction during flood. Once the catchment is inundated, the current velocities remain low due to the opposing current components from the fringe and through the creek, with the fringe currents being more dominant. At ebb tide the water level gradient towards the fringe results in the high ebb current velocities, with no conflicting currents towards the creek.

In general, the elevation and vegetation in the catchment reduces the magnitude of the current velocities, as observed in Table 5 with the current velocities in the forest being one order of magnitude smaller than current velocities in the creeks and the estuary. From this data it is not possible to conclude how large the contribution of the mangrove vegetation is on the current velocity reduction in the creek catchment. Due to the smaller water depths in the creek catchment during inundation, bottom friction will already be larger than in the creeks, resulting in lower current

velocities. The addition of vegetation influences is not possible to determine, but a considerable contribution to the velocity differences is certainly to be expected. The influence of the vegetation however is evident in the velocity profile of the creeks, with the time lag resulting in larger ebb current velocities. On the flow routing through the catchment the vegetation exerts no provable influence. Here the bathymetry of the creek catchment seems to be more important, with the lower lying areas of the creek catchment filling up first during inundation. Indirectly the vegetation can influence the flow routing by accounting for morphological changes, but these appear at a different timescale.

## 5. Sediment transport

The second aspect of the morphological diamond concerns the sediment dynamics, which are influenced by the hydrodynamics and the vegetation in the creek catchment. Consequently the sediment dynamics influence the morphology in the creek catchment. The sediment dynamics (suspended sediment transport) and the hydrodynamics (tidal flows) are of the same timescale (i.e. seconds to days), so any change in hydrodynamics will have direct influence on the sediment dynamics. During spring tide the sediment concentrations throughout the creek catchment are expected to be the highest, since highest water levels are reached and hence largest current velocities can be observed. The most dynamic conditions are thus observed during spring tide. The relation between sediment dynamics and hydrodynamics will be further analyzed in this chapter. The relation and the influence exerted by the sediment dynamics on the morphology of the creek catchment will be analyzed in the next chapter on the morphology. Vegetation is a boundary condition for the sediment dynamics, because on the short time scales (i.e. seconds to days) no direct changes in vegetation will occur with no altering influences on sediment dynamics.



Figure 35 Sediment dynamics within morphological diamond

### 5.1. Data processing

Like for hydrodynamic measurements, sediment dynamics are measured for a complete spring neap tidal cycle. Since the interest of this study lies within the hydrodynamics of a mangrove creek catchment during spring tides, the data collected during biweekly field measurements was filtered for the spring tidal signal. Matlab scripts to obtain the suspended sediment concentrations from the ADV output are presented in appendix 7.3. The ADV output gives a signal-to-noise ratio which is converted into the suspended sediment concentrations. The calibration of the signal-to-noise ratio for the correct suspended sediment concentration resulted in the following relation:

 $y = 6 \cdot 10^{-7} \cdot e^{0.4314x}$ , with x being the signal-to-noise ratio and y representing the suspended sediment concentration.

### 5.2. Results sediment dynamics measurements

Results for the suspended sediment concentrations (SSC) are plotted in graphs. In the graph of each measuring point, the SSC is related to time and plotted together with the current velocity against time. The relationship between the SSC and the current velocities in the same graph shows the variation in suspended sediment concentrations with changing hydrodynamics over a spring tidal cycle. With the current velocities generally being directed in Western direction into the mangrove

forest during flood and in Eastern direction towards the forest fringe during ebb, the change in suspended sediment concentrations can be observed over the entire tidal cycle.

#### 5.2.1. Creek suspended sediment concentrations

Some general trends in the suspended sediment concentrations of the creeks can be observed. All three plots have similar shapes for their relation between suspended sediment concentrations and current velocities, however the shape is by far not identical. The general trend in the plots shows that for high current velocities, the suspended sediment concentrations are large as well. Also similar for the three creek SSC plots are the smaller suspended sediment concentrations during ebb than during flood in the tidal cycle. The difference between ebb and flood however is different for every individual creek.



Figure 36 Suspended sediment concentrations - Main creek (North, K3) - Spring tide



Figure 37 Suspended sediment concentrations - South Creek (P1) - Spring tide



Figure 38 Suspended sediment concentrations - West Creek (N5) - Spring tide

For the main creek the suspended sediment concentrations against current velocities are shown in Figure 36. The two peaks clearly display the variation of suspended sediment concentrations over a tidal cycle. With the increase of (positive) current velocities during flood the sediment concentrations also increase rapidly. At the turning of the tide, current velocities reduce to zero and start to increase again in the opposite direction, leading to a low suspended sediment concentration during the turning of the tide. Once current velocities start to become larger again during ebb, the suspended sediment concentrations in the main creek is 0-80 mg/L during flood and 0-71 mg/L during ebb tide. Suspended sediment concentrations during ebb tide are thus slightly less than during flood tide, with a difference of about 10%.

In Figure 37 suspended sediment concentrations for the South creek at P1 are displayed. The shape of this plot is much more irregular than for the suspended sediment concentrations at K3. Suspended sediment concentrations vary much more with slightly varying current velocities. At the beginning of the flood, suspended sediment concentrations increase with increasing current velocities. However, at the maximum current velocities of around 0.1 to 0.15 m/s, the suspended sediment concentration is reduced already. With the turning of the tide, current velocities reduce further to around zero and so does the suspended sediment concentration. During ebb the current velocities start to increase again and suspended sediment concentration also rise. The concentrations fall again when ebb current velocities reduce again. The range of the suspended sediment concentrations for flood varies between 0-15 mg/L and at ebb the concentrations vary between 0-6.5 mg/L. The difference in maximum suspended sediment concentrations between flood and ebb is thus about 50%.

Suspended sediment concentrations in the West creek at grid point N5 are shown in Figure 38. Ranges in the suspended sediment concentrations in the West creek are for flood 0-11 mg/L and for ebb 0-5 mg/L. The difference between the maximum suspended sediment concentrations during flood and ebb is thus about 50% again. Similar to the other two creeks, the current velocities increase during flood and simultaneously the suspended sediment concentrations also increase. Again, with the turning of the tide from flood to ebb, the current velocities reduce to approximately zero and so

do the suspended sediment concentrations. At ebb the suspended sediment concentrations start to increase again with increasing current velocities. Only the high suspended sediment concentration at the end of ebb tide is irregular.

#### 5.2.2. Fringe suspended sediment concentrations

At measuring points N0 and N1, the time variation of the suspended sediment concentrations over the forest fringe along the estuary can be analyzed. In general, the figures show that the magnitude of the suspended sediment concentrations is different. Suspended sediment concentrations in the estuary are in magnitude much larger than over the forest fringe.



Figure 39 Suspended sediment concentrations - Estuary (NO) - Spring tide



Figure 40 Suspended sediment concentrations - Fringe (N1) - Spring tide

The suspended sediment concentrations in the estuary in front of the forest fringe at NO are shown in Figure 39. During the increase in current velocities at flood the suspended sediment concentrations start to increase as well. At the maximum current velocity during flood the suspended sediment concentrations are already reduced. The lower suspended sediment concentration at about 100 minutes into the tidal cycle is very extreme. The current velocity drops as well at the same moment and because of the direct relation between the current velocity and suspended sediment concentrations, this drop is explicable. Then at the transition from flood to ebb, the current velocities

reduce to approximately zero and so do the suspended sediment concentrations. At ebb tide the current velocities increase again and with that also the suspended sediment concentrations do. During flood the suspended sediment concentrations vary between 0-58 mg/L and during ebb the suspended sediment concentrations vary between 0-30 mg/L. This comes down to a 50% reduction.

For the seaside fringe suspended sediment concentrations are plotted in Figure 40. The time variation of the suspended sediment concentration shows that from flood to ebb the suspended sediment concentration only decreases at the measuring point. Once the fringe gets inundated, relatively high amounts of suspended sediments are observed, in line with the high current velocities. Once the current velocities reduce, because the turning of the tide is approached, suspended sediment concentrations will also reduce. At ebb, the current velocities increase again, but the suspended sediment concentrations remain approximately zero. At the start of the flood inundation of the forest fringe, suspended sediment concentrations are 4.4 mg/L and these gradually reduce to 0.1 mg/L. During ebb, the suspended sediment concentrations will not exceed 0.1 mg/L.

#### 5.2.3. Creek catchment suspended sediment concentrations

Within the creek catchment, suspended sediment concentrations are measured at the grid points N3, O3, and N4. With these points, insight in the transport of sediments through the heart of the catchment is gained. At a first glance, the suspended sediment concentrations in the creek catchment are very low compared to the fringe and creek observations. They all however have a similar magnitude of suspended sediment concentrations within the forest. Also the change of suspended sediment concentrations over one tidal cycle is similar.



Figure 41 Suspended sediment concentrations - Center of catchment (N3) - Spring tide



Figure 42 Suspended sediment concentrations - South catchment (O3) - Spring tide



Figure 43 Suspended sediment concentrations - West catchment (N4) - Spring tide

The creek arm extends into the center of the creek catchment, where suspended sediment concentrations are measured at grid point N3. The relation between current velocity and suspended sediment concentration is displayed in Figure 41. The profile of the suspended sediment concentrations shows that at flood, with high current velocities, suspended sediment concentrations are also highest. Towards the turning of the tide with current velocities of zero, the suspended sediment concentrations decrease. At ebb tide, the suspended sediment concentrations decrease even further and very low concentrations are encountered. Apparently sediment is settling and much less sediment is picked up from the bed again when the velocity increases again. The suspended sediment concentrations at flood range between 0.1-0.9 mg/L and the range at ebb tide is 0.05-0.1 mg/L.

Suspended sediment concentrations in the South of the catchment are displayed in Figure 42. The suspended sediment concentrations start high with high current velocities during flood. Throughout the tidal cycle the suspended sediment concentrations decrease, even when at ebb higher current velocities are encountered once again. At the transition from flood to ebb no decrease to zero is

observed in the suspended sediment concentrations, the concentrations seem to be decreasing over the entire tidal cycle starting with high concentrations during inundation at flood tide. The range in suspended sediment concentrations in the South of the catchment is 0.25-0.5 mg/L during flood tide and 0.04-0.25 mg/L during ebb tide.

For the West of the catchment at grid point N4, suspended sediment concentrations are plotted in Figure 43. Similar to the profile of suspended sediment in the South of the catchment at grid point O3, the plot shows relatively large suspended sediment concentrations during flood. The sediment concentrations decrease towards the turning of the tide and also during ebb tide. During ebb very little suspended sediment is present. In contrast to the South of the catchment, concentrations reduce rapidly with decreasing current velocities towards the turning of the tide and remain low during ebb. The range in suspended sediment concentrations in the West of the catchment are 0.15-0.79 mg/L for flood and the range for ebb tide is 0.08-0.15 mg/L.

## 5.3. Analysis of mangrove sediment dynamics

Results for the sediment dynamics measurements in the form of suspended sediment concentration measurements at a measuring grid are discussed in section 5.2. Combined with the analysis on the hydrodynamics from section 4.3, the sediment dynamics in the creek catchment will be analyzed in this section. A first indication of the results shows a good relation between the obtained hydrodynamic data and the sediment dynamics data.

As a result of the high current velocities in the creeks, also high suspended sediment concentrations are observed in the creeks, which are one or two orders of magnitude higher than for the suspended sediment concentrations in the forest. The high suspended sediment concentrations in the creeks indicate a large supply of sediments through the creeks into the forest. The main creek at measuring point K3 has the highest suspended sediment concentrations, this is the main vain for a larger hinterland of the mangrove forest. The bifurcation towards measuring point N5 supports the high supply of sediments into the forest, because large values for the suspended sediment concentrations are still encountered in the West creek that extends into the center of the catchment.

Over the fringe also a large amount of sediments is supplied into the forest. In the estuary in front of the fringe, suspended sediment concentrations of the same order of magnitude as in the creeks were measured. When the forest gets inundated the water is flowing over the fringe with suspended sediment concentrations originating from the estuary. Due to the large differences in current velocities between the estuary and the forest fringe, suspended sediment concentrations at the forest fringe are one order of magnitude lower than in the estuary. However, the direct link with the estuary gives the expectation of large suspended sediment concentrations at the forest fringe. Subsequently, the suspended sediment concentrations at the forest fringe. Subsequently, the suspended sediment concentrations in the forest at grid points N3, N4, and O3. So it is expected that the forest fringe is also of importance for the input of sediment.

A large difference is encountered in the suspended sediment concentrations during flood and ebb tides in the creek catchment. During ebb tide, the suspended sediment concentrations at the catchment grid points N3, N4, O3 are all close to zero, while during flood tide, concentrations of at

least 0.5 mg/L are encountered. This difference will result in the deposition of sediment through the creek catchment. The deposition of sediments in the creek catchment is further corroborated at the main discharge routings during ebb tide, namely the West creek and the forest fringe. In the West creek at N5 and over the forest fringe at N1 much lower suspended sediment concentrations are measured during ebb tide. So, with less suspended sediment concentrations at these two points with outgoing water flows, sediment apparently has been retained in the creek catchment.

The lower sediment concentrations during ebb are most likely related to the low current velocities in the creek catchment. At measuring point N4 in the catchment a large difference in the ebb and flood current velocities is observed. The large difference between the current velocities at ebb and flood tide would be the most natural explanation for the large differences between the suspended sediment concentrations within the forest, since the low ebb current velocities would then be unable to once again entrain settled sediments. However, at the other two measuring points within the creek catchment, the difference between the current velocities in the tidal cycle is absent. Therefore it is expected that the sediments flocculate while settling. The flocculated material increases in size by an order of magnitude and as a result, ebb tidal currents are often too slow to resuspend them (Furukawa et al., 1996). These processes would result in sediment deposition even at equal tidal velocities. The higher ebb current velocities at grid points N3 and O3 might also lead to a slower settling of sediments, since there is more force to keep them in suspension longer.

The creeks K3, N5, and P1 also show larger suspended sediment concentrations during flood than during ebb, even though the ebb current velocities are higher. Main reason for this could be the amount of sediment left behind in the forest. The difference between flood and ebb suspended sediment concentrations in the main creek at K3, however, is much smaller than for the other two creeks. An explanation for this phenomenon could be the higher current velocities in the main creek over a much larger distance, leading to self scouring of the creek (Mazda et al., 2005; Wolanski, 1992). Fine material is entrained in the creek during ebb and transported out into the estuary.

During high current velocities at the end of flood at measuring points N0 and P1, the suspended sediment concentrations were lower than at lower current velocities earlier in the flooding part of the tidal cycle. This is peculiar, because the expectation is to find higher suspended sediment concentration for higher current velocities. However this could be explained by the location of N0, which is located in the estuary (and P1 is directly impacted by the estuary due to its close location to the mouth of the South creek) and sea water with a low suspended sediment concentration is transported into the estuary at the end flood tide. After mixing of the sea water with the estuarine water and their corresponding suspended sediment concentrations the estuarine suspended sediment concentrations will drop.

All in all, it is very clear that the hydrodynamics have a clear impact on the sediment dynamics through the mangrove creek catchment. Since the vegetation influences hydrodynamics, in large by the magnitude of current velocities through the creek catchment, it consequently has a major impact on sediment dynamics. The drop in current velocities in the creek catchment in comparison to the creeks and the estuary, results in larger suspended sediment concentrations directed into the forest during flood tide than directed out of the forest during ebb tide.

## 6. Sediment deposition

Hydrodynamics and sediment dynamics over a tidal cycle are already described in the previous chapters. The morphological diamond shows that the third aspect in the loop is the morphology of the creek catchment. The morphology on the long term comprises surface elevation changes, which is a cumulative response to short term accretion or erosion, which is investigated in this chapter. The mangrove creek catchment is expected to be most dynamic and show the largest accretion patterns over one spring tidal cycle, since the largest current velocities with the largest sediment concentrations will be present at spring tide. Together with the analysis of the hydrodynamics and the sediment dynamics in the creek catchment, the morphological changes of the creek catchment can be assessed based on spring tide accretion rates. The morphology of the creek catchment is influenced by the sediment dynamics and consequently by the hydrodynamics. On longer timescales the morphology is really changing by the net effect of sediment deposition and erosion which then in turn influences the hydrodynamics, creating a loop. However, the short timescale of one tidal cycle that was investigated in the creek catchment, means that for the hydrodynamics the original bathymetry is a boundary condition. This chapter will analyze the morphological changes through the catchment and the importance of creeks in the accretion of mangrove forests during one spring tide.



Figure 44 Sediment deposition within morphological cycle

## 6.1. Data processing

Data processing for the sediment deposition rates is very straightforward. After drying and weighing the sediments trapped on the tiles during the measurement campaign, the weights were averaged over the number of measurements. So for sixteen grid points four measurements were taken and for the four grid points in row Q only two measurements were averaged. The tiles were 20x25 cm, so furthermore the weights were scaled to get a deposition rate per square meter. After the weights are determined, an indicative calculation is performed to obtain a bandwidth of accretion rates in mm/m<sup>2</sup> at the grid points. The accretion rates in millimeters give a better feel for elevation changes of the catchment floor through sedimentation and the ability of the mangroves to keep up with sea level rise by trapping of sediments.

The calculation for conversion of the deposition weights to the accretion rates in millimeters is explained briefly below:

Dry mass per  $m^3 = \rho_s \times n$ 

 $Volume \ per \ m^2 = \frac{Deposition \ rate}{Dry \ mass \ per \ m^3}$ 

 $\begin{aligned} Accretion \ rate &= \frac{Volume}{Area \ tile} \\ Sediment \ density \ \rho_s &= 2650 \ kg/m^3 \\ porosity \ n &= 0.4 \\ porosity \ n &= 0.6 \\ porosity \ n &= 0.8 \end{aligned}$ 

Density of quartz and clay minerals is approximately equal to  $\rho_s = 2650 kg/m^3$  (Van Rijn, 1993). The porosities chosen were 0.4, 0.6 and 0.8, because this the range between well compacted sand (porosity is 0.4-0.6) and deposits containing clay, silt, sand and organic material (porosity is 0.8) (Van Rijn, 1993). The sediment deposits in the creek catchment are most likely to contain clay and organic matter, however the exact sediment characteristics are unknown for this study. Therefore a bandwidth of porosities is taken to get an indication of the accretion rates.

#### 6.2. Sediment deposition rates in the creek catchment

The sedimentation rates over a spring tidal cycle in the creek catchment of interest is shown in Figure 45. The absolute values of the deposition rates and accretion rates can be found in Table 4. The entire range of deposition rates is 27-209 g/m<sup>2</sup>. The ranges of accretion rates are 0.025-0.20 mm/m<sup>2</sup> for a porosity of 0.4 and 0.017-0.13 mm/m<sup>2</sup> for a porosity of 0.6 and 0.013-0.10 mm/m<sup>2</sup> for a porosity of 0.8. Groups of measuring grid points with a similar magnitude in the deposition rates can be distinguished in the creek catchment. For each of these groups the deposition rate and the accretion calculated for a porosity of 0.8 are given, since this porosity is most likely the best indication for the creek catchment. The deposition and accretion rates at the fringe of the catchment, at grid points L1, M1, N1, O1 and Q1, show high deposition and accretion rates with a range of 95-170 g/m<sup>2</sup> and 0.045-0.080 mm/m<sup>2</sup>. Very low sediment deposition and accretion rates are measured at measurement grid points L2, M2, N2, O2, L3, and L4 directly behind the fringe and alongside the main creek in the North, with a range of 27-74 g/m<sup>2</sup> and 0.013-0.035 mm/m<sup>2</sup>. Other high sediment deposition and accretion rates are encountered at measurement grid points M3, M4, N3 and N4 in the center of the creek catchment and at a large distance from the fringe in the West of the creek catchment with a range of 125-209 g/m<sup>2</sup> and 0.059-0.10 mm/m<sup>2</sup>. A final group of measuring grid points, at O3, O4, Q2, Q3, and Q4, show an intermediate range of sediment deposition and accretion rates with a range of 72-136 g/m<sup>2</sup> and 0.034-0.064 mm/m<sup>2</sup>.



Figure 45 Sediment deposition at measurement grid points

Table 4 Sediment deposition rates at measurement grid points

Location	Deposition rate [g/m <sup>2</sup> ]	Accretion rate [mm] for n=0.4	Accretion rate [mm] for n=0.6	Accretion rate [mm] for n=0.8
L1	101	0.095	0.064	0.048
L2	37	0.035	0.023	0.017
L3	27	0.025	0.017	0.013
L4	33	0.031	0.021	0.016
M1	120	0.11	0.075	0.057
M2	70	0.066	0.044	0.033
M3	125	0.12	0.079	0.059
M4	163	0.15	0.10	0.077
N1	95	0.090	0.060	0.045
N2	36	0.034	0.023	0.017
N3	209	0.20	0.13	0.10
N4	189	0.18	0.12	0.089
01	103	0.097	0.065	0.049
02	74	0.070	0.047	0.035
O3	113	0.11	0.071	0.053
04	72	0.068	0.045	0.034
Q1	170	0.16	0.11	0.080
Q2	127	0.12	0.080	0.060
Q3	136	0.13	0.086	0.064
Q4	83	0.078	0.052	0.039

## 6.3. Analysis of mangrove creek catchment morphological changes

The general trend of accretion in a mangrove forest is supported by the sediment deposition rates observed in the creek catchment. The distinctive pattern of the sediment deposition rates in the mangrove creek catchment shows a clear relation with the hydrodynamics and the sediment dynamics. High sediment deposition is encountered at places with large current velocity changes and with a decrease of suspended sediment concentrations over a tidal cycle, so over flood and ebb tide. Also sediments are expected to flocculate due to cohesive forces of clay particles in saline conditions and increase in size, making it even more difficult for sediment particles to be entrained again, thus causing high sediment deposition rates at places with relatively low flow velocities. The pattern of sediment deposition throughout the creek catchment is not directly explained by an inundation cycle originating at the fringe of the mangrove forest, where large deposition further into the mangrove forest away from the forest fringe. In contrast, in the mangrove forest also high sediment deposition rates are encountered, leading to large accretion deeper into the mangrove forest.

At the fringe of the mangrove forest the high sediment deposition rates are caused by the sudden drop in current velocities at the boundary of the estuary as a result of the dense vegetation on the forest fringe. The current velocities are dropping so fast that most of the sediment is not able to stay in suspension and settles down to the bed.

As observed with the sediment dynamics through the forest, lower sediment concentrations are present during ebb tide which is a result of the decrease in current velocities into the creek catchment in comparison to the estuary. The lower sediment concentrations during ebb tide at the fringe are the result of settled sediment at the forest fringe due to the current velocity drop over the fringe. This results in lower sediment deposition rates encountered at the M2, N2, and O2, because sediment has already settled at the fringe. The lower sediment concentrations result in less deposition, because at the turning of the tide less sediment is available to settle down to the bed of the catchment. At the same distance from the forest fringe is measuring point Q2, which has a sediment deposition rate that is higher than at the other grid points directly behind the forest fringe. This grid point is located in close vicinity of the Southern creek and therefore shows higher sediment concentrations in the creek and consequently into the creek catchment. Similar to the grid points at the fringe, grid point Q2 has a higher sediment deposition rate, because current velocities will be reduced by the vegetation and the sediment will settle down to the bed. This in turn is corroborated by the lower suspended sediment concentrations in the creek at ebb tide.

The sediment deposition patterns in the center and West of the creek catchment at grid points M3, M4, N3 and N4 stem from the creek influence on the creek catchment. Within the creek, higher suspended sediment concentrations are reached due to the higher current velocities. The creek extends into the creek catchment transporting these sediment quantities into the heart of the catchment at grid point N3. In the center of the catchment, current velocities are already reduced by the increasing bottom elevation and vegetation influence and sediment settles down to the bed realizing high sediment deposition rates at N3. Because current velocities are reduced largely in the heart of the creek catchment, high sediment deposition rates are found at grid points M3, M4 and

N4, while these points have distances of at least 30 meters to measuring grid point N3 until where the creek arm penetrates the catchment. The distance from the creek arm gives the expectation of lower sediment deposition rates since current velocities away from the creek arm are expected to be lower. At the measuring points M3, M4 and N4, the asymmetrical tidal current velocities, with much larger flood currents than ebb currents, are in large accountable for the large sediment deposition rates. Sediments suspended in the water column during flood can no longer be entrained at ebb, due to the very small current velocities, and settle.

More symmetrical tidal currents for ebb and flood are present at measuring grid point O3, which consequently results in the more moderate sediment deposition rates at grid point O3. Similarly at measuring grid points O4, Q3, and Q4 more symmetrical tidal currents are expected, since these points are located at equal distances from the creeks as point O3. With larger or equal magnitudes in current velocities during flood compared to ebb and the dropping of suspended sediment concentrations over the entire tidal cycle as observed for measuring point O3, sediments can be carried to these points via the fringe during full inundation or via the creek. At full inundation the water level in the forest is equal to the water level in the estuary and from the hydrodynamics at measuring point O3 it is expected that during full inundation the currents through the forest are perpendicular to the forest fringe. The decreasing suspended sediment concentrations over the tidal cycle mean that sediment is settling down to the bed and being deposited in the forest as observed at these measuring points. Either way, the sediment will settle to the bed at the turning of the tide and during ebb tide. The difference in suspended sediment concentrations between ebb and flood means that large amounts of sediments are deposited at these locations. Once particles have settled onto the bed more force has to be exerted to put them back into motion, due to friction forces with other sediment particles (Van Rijn, 1993). The initiation of motion needs higher current velocities, therefore sediment stays deposited at these grid locations.

At the creek bank of the main creek in the North of the catchment, very small sediment deposition rates were measured at L2, L3, and L4. These are the consequence of the high elevation and the close vicinity to the main creek. In the creek very large current velocities are reached, especially at high water levels at the moment that the creek banks are inundated. With these large currents, the water carries lots of suspended sediment. The elevation of the creek bank is high and the bank will only be inundated at the end of the flood cycle and the start of the ebb cycle. At these moments very high velocities are present in the creek that will also be transferred to the creek bank, even though vegetation will have some obstructing effect. The high current velocities prevent sediments to settle on the banks and ensure that most of the deposited sediments are again entrained in the water column after the turning of the tide.

The importance of the mangrove creeks in the sedimentation patterns in the creek catchment is obvious through the high sediment deposition rates in the center and back of the creek catchment. With the very high creek banks and bank behind the fringe, inundation of the entire forest will occur late in the tidal cycle. However the creek already starts to inundate the center and Western part of the catchment supplying these areas with sediments that will be caught in between the high creek banks.

## 7. Discussion

The results in this study describe hydrodynamic and morphodynamic processes in a mangrove creek catchment. In the past, studies have been performed into the hydrodynamic and morphodynamic processes in mangroves. This discussion will make a comparison with previous work to validate the measurements and to find new insights for hydrodynamic and morphodynamic processes in a mangrove creek catchment. Furthermore, this chapter discusses the validity of the obtained results and the value of the results for future usefulness of mangroves in the battle against climate change.

## 7.1. Mangrove hydrodynamics

The current velocities measured within the creeks range from 0.02 to 0.3 m/s which is much larger in magnitude than the flow velocities in the forest that do not exceed 0.07 m/s. The large difference in magnitude of the current velocities is in part caused by the obstruction due to the vegetation (Mazda et al., 1997; Alongi, 2008) and in part by the decreased water depth in the forest. Also the difference between flood and ebb velocities is different between the creeks and the forest. In the forest current velocities are in general larger during flood than during ebb. For the creeks this is just the opposite.

The measured current velocities (Table 5) are compared with current velocities found in literature, which are presented in Table 6. In literature the creek current velocities all seem to be higher than the observed creek current velocities in the study area. Bryce et al. (2003) and Wolanski et al. (1992) found significantly higher current velocities in the creeks, where only Wolanski et al. (1992) also present forest current velocities and these are also significantly higher. For the studies of Victor et al. (2006), Kitheka (1996), Anthony (2004), and Van Santen et al. (2007) the creek current velocities are all slightly higher than observed in the study area. A relation between the creek current velocities and the forest current velocities is visible in the literature. Higher creek current velocities found in literature. Only Van Santen et al. (2007) and Victor et al. (2006) show comparable current velocities in the mangrove forest and the investigated creek catchment though. All other current velocities in mangrove forests from literature have larger magnitudes, with Wolanski (1992) and Furukawa et al. (1997) being significantly higher. The current velocities in Furukawa et al. (1997) have been measured in close vicinity to the creek however.

Measuring points	Location	Current velocities [m/s] (flood)	Current velocities [m/s] (ebb)
K3	Creek	0.05-0.3	0.08-0.3
N5	Creek	0.05-0.2	0.05-0.31
P1	Creek	0.02-0.15	0.02-0.16
NO	Estuary	0.05-0.21	0-0.12
N1	Forest	0.01-0.04	0.02-0.065
N3	Forest	0.01-0.06	0.01-0.06
03	Forest	0.01-0.04	0.01-0.065
N4	Forest	0.01-0.07	0.01-0.02

#### Table 5 Current velocities over a tidal cycle in creek catchment

Literature	Current velocities [m/s] (creeks)	Current velocities [m/s] (forest)
(Victor et al., 2006)	~0.4	~0.08
(Kitheka, 1996)	~0.6	~0.1
(Wolanski, 1992)	~1.6	~0.3
(Anthony, 2004)	~0.5	~0.1
(Furukawa et al., 1997)		~0.2
(Bryce et al., 2003)	~1.0	
(Van Santen et al., 2007)	~0.3	~0.03

Table 6 Current velocities ranges in mangroves from literature

Absolute values of the current velocities in this research seem to approach the measured current velocities described in literature. However to make a valid comparison between the current velocity values, research area characteristics are of importance. Important for tidal flow velocities in mangroves are the location at the coastline and the tidal prism and thus the dimensions of the creek and the mangrove forest area fed by the creek. The research area in this study was located within the estuary of the Kantang River with a sheltered positioning. The spring tidal range is 3.2 meter (Chansang and Poovachiranon, 1994) and a rough estimation of the creek length is 800-1000 meters land inward. The study area seems to have a somewhat smaller tidal prism than study areas found in literature, since the creek length and accompanying mangrove forest area, with only a landward extension of around 1km, are rather small, although the tidal range is pretty high. In Victor et al. (2006) the study area is more directed towards open sea and the tidal range is 1.5 meters, with an approximated creek length of about 2 km. Bryce et al. (2003) have a study area with a large creek in direct connection to open sea. The width of the creek varies between 15-30m and the creek extends approximately 9.5 km into the mangrove forest. Spring tidal range in their study area is 2.3 m. The study area of Anthony (2004) has more sheltered creeks, similar to the study area in this thesis. The spring tidal amplitude in the study area is 2 meters and the creek length is approximately 8 km. Kitheka (1996) conducted the research in a more sheltered mangrove area with two creeks that were approximately 4.5 and 2.5 km in length. Spring tidal range in the study area is 3 meters, which is similar to the tidal range in this thesis. Van Santen et al. (2007) conducted their research in the Red River delta, with spring tidal ranges of 2.5 meters. The mangrove forest of interest only had dissecting dimensions of about 100 to 120 meters and the creek measurements were performed in the river delta. So, similar to the study area in this thesis, the mangrove area for the tidal prism was modest. The study area in Furukawa et al. (1997) is a mangrove forest along a creek with a spring tidal range of 3 meters. Creek length is not obtainable, but the mangrove area surrounding the creek seems to be quite extensive.

All of the study areas in literature seem to have larger tidal prisms, with in general larger creeks extending deeper into the mangrove forests, than the study area in this thesis. Spring tidal ranges are mostly not larger than for the study area in this thesis however. So the slightly larger current velocities in literature can be explained readily by the area characteristics. Creeks in comparable studies are serving a larger mangrove forest area meaning a higher inundation volume and higher current velocities through the supply route of the creeks. The more extreme current velocities in the creeks are possibly related to the location on the coastline. A more direct connection to open sea can enforce higher current velocities as encountered in Bryce et al. (2003). With these area

characteristics in mind the differences in the current velocities can be judged a bit differently. The current velocities now seem to be more in coherence with current velocities found in literature, because the differences can be explained in large by the area characteristics.

## 7.2. Mangrove sediment dynamics

Suspended sediment concentrations have a relation with current velocities that is  $s = mu^n$ , with n possibly ranging between 2 and 5 (Van Rijn, 1993). So it can be expected that with the lower current velocities in the study area, significantly lower suspended sediment concentrations are encountered. Indeed, measured sediment concentrations in the study area (Table 7) are smaller than reported in literature (Table 8). However, the difference in suspended sediment concentrations is far too large, to be explained by the difference in current velocities only. When compared to previous field studies, suspended sediment concentrations in the forest are consistently larger in literature by at least two orders of magnitude than in this thesis. The only good agreement in suspended sediment concentrations is for the creek with Adame et al. (2010) and perhaps Bryce et al. (2003) because current velocities in this study are also much larger.

Measuring points	Location	Suspended sediment concentrations [mg/L] (flood)	Suspended sediment concentrations [mg/L] (ebb)
K3	Creek	0-80	0-71
N5	Creek	0-11	0-5
P1	Creek	0-15	0-6.5
N0	Estuary	0-58	0-30
N1	Forest	0-4.4	0-0.1
N3	Forest	0.1-0.9	0.05-0.1
03	Forest	0.25-0.5	0.04-0.2
N4	Forest	0.15-0.79	0.1-0.11

#### Table 7 Suspended sediment concentrations in the study area

#### Table 8 Suspended sediment concentration in literature

Study	Location	Measuring technique	Suspended sediment concentrations [mg/L] (SSC)
(Bryce et al., 2003)	Creek	OBS	100-400
(Van Santen et al., 2007)	Creek	OBS	300-600
	Forest	OBS	30-50
(Anthony, 2004)	Creek	Sampling	6000-50000
(Brinkman et al., 2005)	Forest	OBS	10-750
(Furukawa et al., 1997)	Forest	Sampling	40-150
(Vo-Luong and Massel, 2006)	Forest	OBS	100-300
(Adame et al., 2010)	Creek	Sampling	90-134

The different studies summarized in Table 8 did use different measuring techniques to obtain results for suspended sediment concentrations. Mostly optical backscattering signals are used to determine the suspended sediment concentrations. This is done by Bryce et al. (2003), Van Santen et al. (2007), Brinkman et al. (2005), and Vo Luong and Massel (2006). The other studies of Anthony (2004), Furukawa et al. (1997), and Adame et al. (2010) used water sampling as the chosen method for

determining suspended sediment concentrations. Apart from Anthony (2004), which presents inexplicable large suspended sediment concentrations, it can be observed that optical backscattering gives higher suspended sediment concentration. In this thesis acoustic backscattering was used, which in turn resulted in very low suspended sediment concentrations.

So from the different studies a large variation in suspended sediment concentrations is observed which is also dependent on the measuring technique used. Therefore a good comparison of the suspended sediment concentrations is very difficult. Moreover, the difference in suspended sediment concentrations will also be dependent on the bed material available for transport, which in turn depends on the characteristics of the study area and its environment. With the Kantang River present at the study area, a large input of sediment can be expected. More information on sediment characteristics is needed however, to relate sediment input to suspended sediment concentrations in the creeks and mangroves.

### 7.3. Sediment deposition

The sediment deposition rates from literature are presented in Table 9, however not all values can be compared directly due to the difference in measurement durations. To compare the two studies of Van Santen et al. (2007) and Cahoon et al. (1997), in which annual sediment deposition rates are presented, the daily rates are calculated by dividing the annual rates by 365 days.

Study	Sediment deposition rates [g/m²/day]
(Van Santen et al., 2007)	24-164
(Cahoon et al., 1997)	3-11
(Furukawa et al., 1997)	49-350
(Adame et al., 2010)	4-90
(Victor et al., 2006)	45–325

#### Table 9 Sediment deposition rates from literature

The observed range of sediment deposition in the studied creek catchment is 27-209 g/m<sup>2</sup>/day, which is in good comparison to the deposition rates found in Furukawa et al. (1997) and Victor et al. (2006). In these two studies the maximum deposition rates in the range are a bit higher than the measured deposition rates in the creek catchment, but they are of the same order of magnitude. The deposition rates found by Adame et al. (2010) are one order of magnitude smaller than the measured deposition rates in the creek catchment. The studies of Van Santen et al. (2007) and Cahoon et al. (1997) show daily (assumed to be per two tides) rates of 24-164 g/m<sup>2</sup>/day and 3-11 g/m<sup>2</sup>/day. The sediment deposition rates in Van Santen et al. (2007) are of the same order of magnitude as the measured deposition rates, but the deposition rates in Cahoon et al. (1997) are one order of magnitude smaller, similar to Adame et al. (2010).

For better comparison between the sediment deposition rates in the creek catchment and mangrove forests in literature, also area characteristics are important. The density of vegetation and location in the estuary are important for the activity and the deposition of sediment. The study area in this thesis has a dense vegetation cover of mixed species and is located within the estuary along a tidal creek. In Van Santen et al. (2007) the study area lay in the Red River estuary, where a vegetation cover of mixed species was present. The front of the study area consists of pioneer density, which is not very dense and the back of the study area has a dense vegetation cover, where the least sedimentation is encountered since it is least exposed to the open sea and therefore probably less active. Cahoon et al. (1997) studied mangroves in three settings, namely basin, fringing and scrub mangroves. The fringing mangroves are dominated by Rhizophora and the basin mangroves mainly consist of mixed species, such as Rhizophora and Avicennia, and a dense vegetation cover. The study areas had no tidal creeks and the tidal exchange in the basin mangroves is very small and therefore the area is not as active as the fringing mangroves. The study area of Furukawa et al. (1997) consisted of fringing mangroves alongside a tidal creek with a dense vegetation cover with mixed species, such as Rhizophora, Bruguiera and Ceriops. Multiple study areas were investigated in Adame et al. (2010), which have an unspecified vegetation cover. Five out of six of their study areas are located in a bay and one location is located directly at the ocean. Victor et al. (2006) obtained deposition rates in a study area that consisted of fringing mangroves facing open sea with a tidal creek present. The vegetation cover was dense and consisted of mixed species.

The study areas of Furukawa et al. (1997), Victor et al. (2006) and Van Santen et al. (2007) are similar to the study area in this thesis, all with a mixed vegetation cover and located in an estuary with tidal creeks penetrating the mangrove forest. Also the sediment deposition rates in these areas are comparable and are of the same order of magnitude as the results for this study. The two other study areas of Cahoon et al. (1997) and Adame et al. (2010) show results that are one order of magnitude smaller and this can possibly be attributed to different area characteristics. The sediment supply to the basin mangroves in the study area of Cahoon et al. (1997) is probably low, due to the smaller tidal exchange. The fringing mangroves in this study show the higher deposition rates, but are still smaller than in the study area of this thesis. This is most likely explicable by area characteristics that are unknown, such as sediment supply and tidal range. Also the difference in deposition rates between this thesis and the study of Adame et al. (2010) is probably explained by area characteristics like sediment supply, vegetation cover, tidal ranges and exact locations of the study areas. The exact location of the measurements is unknown, so no information on the presence of tidal creeks and vegetation cover is known, which could be of importance for the deposition rates.

The sediment deposition rates in the different studies are all obtained using different measuring techniques; Van Santen et al. (2007) used canvas traps, where Cahoon et al. (1997) used marker horizons and Adame et al. (2010) used filter papers. For the studies of Furukawa et al. (1997) and Victor et al. (2006) the type of trapping is unclear. The comparison of these results is therefore not straightforward. The similar ranges found in sediment deposition rates, at least give an indication that accretion is a distinct feature of mangrove forests.

## 7.4. Morphological diamond

This research tries to take up a distinct position in the mangrove forest studies into hydrodynamics and morphodynamics. The entire morphological cycle is combined in the measuring campaign to have a complete overview of the links between hydrodynamics and morphodynamics. Unique in the hydrodynamic analysis of a mangrove creek catchment in this thesis is the spatial analysis of the hydrodynamics and morphodynamics in a mangrove creek catchment. The comparison of hydrodynamics with literature shows that the order of magnitude in current velocities was in accordance with earlier research. So this study adds to the knowledge on current velocities in mangrove forests. The earlier studies only concentrated on transects, such as Furukawa et al. (1997) or on current direction at a single point in the mangrove forest (Wolanski, 1992). In this study also the flow routing through the mangrove forest was of interest. For the analysis of the flow routing, a grid of measuring points was chosen to obtain insight in the inundation pattern throughout a creek catchment, which is unique and gives much more insight in the role of mangrove creeks for inundation of the mangrove forest during a tidal cycle.

The very low suspended sediment concentrations in this thesis seem unreliable when compared to previous studies. However, some confidence may be put in the obtained results. The patterns of the suspended sediment profiles for the grid points in the creek catchment are in good agreement with the velocity profiles in the creek catchment. Also the suspended sediment concentration behavior in the creek can be judged valid with support of the measured current velocities and suspended sediment concentration differences with the forest, so the measuring technique seems to be valid. Current velocities in the creeks are about 5 times higher than those in the forest (Table 5) and suspended sediment concentrations should thus be about 25  $(5^2)$  times higher in the creek than in the forest, which appears to hold for the results as presented in Table 7. Only the magnitude of the suspended sediment concentrations seems not realistic and can possibly be explained by a poor calibration of the Signal-to-Noise Ratio. A softening factor for the very low suspended sediment concentrations is the wave climate present in the different study areas. The studies of Brinkman et al. (2005) and Vo Luong and Massel (2006) have a very open connection to the sea and waves enter the forest over the fringe directly from the sea, making the areas very active. The suspended sediment concentrations in the forest can also become very high in these areas. The study area in this thesis, on contrary, is sheltered and during the measuring campaign no significant wave influences were encountered. Together with the hydrodynamic measurements, the suspended sediment concentrations were measured on a spatial grid to find the spatial distribution of suspended sediment concentrations. The spatial distribution is a good indication of transportation of sediments through the creek catchment, especially because it is directly linked to the hydrodynamics on the same spatial grid.

Confidence can be put in measuring technique of using tiles for measuring sediment deposition and also in the results of the sediment deposition rates. The rates are in good coherence with literature and the results are a logical outcome of the morphological diamond. Even though the suspended sediment concentrations are a couple of magnitudes lower than observed in literature, the relation observed between the change of suspended sediment concentrations over time and the deposition rates is in good coherence. The magnitude may not be comparable with literature, but relatively the suspended sediment concentrations support the deposition rates measured throughout the creek catchment. Therefore, deposition rates are a logical consequence of the observed hydrodynamics and the sediment dynamics show very good coherence with the sediment deposition and show that through hydrodynamics the vegetation plays a role in the deposition of sediments. This was already known from previous studies such as Adame et al. (2010) and Anthony (2004). However the distribution of the sediments through a creek catchment due to mangrove creeks and vegetation patterns is new.

The coupling between spatial variation in hydrodynamics, morphodynamics, vegetation and elevation in a mangrove creek catchment has never been done before.

## 7.5. Long-term development of mangrove forests

To give an indication of annual accretion in the mangrove forest studied in this thesis, a calculation is made to give a qualitative indication of the long-term persistence against sea level rise of the creek catchment. The extrapolated yearly minimum deposition rate is 9.9 kg/m<sup>2</sup>/year and the maximum deposition rate is 76 kg/m<sup>2</sup>/year (based on multiplying daily sediment deposition by 365 days). This comes down to a minimum accretion rate of 5 mm/year and a maximum accretion rate of 36 mm/year. The accretion rate was determined for a porosity of 0.8 and using the calculation method of section 6.1. Since only during spring tide measurements were taken for the deposition rates this annual deposition rate is an indication of the maximum accretion. This can be a reasonable indication, because the creek catchment is considered to be most active during spring tide. Also the observations showed that during ebb tide hardly any erosion takes place with practically no suspended sediment concentrations. With a sea level rise prediction of 48 cm in the next century, meaning an average of 4,8 mm/year (IPCC, 2001), the yearly accretion rate seems large enough to withstand sea level rise and maintain the coastline. However, erosive events are not taken into account for this indicative calculation and some other factors such as consolidation also play a role, so the actual accretion rates will be smaller. More detailed measurements will be needed to better understand the long-term sustainability of mangroves.

The accreting ability of a mangrove forest is the main argument for the protecting capabilities of mangroves against sea level rise. The accretion rates in this thesis show that the creek catchment of the study area could possibly withstand sea level rise. The large accretion in the entire creek catchment is made possible by the supply of sediments into the creek catchment through the creeks. Based on the comparison with literature, similar results are found for hydrodynamics and sediment deposition in other study areas with similar area characteristics. The comparable area characteristics in Victor et al. (2006) and Van Santen et al. (2007) give similar results for the hydrodynamics and sediment deposition rates within the mangrove forest. For other studies, which mostly consist of bigger scale tidal creek systems, different results are presented, such as higher current velocities. These differences in hydrodynamics are then readily explained by the area characteristics. For sediment availability. Sediment dynamics are not comparable, because of a too large deviation in magnitudes.

The comparability of other studies with this thesis gives confidence for generalizing the findings in this thesis for mangrove forests in general. Meaning that mangrove forests can really battle sea level rise and mangrove creeks have their role in supplying sediments to the mangrove forest.

## 8. Conclusions and recommendations

In this study the importance of tidal creeks for a mangrove creek catchment has been investigated. Of main interest was the supply and distribution of sediments into the forest, to find the value of mangrove forests on long-term coastal protection. The research questions are answered concisely to conclude on the importance of the creeks for the long-term persistence of mangroves. After answering the research questions, some recommendations on future research are given.

## 8.1. Conclusions

### 1. How to study hydrodynamics and morphodynamics in a mangrove forest?

To find the importance of tidal creeks in comparison to the forest fringe for the supply and spatial distribution of sediments into a mangrove forest, a study area is required that borders both open sea or an estuary and a tidal creek. In this study area a mix of mangrove vegetation is required and the vegetation needs to be surveyed to be able to investigate the influence of vegetation. A vegetation survey is to be performed by identifying different zones of vegetation with distinctive characteristics such as tree density, number of trees per species and species size for chosen plots in the different zones. Next, an elevation survey has to be executed to obtain an elevation model of the study area. Together with an elevation map, vegetation sets the boundary conditions for hydrodynamics, sediment dynamics and sediment deposition in mangroves. With all this, the entire morphological diamond can be studied and a total system analysis for the importance of tidal creeks is performed.

The hydrodynamics, sediment dynamics and sediment deposition are measured on a spatial grid to find the spatial distribution of sediments from the circulation of sediments and water through a mangrove forest. The surrounding creeks and the estuary are taken into account for the measurements as well, to find the supplying capabilities of the creeks into a mangrove forest. For hydrodynamic measurements, current velocities and current directions were determined on the spatial grid using ADV's. For sediment dynamics the same ADV's were used on the same spatial grid to obtain suspended sediment concentrations in the mangrove forest. Sediment deposition was measured on a larger spatial grid using sediment traps, to obtain more detailed information on where sediment settles.

### 2. What is the flow routing in the mangrove creek catchment over a tidal cycle?

The magnitudes of the current velocities in the creeks and the creek catchment are different. Large current velocities are measured in the creeks with a range of 0.02-0.3 m/s and much smaller current velocities are encountered in the creek catchment with a range of 0.01-0.07 m/s. For all creek current velocities the same order of magnitude was encountered. Similar, the mangrove forest current velocities are also of the same order of magnitude. The order of magnitude of current velocities was supported by literature on previous field studies in mangroves and is a common feature in mangrove forests. The large difference in current velocity magnitudes between the creeks and creek catchment is readily explained by bottom elevation and contribution to flow friction by vegetation. The influence of the vegetation and bed levels on current velocities is most clear at the forest fringe, where flow velocities decrease one order of magnitude compared to the current velocities in the estuary. Vegetation also plays a key role in the profile of the current velocities versus

water level at ebb tide. Larger ebb current velocities are the direct consequence of the retaining capability of mangrove vegetation. The vegetation causes a larger gradient between the forest and the estuary, and thus the creeks, resulting in higher current velocities at ebb than at flood.

Mangrove creeks are very important for the inundation of the mangrove forests. To inundate the forest itself, the supply of water at the rise of the tide is established by the mangrove creeks. The profiles of current velocities versus water levels show that at overbank water levels, when the mangroves start to inundate, large accelerations are present in the creek current velocities. At this point the larger volume of water for inundation is supplied to the forest via the mangrove creeks. The importance of the mangrove creeks in the inundation of the mangrove forest is further supported by the analysis of the current directions through the creek catchment. At the center of the mangrove creek catchment a creek arm ends. Over the tidal cycle, the water is first flowing through this creek arm into the forest. When water levels are sufficiently high, water starts to flow over the forest fringe as well. At outgoing tide, this sequence is reversed. For all current direction measurements, the influence of the creek is present, except at the forest fringe where direct inundation from the estuary takes place. At full forest inundation the entire creek catchment however has a flow orientation perpendicular to the forest fringe, as was observed for the measuring points at the center of the creek catchment.

# 3. What is the magnitude of sediment concentrations on both a temporal and spatial scale through a mangrove creek catchment during a tidal cycle?

The suspended sediment concentrations through the mangrove creek catchment show a similar pattern as the current velocities. In the creeks, much larger suspended sediment concentrations were measured, ranging from 0-80 mg/L, than in the creek catchment, ranging from 0-0.9 mg/L. The difference between the creeks and creek catchment suspended sediment concentrations is explained by the difference in current velocities between the creeks and the creek catchment. Suspended sediment concentrations throughout the creek catchment have a similar magnitude, as for the creeks they are also of similar magnitude, showing that hydrodynamics are the key factor in the amount of sediments supplied to the creek catchment together with sediment availability. However, literature shows a big difference in measured suspended sediment concentrations in comparison to this study. Therefore some questions are raised on the solidity of the suspended sediment concentration measurements. The general trend in suspended sediment concentrations is still valid though.

Also the development of the suspended sediment concentrations over a tidal cycle is legitimate when related to the hydrodynamic measurements. In the creeks, the suspended sediment concentrations are lower during ebb tide than during flood tide, meaning that there is a net influx of sediments into the mangrove creek catchment. This is further supported by the course of the suspended sediment concentrations in the mangrove creek catchment during a tidal cycle. The suspended sediment concentrations in the creek catchment are very high during flood, when large current velocities transport the sediments into the creek catchment over the fringe and through the creeks. At the turning of the tide, the suspended sediment concentrations are reduced to approximately zero meaning no net outflux of sediments from the creek catchment occurs. In general the ebb velocities in the creek catchment are lower than the incoming velocities at flood and therefore less powerful to again entrain the sediments in the water column. This causes the
sediments to get stuck in the mangroves, once transported into the forest during flood. However, also if ebb current velocities are larger than flood current velocities, sediments can get stuck in the mangroves. This is caused by flocculation of the suspended mud during the lower flow velocities of the turning tide. Sediment particles flocculate and increase in size and are unable to stay in suspension and to get entrained again.

The creeks are very important in the supply of sediments to the creek catchment. At the forest fringe, the suspended sediment concentrations are reduced largely due to the drop in current velocities caused by a dense vegetation and sudden increase in bottom elevation. Through the creeks, the suspended sediment concentrations remain high. Therefore a large influx of sediments into the mangroves is to be attributed to the creeks.

4. Is their net accretion or erosion in a mangrove creek catchment and what is the spatial distribution of this net accretion/erosion?

The net influx of sediments into the creek catchment results in accretion of the creek catchment floor. The sediment deposition rates in the creek catchment range between 27-209 g/m<sup>3</sup>/day. A lot of confidence is put in these values as they are well in concordance with other study areas. At every grid point in the creek catchment, deposition rates have been measured over several spring tides and no erosion was present.

The spatial distribution of the sediment deposition, however, is not uniform. Large differences in deposition rates are encountered throughout the creek catchment. These differences are directly linked to the hydrodynamics and the bathymetry of the creek catchment. The sudden drop in current velocities at the fringe causes a large deposition at the forest fringe meaning that far less sediment is available for further transport over the fringe into the creek catchment. However, in the back of the creek catchment also large sediment deposition rates are measured. So sediment needs to be supplied from another source than the fringe. This sediment is provided by the creek arm that extends into the creek catchment and carries large suspended sediment concentrations. Also the bathymetry plays an important role in that the supply of most sediments is through the creek arm extension during most of the tidal cycle, due to the high banks alongside the main creek and behind the forest fringe.

## 5. What is the importance of tidal creeks in the supply of sediments to a mangrove forest?

A mangrove forest traps a lot of sediment and accretes the substrate on which it grows fast enough to cope with sea level rise. The supply of these sediments for accretion is mainly through tidal creek system, because the sediments being transported over the fringe are mainly deposited at the fringe. The tidal creeks show a large concentration of suspended sediment that is being transported. With the tidal creeks extending deep into a mangrove forest, consequently high sediment deposition rates are found in the center of a mangrove forest.

The comparison with other literature and the different area characteristics in combination with hydrodynamic and morphodynamic measurements shows that the hydrodynamic and morphodynamic processes are similar in different mangrove areas. This supports the conclusions that for mangrove forests in general the tidal creeks are very important in supplying sediment for

accretion. With this (large) accretion, mangrove forests are capable of keeping up with sea level rise. The net accretion in the mangrove forest is capable of counteracting sea level rise as it accretes up to 36 mm/year (barring erosive events), with a sea level rise of just 4.8 mm/year.

## 8.2. Recommendations

Based on the performed research in this study some recommendations are made for implementing mangroves into coastal zone management and for future research. These research recommendations can be divided into extending the current research, improvements on the current research and recommended measuring techniques for future research.

## 8.2.1. Mangroves in coastal zone management

The large accretion abilities of mangroves, as a consequence of sediment supply through tidal creeks deep into the mangrove forest, enable them to counteract sea level rise. Therefore the conservation of mangroves is very important in places where they are present at the moment, because they have a proven protective function for the coastal zone by keeping up with sea level rise.

Planting new mangroves in coastal regions can give an ecological solution for the protection of the coastal areas. Important when planting a wide mangrove forest patch will be to have some sort of tidal creek system in place, to provide circulation of water (for nutrient supply) and sediments to the back of the forest, so that the mangrove forest can survive and keep accreting against rising sea levels.

## 8.2.2. Future mangrove research

Extending the current research could be done by expanding the measurement grid for hydrodynamic and sediment dynamic measurements in the future, to have an even more direct link between these processes and sediment deposition. Furthermore, fluxes of sediments through the creek and over the fringe are very valuable for a more quantitative comparison between the tidal creeks and the forest fringe for sediment supply. To obtain these sediment fluxes, velocity profiles in the creeks and on the forest fringe are required in combination with suspended sediment concentrations at the measuring heights of the velocity profile.

Improvements of the current research could be obtained for the suspended sediment concentrations. The suspended sediment concentration obtained through the ADV measurements were not plausible, which could be assigned to a bad calibration of the signal-to-noise ratio. So a better calibration of the signal-to-noise ratio and more extensive testing for using ADV's in suspended sediment concentration measurements is recommended.

The measuring techniques used in this study consisted of ADV measurements and sediment trapping using tiles. ADV measurements are common and work very smoothly. The use of tiles in sediment trapping however was new and was an own design. The measuring technique proved to be valuable for trapping sediments, with a rough surface for the trapping and a smooth surface at the forest floor that was rinsed easily.

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## Glossary

ADV:	Acoustic Doppler Velocimeter. Measures flow velocities using the reflection of sound off of particle present in the water column.
Creek catchment:	The area, or at lEast part of it, that is inundated by the tidal creek during flood and the area that discharges water during ebb through the tidal creek. In this thesis it is the research area, which has a direct link to a tidal creek
Flocculation:	The binding of clay particles in saline conditions. The binding causes the clay particles to increase in size.
Fringe:	The edge of the mangrove forest either bordering the estuary, bay, delta or open sea.
Hydrodynamics:	Motion of fluids. Important characteristics of water flows are flow velocities, flow direction, turbulence, water depth.
Intertidal regions:	Areas at the land-sea interface that are periodically inundate due to tides. At low water the areas remain dry and during high water they are inundated.
Morphodynamics:	Motion of sediments. Important characteristics of sediment transport are suspended sediment concentrations, sediment deposition and accretion.
Pioneer vegetation:	Mangrove vegetation settling in uninhabited mudflat regions, starting the possible expansion a mangrove forest.
Seedling:	Young mangrove plant that has just established itself on the forest floor en possibly growing to become a adult mangrove tree.
Thalweg:	Deepest part of the creek
Tidal creeks:	River like creek arms that fill during flood and are drained during ebb. They are not in connection with the hinterland and only serve to supply water to the intertidal zone.
Zonation:	Distinctive regions with similar characteristics in mangrove vegetation in this thesis report.

# Appendices

## 1. Mangrove root structures

A very distinct characteristic of mangroves is their unique root system, which is highly variable for different species. Five distinctive root structures can be distinguished for mangroves. With the focus on the interaction between hydrodynamics and morphodynamics with mangrove trees, the root characteristics are of great interest, since they all have an impact on the hydrodynamic and morphodynamic processes in a mangrove ecosystem. The roots of mangrove trees are inundated during high tides and form the frontline of the hydrodynamic interactions and consequently influence morphodynamics. The five root systems are depicted in Figure 46 and consist of pneumatophores, knee roots, stilt roots, plank roots, and buttress roots. Among the most common species all these root systems can be encountered, with stilt roots being found for Rhizophora, pneumathophores for Avicennia and Sonneratia, knee roots for Bruguiera, buttress roots for Xylocarpus and Heritiera, and plank roots for Xylocarpus (Prosperi et al., 2005).



Figure 46 Mangrove root systems A: Prop roots B: Pneumatophores C: Knee roots D: Butress roots E: Plank roots

## 2. Mangrove presence

## 2.1. Mangrove species distribution

The low latitude confinement of mangroves is illustrated in Figure 47. In this figure the areas with mangrove populations are depicted. Due to their temperature and precipitation restrictions, mangroves mainly thrive in the tropics. Some expansions are seen to temperate zones when temperatures are favorable with limited exposure to frost, since mangroves cannot survive in subzero temperatures (Augustinus, 1995; Krauss et al., 2008). The majority is located between 5° N and 5° S latitude, however the extension of mangrove presence reaches from 31°22′ N in Japan and 32°20′ N in Bermuda, to 38°45′ S in Australia, 38°59′ S New Zealand and 32°59′ S on the East coast of South America (Spalding et al., 1997). Mangrove area decreases with the increase in latitude, except between 20 and 25° N latitude (Figure 2), which is where the Sundarbans, the largest tract of mangrove forests in the world, are located (Giri et al., 2011).

Worldwide mangroves can be divided into two regions, namely the Old World and the New World. The Old World is considered as the origin of mangroves, hence the name Old World, and can be found at the Eastern Hemisphere, reaching from the coasts of East Africa to Australia (covering coasts along the Indian and the Western Pacific Ocean). The New World is located on the Western Hemisphere, reaching from Western America to West Africa (covering coasts along the Eastern Pacific and the Atlantic Ocean). Most species are encountered in the Old World. In the New World only 11 species are encountered, which are not all unique in relation to the Old World (Kathiresan, 2005). The total amount of mangrove species, comprising of trees and shrubs, encountered on the globe is approximately sixty, with a mixing of the mangrove species among different mangrove ecosystems (Augustinus, 1995). One mangrove ecosystem does not have a uniform species distribution, similar as mangroves are not exclusive to one region. The most common genera of species in mangrove ecosystems are Rhizophora, Avicennia, Bruguiera and Sonneratia, but there are many more species such as Xylocarpus and Heritiera (Blasco et al., 2005; Prosperi et al., 2005). A full list of mangrove species with some characteristics is included in appendix 3.

Recent studies show that the worldwide mangrove cover consisted of 137,760 km<sup>2</sup> in the year 2000 (Giri et al., 2011). This is 12,3% less than previous estimates made by the Food and Agriculture Organization (FAO) of the United Nations (FAO, 2007). Mangroves form less than 0,7% of the world's total rainforests, while mangroves rival the biomass of rainforests (Alongi, 2008).



Figure 47 Main geographic areas of mangroves (Augustinus, 1995)

The restrictions on the presence of mangroves at the transition between terrestrial ecosystems and marine ecosystems are determined by a complex of conditions that restricts mangrove growth on different scales. The distribution of mangroves is related to eight basic environmental features: air temperature, precipitation, protected coastline, shallow shores, currents, salinity, tidal range, and substrate (Chapman, 1977; Alongi, 2008). Climatic factors are the main factors influencing the mangrove distribution on a global scale, as mentioned before. The other factors determine the presence or absence of mangrove ecosystems on a more local scale. The factors for mangrove presence are further described in the next section of the appendix.

#### 2.2. Scales for mangrove presence

The basic features for mangrove presence are wave activity, currents, salinity and tidal range. These features are hydraulic conditions that are closely related to a protected coastline and shallow shores, which are very site specific. Mangrove ecosystems need hydrodynamic activity for survival, but too much hydrodynamic activity will inhibit mangrove development. The protected coastline and shallow shores reduce hydrodynamic activity for mangrove survival. The hydrodynamic processes that mangroves have to cope with are wave activity and tidal inundation and for each of these two processes, thresholds are present for which mangroves can survive along tropical coastlines (Friess et al., Submitted). Mangroves are not capable of coping with too much wave activity (Mazda et al., 2007; Alongi, 2008), since wave activity acts as a force on mangrove tree roots, stems and canopies. Uprooting of trees can happen as a result of too much force being exerted by the waves. The amount of wave energy that is exposed to a mangrove forest is a threshold for the existence of mangroves in a coastal region, because too much wave energy will exert too much force on the mangrove root systems.

The nutrient supply for mangroves is established by rivers or longshore currents and stem from the basic feature of currents. Mangroves are capable of living in regions with a great variety of nutrient availability. However most mangrove forests have limited availability due to infertility of upland soils in tropical regions and limited terrigenous input (Krauss et al., 2008). Nutrient availability influences the growth rate of mangroves, so the only restrictions on mangrove presence for nutrient supply is that there has to be nutrient availability in the region for mangroves to occur.

Mangroves are in need of periodic inundation of their root systems with the substrate on which they grow to exist. The frequency and duration of these periodic inundations from tidal activity are a threshold for tree establishment and survival (Friess et al., Submitted; Mazda et al., 2007). Too frequent and/or long inundation of a mangrove forest will cause the trees in the forest to perish. Different mangrove species have different thresholds for survival. Precipitation is an important climatic factor that contributes to inundation times in certain mangrove forest types, which will be explained in the coming paragraph, when tidal influences are limited (Woodroffe, 1992). The periodic inundation of the intertidal areas with saline water creates a habitat in which only the mangroves can survive, due to their tolerance higher salinities.

Based on the inundation thresholds for survival of mangrove trees a classification into inundation classes with corresponding species can be given, as observed in Table 10. The different thresholds for different mangrove species result in a zonation of mangrove species on the intertidal slope (Thampanya et al., 2002).

Inundation class	Tidal regime	Elevation (m above MSL)	Inundation frequency (times per month)	Duration of inundation (min/day)	Duration of inundation (min/inundation)	Vegetation (Species)
1	All high tides	<0	56-62	>800	>400	None
2	Medium high tides	0-0,9	45-59	400-800	200-400	Avicennia spp., Sonneratia
3	Normal high tides	0,9-1,5	20-45	100-400	100-200	Rhizophora spp., Ceriops, Bruguiera
4	Spring high tides	1,5-2,1	2-20	10-100	50-100	Lumnitzera, Bruguiera, Acrostichum aureum
5	Equinoctial tides	>2,1	<2	<10	<500	Ceriops spp., Phoenix paludosa

Table 10 Adapted inundation classification and the related SouthEast Asian mangrove species (Van Loon et al., 2007)

The hydrological conditions in mangrove ecosystems determine in large the richness of species encountered in these ecosystem. The hydrological conditions, such as tides and river discharge and precipitation amounts, are of importance for the richness of species. In a mangrove ecosystem that is rich of different species, a zonation on the intertidal slope can be observed (Thampanya et al., 2002). Although this zonation cannot always be clearly observed in the field, the distribution of species in the mangrove ecosystems is very much dependent on hydrological conditions, and in particular the tidal influences.

The tidal classes as presented in Table 10 show that different species exist at different heights on the intertidal slope as a result of the different inundation frequencies and durations. Species such as Avicennia and Sonneratia are observed at very low heights on the mudflat with frequent and long inundation periods. These two species are the pioneer species that can withstand these harsh hydrodynamic conditions (Thampanya et al., 2002). Further up the slope other species such as Rhizophora and Bruguiera can also settle further reducing the hydrodynamic activity for other less resilient species, building a zoned forest.

## 3. List with mangrove species

Mangroves all have the same living environment and are therefore, but between species differences can be observed in their characteristics. The largest differences can be observed in the form of growth and the corresponding root structure. In Table 11 all mangrove species are mentioned with their characteristics, such as form, root system and their regions of existence if known.

 Table 11 Mangrove species with characteristics and aerial existence (Augustinus, 1995; Prosperi et al., 2005)

Flora		Characteristics							
Genus	Species	Form	Root system	Bio reg	ogec gion	ograj s	phic		
Acanthus	ebracteatus	Shrub	-					5	6
	ilicifolius	Shrub	Aerial roots					5	6
Acrostichum	aureum	Fern	woody rhizome	1	2	3	4	5	6
	danaeifolium	Fern	-	1	2				
	speciosum	Fern	-					5	6
Aegialitis	annulata	Shrub	-					5	6
	rotundifolia	Shrub						5	
Aegiceras	corniculatum	Shrub	-					5	6
Aglaia	cucullata	Tree						5	
Avicennia	alba	Tree	slender-like stilt roots; finger- like pneumatophores					5	6
	bicolor	Tree	pneumatophores	1					
	germinans	Tree	pneumatophores	1	2	3			
	integra	Tree	pneumatophores						6
	marina	Shrub/ Tree	finger-like pneumatophores	1			4	5	6
	officinalis	Tree	pneumatophores					5	6
	rumphiana	Tree	pneumatophores					5	6
	schaueriana	Tree	pneumatophores		2				
Bruguiera	cylindrica	Tree	knee roots					5	6
	exaristata	Shrub/ Tree	-						6
	gymnorrhiza	Tree	knee roots				4	5	6
	hainesii	Tree	-					5	6
	parviflora	Tree	-					5	6
	sexangula	Tree	knee roots					5	6
Camptostemon	philippensis	Tree	-					5	
	schultzii	Tree	-						6
Ceriops	australis	Shrub/ Tree	-						6
	decandra	Shrub/ Tree	pyramidal stem base with stilt roots					5	6
	tagal	Shrub/ Tree	pyramidal stem base with stilt roots				4	5	6
Conocarpus	erectus	Shrub/ Tree	-	1	2	3			
Cynometra	iripa	Shrub	-					5	6
Diospyros	littoralis	Tree	-						6
Dolichandrone	spathacea	Tree	-					5	6
Excoecaria	agallocha	Tree	spreading and intermingled lateral roots; elbow-shaped pegs					5	6

	indica	Tree	-					5	
Heritiera	fomes	Tree	-					5	
	globosa	Tree	-					5	
	littoralis	Tree	buttress roots				4	5	6
Kandelia	candel	Shrub/	-					5	
Laguncularia	racemosa	Shrub/ Tree	-	1	2	3			
Lumnitzera	littorea	Shrub/ Tree	pneumatophores with looped laterals; aerial bend knee roots					5	6
	racemosa	Shrub/ Tree	pneumatophores sometimes with looped laterals				4	5	6
	rosea	Shrub	-						6
Mora	oleifera	Tree	-	1					
Nypa	fruticans	Palm	Subterranean Rhizome stout		2	3		5	6
Osbornia	octodonia	Shrub/ Tree	-					5	6
Pelliciera	rhizophorae	Tree	-	1	2				
Pemphis	acidula	Shrub	-				4	5	6
Phoenix	paludosa	Palm	-						6
Rhizophora	apiculata	Tree	stilt roots					5	6
· · ·	mangle	Shrub/	stilt roots	1	2	3			
		Tree							
	mucronata	Tree	stilt roots				4	5	6
	racemosa	Tree	stilt roots	1	2	3			
	samoensis	Tree	stilt roots						6
	stylosa	Shrub/ Tree	stilt roots					5	6
	harrisonii	Tree	stilt roots	1	2	3			
	lamarckii	Tree	stilt roots					5	6
	selata	Tree	-						6
Scyphiphora	hydrophyllacea	Shrub	-					5	6
Sonneratia	alba	Tree	pneumatophores				4	5	6
	apetala	Tree	pneumatophores					5	
	caseolaris	Tree	pneumatophores					5	6
	griffithii	Tree	pneumatophores					5	
	lanceolata	Tree	pneumatophores					5	6
	ovata	Tree	pneumatophores					5	6
	gulngai	Tree	pneumatophores					5	6
	urama	Tree	pneumatophores						6
	alba x ovata	Tree	pneumatophores					5	
Tabebuia	Palustris	Shrub	-	1					
Xylocarpus	granatum	Tree	buttress roots continuing outward as plank roots				4	5	6
	mekongensis	Tree	-					5	6

## 4. Mangrove settings

As mentioned mangroves can only be found on the border of saline aquatic and terrestrial systems, meaning that the mangroves form the shorelines in a lot of regions. The mangrove shorelines occur in a number of different environmental settings, comprising of particular suites of recurring landforms and differing in the physical processes in sediment transport. The environmental settings is divided into 5 classes by Woodroffe (1992) and are shown in Figure 48, consisting of:

- 1. River-dominated
- 2. Tide-dominated
- 3. Wave-dominated barrier lagoon
- 4. Composite river and wave-dominated
- 5. Drowned bedrock valley

Woodroffe (1992) characterizes the environmental settings by 2 components, namely the geophysical characteristics (climate, tides, and sea level) and the geomorphological characteristics (dynamic history of land surface, micro-topography, elevation, sediments, and drainage). These two components are now described for each of the environmental settings.





Figure 48 Environmental settings of Mangroves (Woodroffe, 1992)

#### **River dominated setting**

Most of the extensive mangrove forests can be found in the deltas of tropical rivers. These deltas receive enormous amounts of sediments from the headwaters and are extremely dynamic. The deltas can be divided into an active deltaic plain and an abandoned deltaic plain. The active deltaic plain is dominated by those distributaries which carry most of the fluvial discharge, whereas the abandoned deltaic plain is characterized by distributaries that are no longer active. Another distinction in the delta can be made between the upper deltaic plain and the lower deltaic plane. In the upper deltaic plain marine and tidal influences are minor, since they are situated remotely from the sea. The presence of mangrove forests is mostly restricted in the active deltaic plane, as a result of the strong freshwater flows from the discharging river. In contrast the mangrove forests are usually very extensive in the abandoned deltaic plain, because the distributaries no longer discharge large amounts of freshwater. This contrast is depicted in Figure 48A. The distribution of the mangroves within a delta is also very much dependent on micro-topographic characteristics related to elevation and frequency of inundation. The patterning of mangrove forests is a function of geomorphologic features such as distributary channels, point bars, and natural river levees.

#### Tide-dominated setting

Tide-dominated mangrove settings are characteristic of areas with high tidal range where there is an extensive, low-gradient intertidal zone available for mangrove colonization. In this zone, estuaries are characterized by strong bidirectional tidal velocities and a large tidal range (>4m). The geography of the estuaries is that with a broad funnel-shaped mouth and often linear islands or shoals parallel with flow directions. In the tide-dominated setting there are recurrent patterns of mangrove species originating from a series of geomorphologically defined habitats on the saline flats. Figure 48B illustrates a typical patterning of such habitats in mangrove forests of North and Northwestern Australia, where colluvial and alluvial deposits, and chenier ridges mark former shorelines and provide habitats for mangroves. Abandoned portions of some deltaic plains also contain former distributaries that are now dominated by tidal flows. These show many of the morphological characteristics, such as the rapidly tapering funnel-shaped form, of tide-dominated estuaries.

#### Wave-dominated setting

Coasts that are dominated by wave energy and on which there is an abundant supply of sand, formation of shore-parallel sandy ridges takes place. These sandy ridges often form as barrier islands enclosing a series of elongate lagoons, as depicted in Figure 48C High wave energy and sandy substrates are not generally favourable conditions for formation of mangrove forests, but mangrove forests are able to establish themselves in the sheltered lagoons. The most extensive mangroves on wave-dominated coasts occur in either of two settings. First, the extensive fluvial-dominated environments developed where a large river reaches a wave-dominated shoreline. Secondly, mangroves can be extensive in drowned river valleys, which are coastal embayments which have not filled in entirely with fluvial sediments.

#### Composite river and wave-dominated setting

In the composite setting, rivers bring large volumes of sediments to a wave-dominated coast, where a complex of landforms develops within which there can be extensive mangrove forests. Lagoons are well-developed in many deltas where fluvial sands are redistributed along the coast from a large delta. There are deltas that demonstrate a well-marked segregation of mangrove species according to landform type: point bar, levee, lagoon, distributary channel and interdistributary basin. The dynamics of landforms in turn reflect the shift of active sedimentation and the subsidence of former deltaic plains.

#### Drowned bedrock valley setting

Many large coastal embayments in the tropics and the subtropics have drowned by the postglacial rise in sea level, and are known as rias. These provide sheltered environments within which mangrove forests develop on muddy substrates (Figure 48E). Embayments go through a series of evolutionary stages as a result of infill with mud from the hinterland. Mangroves are initially associated with embayment-head alluvial and deltaic environments, but are most extensive during intermediate stages when complex shoals and intertidal habitats develop. At later stages of infill of the river mangroves tend to be extinguished when the river reaches a state where it flows over an almost entirely infilled plain and discharges directly into the sea.

## 5. Classification of Mangroves

The environmental settings are a broad division of the regions where mangrove ecosystems are found. Some of these regions have a clear distinction between tidal and riverine processes, whereas other regions have a combination of these processes with a difference in the dominance of either processes. Therefore it is not easy to make a habitat distinction and classification for mangroves based on land-forms within the environmental settings. To discriminate between different mangrove forest types, a functional mangrove classification that are encountered within the environmental settings, based on physiological characteristics of mangroves, can be made consisting of 6 different classes. The functional mangrove classification is mainly based on the form of the forest and especially the trees in the forest, and the dominating physical processes. In Figure 49 the functional classes of mangrove forests are positioned in a triangle of dominant physical processes. The six classes distinguished by Lugo & Snedaker (1974) are:

- Overwash mangroves
- Fringe mangroves
- Riverine mangroves

- Basin mangroves
- Scrub mangroves
- Hammock mangroves

The different physical processes related to the river dominated, tide dominated and interior habitats of mangrove forests control the transport and deposition of sediments, and the supply of nutrients to the forest. The two most important physical processes are the unidirectional flow of river dominated habitats and the bidirectional flow of tide dominated habitats (Woodroffe, 1992). The river dominated habitats are often characterized by a strong nutrient influx and large outwelling from the forest. For tide dominated forests there is very little net import of material, because of strong bi-directional fluxes.

Most mangrove forests have influences of both the important physical processes, because of their location in tidal estuaries and river deltas. In some cases the mangrove forests can be insulated from these processes because of their interior lying. In the most extreme case the inundation will occur only due to the retention time of precipitation in the mangrove ecosystem.

There are three extreme cases of mangrove classes, namely Riverine, Tidal and Hammock, that are at the tip of the triangle and these mangrove forests are dominated by these individual physical processes. However, this does not mean that the other physical processes are not present, just not as profound as the dominant one. The other classes are influence by all three tips of the triangle and these classes are more defined on the basis of the location and appearance of the mangrove trees. For a scrub mangrove forest for instance the height of the individual mangrove trees is of importance for the classification, but a scrub forest can be present at all sides of the triangle, with river and/or tide dominating processes and also as an interior forest. A fringing forest can be for instance found anywhere on the line between river dominated or tide dominated habitats.



Figure 49 Relationship between forest types and dominant physical processes (Woodroffe, 1992)

## 6. Long-term development of mangrove forests

The long-term development can be characterized by a rapid prograding mode and a cut and recover mode, which are both shown in Figure 50A for an accreting or stable mangrove ecosystem (Chappell et al., 1984). For eroding mangrove ecosystems two development types (see Figure 50B) are distinghuished by Semeniuk (1980). The two classifications during accretion and erosion can be linked to each other. The rapid prograding mode occurs when there is an abundant supply of mud, a gentle gradient (1:1000), wide mangrove fringes, and little if any evidence of periodic storm impacts. The erosion counterpart is the type 1 erosion, which also has a gentle gradient shoreline with a broad mangrove fringe that gradually retreats through sheet erosion. The cut and recover mode occurs where there is little mud supply and a steeper gradient (1:200). In this case the mangrove fringe is narrower (100-150m). The erosion type 2 is similar to the cut and recover only now the shoreline is retreating through wave-induced cliff erosion of the muddy substrate on which the mangroves are rooted (Semeniuk, 1980). It also has a steeper gradient shoreline on which the mangrove fringe is narrower and less clearly zoned. The steep gradients of the shoreline are with enough sediment availability restored into more gentle slopes where mangroves can grow again during the sedimentation and recovery period, until the next big storm arrives, which can have again a big erosion effect. Sediment availability is key in the processes of accretion and erosion and determines which long-term development survives.

In general the shoreline is thus dynamic and, based on the availability of sediments and hydraulic conditions at local positions along the shoreline, either expanding from sedimentation or retreating due to erosion. With sufficient sediment available and enough recovery time of mangroves between storm events, accretion takes place in the forest. The accretion means that the forest elevates the substrate it grows own. This vertical growth of the shorelines, where mangroves grow, can have positive consequences for keeping up with the expected global sea level rise.



Figure 50 Erosion patterns of mangroves (Chappell & Grindrod, 1984; Semeniuk, 1980)

## 7. Matlab scripts for data processing

## 7.1. Converting measuring data to net current velocities for plotting

The measured data for current velocities by the ADV's consists of three velocity components in the x, y and z-plane. From the matlab script printed below plots are obtained for the current velocity versus the water level, from the velocity components in the x and y plane. The steps to obtain these plots is described shortly:

- First the data file of the measurements is loaded into Matlab together with the file of the time series of measurements.
- The pressure from this data file is first converted into water level by calculating water depth from the pressure and then adding the elevation of the measuring point.
- The start and end of individual tides is determined, so that spring tide can be selected.
- The time file and the data file are not of similar length. A time stamp is only given to the start of a measuring burst, so the time file is extended with a time stamp for every sample.
- For every measuring burst, all samples are averaged to obtain average velocity components per measuring burst.
- The averaged velocities are filtered for the right correlation of the signal. Only correlations higher than 70 are considered valid measurements
- The resultant current velocity for every burst interval is calculated from the averaged and filtered velocity components by using Pythagoras' theorem and taking the currents into the forest as positive.
- The resultant current velocity is then plotted versus water level

```
%% PLOTTING ADV VELOCITY MEASUREMENTS (NET) AGAINST WATER LEVELS AND
TIME
% This script averages velocity and water level measurements per burst.
% Averaged data are being plotted per tidal cycle (net velocity vs.
water
% level and vs. time).
clear all; close all; clc;
%% LOAD DATA
% Modify these parameters to the settings of the ADV.
Fs=16; % frequency (Hz)
Bi=1500; % burst interval (s)
Sb=4096; % samples per burst (#)
rho=1025; % density water (kg m-3)
g=9.81; % gravitational acceleration (m s-2)
height=0.07; % level of end bell black tube!!! (m)
offset=21; %offset in no. of bursts
data=load('CR GRE02.dat'); % loads data file
data=[data(:,3) data(:,4) data(:,5) data(:,12) data(:,13) data(:,14)
data(:,15)]; % loads data file
p=data(:,7); % measured pressure (dbar)
H=((p*10000)/(rho*g)+height)+7.89; % water level (m)
data=[data(:,1),data(:,2),data(:,3),data(:,4),data(:,5),data(:,6),H];
%Rewriting matrix, so that pressure is replaced by water level
timeadd=[0:0.36580739122756:1126757-0.36580739122756]';
newtime=timeadd(:,1)/3600;
```

```
time=load('CR GRE02.sen'); % loads data file, note that (null) in sen-
file cannot be handled by MATLAB
%% SEPERATE THE DATA IN SMALLER MATRICES CONTAINING ONE TIDE
% This is necessary as MATLAB cannot cope with the massive data matrix
just
% loaded.
for n=19; %[0:1:19];%0:2:12 n=number of tide of interest
nbursts=round(44700/Bi); % # of bursts per tidal cycle of 12.25 hours
dstart=n*nbursts*Sb+1+(offset*Sb); % starting at burst (#)
dend=dstart+nbursts*Sb-1; % ending at burst (#)
ddata=[data(dstart:dend,1) data(dstart:dend,2) data(dstart:dend,3)
data(dstart:dend,4) data(dstart:dend,5) data(dstart:dend,6)
data(dstart:dend,7)];
if dstart==1;
    tstart=1;
else tstart=(dstart-1)/Sb*257-256; %finding the starting time for every
tide
end
tend=tstart+nbursts*257-1; %finding end time for every tide
ttime=[time(tstart:tend,3) time(tstart:tend,1) time(tstart:tend,2)
time(tstart:tend,4) time(tstart:tend,5) time(tstart:tend,6)];
dt=[1/Fs*(1:Fs)]';
%% EXTEND TIME VECTOR TO LENGTH MEASUREMENT DATA
timevec=zeros(length(ddata),6);
cc1=1;
cc2=Fs;
cc3=Sb/Fs+1;
for jj=0:cc3:(length(ttime)-cc3)
    for ii=1:(Sb/Fs);
        kk=jj+ii;
        timevec(cc1:cc2,1:5)=repmat(ttime(kk,1:5),Fs,1);
        timevec(cc1:cc2, 6) = repmat(ttime(kk, 6), Fs, 1) + dt;
        ccl=ccl+Fs;
        cc2=cc2+Fs;
    end
end
timenum=datenum(timevec);
%% AVERAGING DATA PER BURST
avdata=zeros(nbursts,7);
avtime=zeros(nbursts,1);
for ll=1:1:nbursts
    avstart=(ll-1)*Sb+1;
    avend=ll*Sb;
    avtime(ll)=timenum(avstart); % take time step at beginning of burst,
averaging of timenum could give strange outcomes
    for mm=1:1:7
    avdata(ll,mm) = sum(ddata(avstart:avend,mm))/Sb;
    end
end
%% FILTERING DATA
cmin=70; % minimum required correlation
xfil=find(avdata(:,4)>70);
datafil=avdata(xfil,:);
timenumfil=avtime(xfil);
```

```
%% CALCULATING NET FLOW VELOCITIES
sizedatafil=size(datafil);
numrows=sizedatafil(1,1);
netveldata=zeros(numrows,2);
for mm=1:1:numrows;
if datafil(mm,2)>0; % Y points West so if Y>0 water flows into the
catchment
netveldata(mm,1)=sqrt((datafil(mm,1))^2+(datafil(mm,2))^2);
    else netveldata(mm,1)=-1*sqrt((datafil(mm,1))^2+(datafil(mm,2))^2);
    end
end
netveldata(:,2)=datafil(:,7);
%% PLOTTING DATA (velocity vs. depth)
hold on
color1=n*0.0125;
color2=n*0.0125;
color3=n*0.0125;
plot(netveldata(:,1), netveldata(:,2), '.-
', 'MarkerSize', 20, 'Color', 'k', 'LineWidth', 3)
%% Water level plot
plot(newtime,data(:,7),'.-','MarkerSize',20,'Color','k','LineWidth',3);
ylabel('Water level (m)', 'FontSize', 28);
xlabel('Time (hours)', 'FontSize', 28);
```

#### 7.2. Plotting current velocity directions

Plotting of the current directions in large follows the procedure of plotting the resultant current velocities against the water level. Only difference is that the resultant of the velocity components in the x and y plane is not calculated. Instead, a plot from the x and y velocity components, is made using the 'compass' command. The compass plotting command is described below and replaces the calculation of the resultant current velocity and the consequent plotting commands in the Matlab script of calculating the current velocities.

```
figure('DefaultAxesFontSize',30);
hl=compass(datafil(:,1),-datafil(:,2));
view(90,-90)
set(hl,'linewidth',3)
```

#### 7.3. Converting measuring data to suspended sediment concentrations for plotting

The measured data by the ADV's was also used to obtain suspended sediment concentrations. The suspended sediment concentrations were obtained from the signal-to-noise ratio in the data file of the ADV measurements. After calibration to obtain a relation between the signal-to-noise ratio and suspended sediment concentrations, the relation is implemented in a Matlab script to plot the suspended sediment concentration versus time. The procedures for plotting this data in the Matlab script, which is an adjusted script from the current velocity script, is described below:

- First the data file of the measurements is loaded into Matlab together with the file of the time series of measurements.

- The consequent script is the same as for the net current velocities, because these will be plotted together with the suspended sediment concentrations
- After the averaging of the data per measurement burst, where also the signal-to-noise ratio is averaged per measurement burst. The data is filtered for correlations over 70, to have valid measurements where the ADV is submerged.
- The filtered data is then put into a matrix where the signal-to-noise ratios for the x, y and z directions are averaged into one signal-to-noise ratio.
- The averaged signal-to-noise ratio is converted into a suspended sediment concentration, using the relation found in the calibration
- To plot the suspended sediment concentrations against time a time series is created for the start of the tide and the suspended sediment concentrations during this spring tide.
- As a last step the suspended sediment concentrations and current velocities are plotted into the same graph versus time.

```
%% PLOTTING SSC MEASUREMENTS (CALIBRATED) AGAINST WATER LEVELS AND TIME
% This script averages SSC, velocity and water level measurements per
burst.
% Averaged data are being plotted per tidal cycle (net velocity vs.
water
% level and vs. time).
clear all; close all; clc;
%% LOAD DATA
% Modify these parameters to the settings of the ADV.
Fs=16; % frequency (Hz)
Bi=1500; % burst interval (s)
Sb=4096; % samples per burst (#)
rho=1025; % density water (kg m-3)
g=9.81; % gravitational acceleration (m s-2)
height=0.07; % level of end bell black tube!!! (m)
offset=21; %offset in no. of bursts
data=load('CR GRE02.dat'); % loads data file
data=[data(:,3) data(:,4) data(:,9) data(:,10) data(:,11) data(:,12)
data(:,15)]; % loads data file
p=data(:,7); % measured pressure (dbar)
H=((p*10000)/(rho*q)+height); % water level (m)
data=[data(:,1),data(:,2),data(:,3),data(:,4),data(:,5),data(:,6),H];
%rewriting matrix to replace pressure with water level
time=load('CR GRE02.sen'); % loads data file, note that (null) in sen-
file cannot be handled by MATLAB
%% SEPERATE THE DATA IN SMALLER MATRICES CONTAINING ONE TIDE
% This is necessary as MATLAB cannot cope with the massive data matrix
just
% loaded.
for n=19;%[0:1:23];%21; %0:2:12 n=number of tide of interest
nbursts=round(44700/Bi); % # of bursts per tidal cycle of 12.25 hours
dstart=n*nbursts*Sb+1+(offset*Sb); % starting at burst (#)
dend=dstart+nbursts*Sb-1; % ending at burst (#)
```

```
ddata=[data(dstart:dend,1) data(dstart:dend,2) data(dstart:dend,3)
data(dstart:dend,4) data(dstart:dend,5) data(dstart:dend,6)
data(dstart:dend,7)];
if dstart==1;
    tstart=1;
else tstart=(dstart-1)/Sb*257-256; %Finding the starting time of every
tide
end
tend=tstart+nbursts*257-1; %Finding end time of every tide
ttime=[time(tstart:tend,3) time(tstart:tend,1) time(tstart:tend,2)
time(tstart:tend, 4) time(tstart:tend, 5) time(tstart:tend, 6)];
dt=1/Fs*(1:Fs)';
%% EXTEND TIME VECTOR TO LENGTH MEASUREMENT DATA
timevec=zeros(length(ddata),6);
cc1=1;
cc2=Fs;
cc3=Sb/Fs+1;
for jj=0:cc3:(length(ttime)-cc3)
    for ii=1:(Sb/Fs);
        kk=jj+ii;
        timevec(cc1:cc2,1:5)=repmat(ttime(kk,1:5),Fs,1);
        timevec(cc1:cc2, 6) = repmat(ttime(kk, 6), Fs, 1) + dt;
        cc1=cc1+Fs;
        cc2=cc2+Fs;
    end
end
timenum=datenum(timevec);
%% AVERAGING DATA PER BURST
avdata=zeros(nbursts,7);
avtime=zeros(nbursts,1);
for ll=1:1:nbursts
    avstart=(ll-1)*Sb+1;
    avend=ll*Sb;
    avtime(ll)=timenum(avstart); % take time step at beginning of burst,
averaging of timenum could give strange outcomes
    for mm=1:1:7
    avdata(ll,mm) = sum(ddata(avstart:avend,mm))/Sb;
    end
end
%% FILTERING DATA
cmin=70; % minimum required correlation
xfil=find(avdata(:,6)>70);
datafil=avdata(xfil,:);
timenumfil=avtime(xfil);
%% CALCULATING NET FLOW VELOCITIES
sizedatafil=size(datafil);
numrows=sizedatafil(1,1);
netveldata=zeros(numrows,2);
for mm=1:1:numrows;
    if datafil(mm,2)>0; % Y points West so if Y>0 water flows into the
catchment
```

```
netveldata(mm,1)=sqrt((datafil(mm,1))^2+(datafil(mm,2))^2);
    else netveldata(mm,1)=-1*sqrt((datafil(mm,1))^2+(datafil(mm,2))^2);
    end
end
netveldata(:,2)=datafil(:,7);
%% CALCULATING SSC CONCENTRATIONS
SSCdata=zeros(numrows,2);
for nn=1:1:numrows;
    SSCdata(nn,1) =mean([datafil(nn,3), datafil(nn,4), datafil(nn,5)]);
    SSCdata(nn, 2) = 6E - 7 * exp(0.4314 * SSCdata(nn, 1));
end
timeend=numrows.*25-25;
timevector=[0:25:timeend]';
%% PLOTTING DATA (SSC vs. depth)
hold on
color1=n*0.0125;
color2=n*0.0125;
color3=n*0.0125;
[AX,H1,H2] = plotyy(timevector,SSCdata(:,2),timevector,netveldata(:,1));
set(get(AX(1), 'Ylabel'), 'String', 'SSC
(mg/L)', 'FontSize',28, 'Color', 'k');
set(get(AX(2), 'Ylabel'), 'String', 'Current velocity
(m/s)', 'FontSize', 28, 'Color', [0.6 0.6 0.6]);
xlabel('Time (minutes)', 'Fontsize', 28);
set(AX(1),'XColor','k','YColor','k','FontSize',16);
set(AX(2),'XColor','k','YColor',[0.6 0.6 0.6],'FontSize',16);
set(H1, 'Marker', '.');
set(H1, 'LineStyle', '-');
set(H1, 'MarkerSize', 20);
set(H1, 'LineWidth', 3);
set(H1, 'Color', 'k');
set(H2, 'Marker', '.');
set(H2, 'LineStyle', '-');
set(H2, 'MarkerSize', 20);
set(H2, 'LineWidth', 3);
set(H2,'Color',[0.6 0.6 0.6]);
end
```

### 8. Current directions at measuring points over a tidal cycle

An overview figure of the current velocity directions is shown in section 4.2.5. A more magnified display of the current velocity directions per measuring points is displayed in this appendix. In the plots of the current directions also the directions over the spring tidal cycle are indicated by numbers. Number one indicates the first measurement during flood tide and the highest number is the last current direction during ebb tide. The corresponding current velocities to the numbers are shown in the tables corresponding with the current direction plots.

## 8.1. Creek current velocities



Figure 51 Current velocity directions over one spring tidal cycle - Main Creek (North, K3)

No.	<b>Current velocity</b>	No.	<b>Current velocity</b>
	[m/s]		[m/s]
1	0,054	12	0,11
2	0,073	13	-0,068
3	0,091	14	-0,24
4	0,11	15	-0,27
5	0,16	16	-0,27
6	0,15	17	-0,28
7	0,20	18	-0,28
8	0,30	19	-0,16
9	0,26	20	-0,091
10	0,23	21	-0,088
11	0,18	22	-0,084

Table 12 Current velocities over one spring tidal at measuring point K3



Figure 52 Current velocity directions over one spring tidal cycle – South creek (P1)

No.	<b>Current velocity</b>	No. Current veloc		
	[m/s]		[m/s]	
1	0,021	9	-0,037	
2	0,035	10	-0,065	
3	0,086	11	-0,093	
4	0,13	12	-0,16	
5	0,15	13	-0,17	
6	0,11	14	-0,026	
7	0,061	15	-0,022	
8	0,034			

Table 13 Current velocities over one spring tidal cycle at measuring point P1



Figure 53 Current velocity directions over one spring tidal cycle – West creek (N5)

No.	<b>Current velocity</b>	No. Current velocity		
	[m/s]		[m/s]	
1	0,092	9	0,0062	
2	0,063	10	-0,067	
3	0,11	11	-0,054	
4	0,17	12	-0,24	
5	0,10	13	-0,33	
6	0,043	14	-0,27	
7	0,019	15	-0,11	
8	0,0091	16	-0,13	

## 8.2. Fringe current velocities



Figure 54 Current velocity directions over one spring tidal cycle - Estuary (N0)

No.	Current velocity	No.	Current velocity
	[m/s]		[m/s]
1	0,058	11	0,059
2	0,067	12	-0,038
3	0,10	13	0,026
4	0,11	14	-0,025
5	0,079	15	-0,034
6	0,13	16	-0,061
7	0,18	17	-0,055
8	0,22	18	-0,053
9	0,19	19	-0,076
10	0,14	20	-0,11

Table 14 Current velocities during one spring tidal cycle at measuring point N0



Figure 55 Current velocity directions over one spring tidal cycle - Forest fringe (N1)

No.	Current					
	velocity [m/s]					
1	0,040					
2	0,041					
3	0,032					
4	0,023					
5	0,015					
6	0,0097					
7	-0,015					
8	-0,045					
9	-0,053					
10	-0,064					

Table 15 Current velocities during one spring tidal cycle at measuring point N1

### 8.3. Creek catchment current velocities



Figure 56 Current velocity directions over one spring tidal cycle - Center of catchment (N3)

No.	<b>Current velocity</b>					
	[m/s]					
1	-0,029					
2	0,039					
3	0,064					
4	0,051					
5	0,0085					
6	-0,062					
7	-0,059					
8	0,027					

Table 16 Current velocities over one spring tidal cycle at measuring point N3



Figure 57 Current velocity directions over one spring tidal cycle - South catchment (O3)

No.	Current velocity
	[m/s]
1	0,038
2	0,030
3	0,013
4	-0,014
5	-0,042
6	-0,048
7	-0,063

Table 17 Current velocities during one spring tidal cycle at measuring point O3



Figure 58 Current velocity directions over one spring tidal cycle - West catchment (N4)

No.	<b>Current velocity</b>						
	[m/s]						
1	0,067						
2	0,046						
3	0,036						
4	-0,011						
5	-0,017						
6	-0,013						

Table 18 Current velocities during one spring tidal cycle at measuring point N4