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Sediment dynamics in a mangrove creek catchment in Trang, Thailand

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ABSTRACT: Although mangroves thrive along many vulnerable coasts prone to sea level rise, studies into the sediment dynamics in mangroves are still scarce. This paper describes the first results of a thorough field campaign in a mangrove creek catchment in the Kantang River estuary at the West coast of Southern Thailand. Elevation and vegetation in this study area have been mapped and flow velocities, suspended sediment concentrations and sediment deposition rates have been monitored for several spring-neap tidal cycles during an extensive field study. This paper presents the first results for measurements of sediment dynamics during spring tides. Measured flow velocities, suspended sediment concentrations and sediment deposition rates comply with previous observations in mangroves. Patterns in suspended sediment concentrations and sediment deposition rates throughout the creek catchment show clear linkages to the elevation of the study area. It becomes clear that most sediments transported into the creek catchment via the forest fringe facing the Kantang River are directly deposited on this fringe. This is caused by a sudden drop in flow velocities over the fringe due to the abruptly increasing resistance by the elevated bed level and vegetation density at the forest fringe. Sediment input via the main creek is also limited, since the creek banks are relatively high and flow velocities over these banks are parallel to the creek. It is concluded that sediment supply for the inner part of the creek catchment behind the forest fringe and creek banks is dependent of the sediment input through the (smaller) creeks penetrating deep into the creek catchment.

1 INTRODUCTION

Mangroves consist of trees and shrubs adapted to grow on water-logged soils in the intertidal area of tropical and sub-tropical coasts. Mangroves provide a thriving habitat for many animals and they provide mankind with an abundance of ecosystem services (e.g. wood and food). Next to that the presence of mangrove vegetation in the intertidal zone impacts on coastal dynamics. Hydrodynamic energy is being attenuated (Brinkman, 2006; Massel et al., 1999; Mazda et al., 2006) and sediments are being trapped (Adame et al., 2010; Anthony, 2004; Augustinus, 1995).

Sedimentation in mangroves is a very important feature from the perspectives of stabilization of coasts and climate change impacts. Alongi (2008) found that field studies in mangroves generally show average sedimentation rates that are slightly higher than the local rates of mean sea level rise. However, field data on the flow paths of water and sediments through mangroves is limited yet. Sediment dynamics in mangrove creeks have been studied in several field sites (e.g. Bryce et al., 2003), as well as sediment deposition in a mangrove catchment (e.g. Furukawa et al., 1997). However, the linkage between sediment transport and deposition in mangroves and the input and output of sediment through creeks and over the mangrove fringe (bordering the sea/river) is relatively unknown.

In this paper we investigate sediment dynamics in a mangrove creek catchment in Southern Thailand. The study area will be presented in section 2. Section 3 describes the collection of field data during a 6 months field campaign. This section also introduces the measurement methods applied to describe the study area and to monitor the hydrodynamics and sediment dynamics within the study area. The results of these field measurements are presented in section 4. The first part of this chapter consists of a detailed description of the study area, since elevation and vegetation are strongly impacting on both hydrodynamics and sediment dynamics in mangroves. Next, results for measured flow velocities, suspended sediment concentrations and sediment deposition will be presented to shed light on sediment flows into and through the study area. Finally, the results of these measurements will be discussed and compared to other field observations in section 5 and section 6 presents the conclusions of the field measurements presented in this paper.

2 STUDY AREA

The East coast of Southern Thailand facing the Andaman Sea is fronted by numerous islands and headlands creating sheltered shorelines that accommodate widespread mangrove coverage. Field measurements have been carried out in a mangrove area surrounding the Kantang River estuary in Trang Province. The results presented in this paper have been collected in a part of a creek catchment along the Western bank of this estuary, at about 6 km inland from the actual coastline (7o19’18”N 99o29’45”E). The study area itself is bordered by the Kantang River at the East, a larger creek in the North and some smaller creek branches to the West and the South (figure 1).

Figure 1(I) Location of the field site. Left: the Thai Andaman coast. Right: the coast of Trang Province.

Since the study area is located relatively close to the river mouth, the area is subject to both tidal and riverine processes (Woodroffe, 1992). According to Lugo and Snedaker's (1974) functional classification this mangrove area is characterized as a fringing mangrove forest being inundated by daily tides and accumulating organic debris, which is in line with field observations. The climate along the Andaman coast is monsoonal, with a rainy season from May to October and a dry season from November to April. Tides are semidiurnal with amplitudes ranging from 1.1-3.2 m (Chansang and Poovachiranon, 1994).

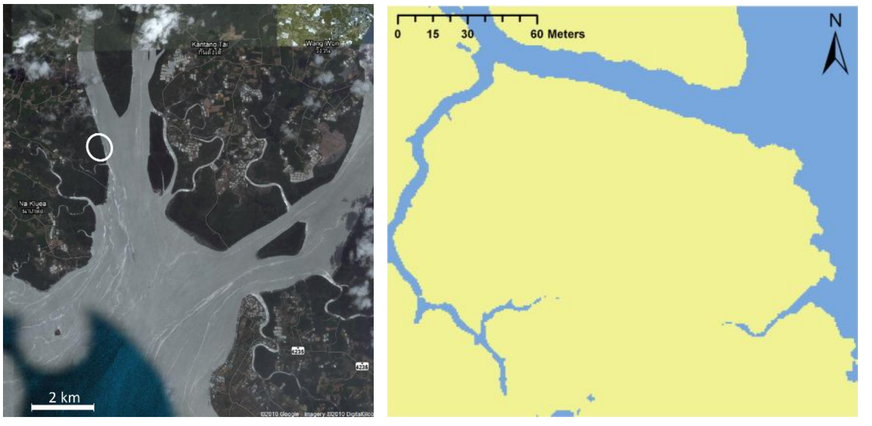

Figure 1(II) Location of the field site. Left: the mangrove area around Kantang Tai village. Right: a map of the creek catchment under study

3 METHODOLOGY

3.1 *Field campaign*

An extensive field campaign has been executed from December 2010 to May 2011. These six months were supposed to be the dry season, but according to local standards it was very rainy and Southern Thailand was even struck by serious floods within this period. Within this period, sediment dynamics in this study area have been monitored during five spring-neap tidal cycles. The monitoring grid consisted of 20 locations within the higher elevated forest and 4 more points in the waters (creeks and estuary) surrounding the study area (figure 2). Monitoring locations within the elevated part of the study area are covering both the forest fringe and the bank of the largest creek to the North. Subsequently a grid has been deployed from these outer borders so to obtain a proper spreading over the entire area. The data collection points in front of the mangrove fringe and in the three creeks surrounding the study area have been added to obtain insight into the flow paths of water and sediment into and out of the study area.

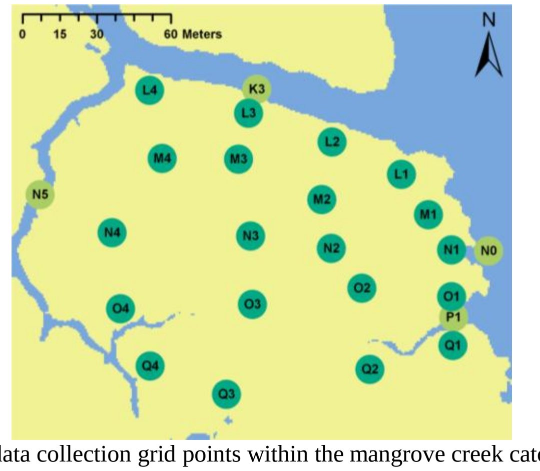

Figure 2 Distribution of the data collection grid points within the mangrove creek catchment. 20 Points are located within the forest, 4 more points are located in creeks and in front of the forest fringe

3.2 *Measuring equipment*

Sediment dynamics in a mangrove depend on: the hydrodynamic forces transporting the sediments into and out of the forest; sediment supply (e.g. from rivers) resulting in certain suspended sediment concentrations; and elevation and vegetation gradients leading to changing flow resistance and sediment trapping, both directly due to the presence of sediment trapping obstructions like trees and mounds and indirectly by impeding hydrodynamics. Each of these controlling factors has been monitored over different time spans in several positions in the creek catchment.

The elevation data has been obtained with a Total Station (Trimble). Due to difficulties with obtaining absolute heights by an RTK GPS in a mangrove forest, a reference level has been chosen within the Kantang River. Due to the dense vegetation within the study area, the Total Station had to be moved for about 20 times to be able to cover the entire area. Moreover, the geometry of the study area was very variable due to the presence of the creeks and many mud mounds. To catch all these features in the elevation map 4400 data points were collected. Data point densities increased as elevation gradients became larger.

Vegetation in the study area has been mapped roughly, based on species composition and density of the forest. For each distinguishable zone within the study area, a representative plot of 15x15 m^2 has been investigated more thoroughly. Within each of these plots trees have been counted and categorized per species. For each species diameter at breast height (DBH) has been measured for a representative small, average and large tree in each plot and pictures have been taken of these samples.

Flow velocities and directions have been measured with Acoustic Doppler Velocimeters (ADV's, Nortek) with cable probes (figure 3). These have been proven to be very useful and accurate for fieldwork in vegetated intertidal areas (Horstman et al., 2011). ADV's have been mounted upside down at such a height that flow velocities were monitored at 7 cm above the substrate. End bells of the ADV's containing pressure sensors were mounted at 7 cm above the substrate as well. Data have been collected at 16 Hz with a burst length of 4096 samples (i.e. 256 s) and a burst interval of 1500 seconds. ADV's were installed during spring tide (due to the necessity of spring low tide for installation in some locations) and collected data over an entire spring neap tidal cycle (i.e. 14 days) each time. ADV data have been processed as in Horstman et al. (2011). This paper presents flow velocity data and water levels for one spring tide at K3, N0, N1, N5 and P1.

Suspended sediment concentrations (SSC's) had to be measured very low-tech, since no appropriate equipment was available. Water samples have been collected with bottles (530 mL content) mounted at 7 cm and 25 cm above the substrate (figure 3). These bottles have been deployed each time at the starting day of the ADV measurements and were retrieved the next day. After retrieving the bottles from the field, the samples have been filtered and rinsed on 0.7 μm glass fiber filters (Whatman). Subsequently, samples have been oven dried at 105o for 24 hours and weighed. SSC's have been calculated by dividing dry mass of the sediment content of each sample by the total volume of the bottles.

Sediment deposition is a rather problematic variable to monitor. Stable traps were needed that could be left out in the field for an entire spring-neap tidal cycle. At the same time, they had to be flat, be leveled with the surrounding substrate and have a roughness comparable to the substrate. To comply with all these requirements, ceramic tiles (20x25 cm^2) have been used, with a smooth layer of mortar on the back of the tiles (figure 3). These tiles were put out in the field upside down, so the smooth lower side could easily be cleaned when the traps were collected. Deposition rates had to be monitored for both 1 day and 14 days. 1 Day is equal to the duration the SSC bottles were out in the field and facilitates direct linking of sediment deposition to the flow velocities measured during that same day. 14 Days cover an entire spring-neap tidal cycle and this longer duration will give a better insight into longer-term sediment deposition rates, since reworking of sediments will reduce net sediment deposition over time. After collecting the tiles, sediments have been rinsed off and processed the same way as the SSC samples.

Figure 3 From left to right: Deployment of an ADV at P1; a sediment trap after 1 day out in the field at M3 and SSC samples taken at N3

4 RESULTS

4.1 *Elevation & vegetation*

Bottom elevation of the study area has been mapped with a Total Station with elevations relative to an offshore location. The elevation map of the study area (figure 4) shows a general increase of the bed level towards the West, with increasing distance from the river bank. Next to that there are distinct banks along the larger creeks at the North and West of the study area. The mounds in the study area are mud mounds that are being built by mud lobsters. These mounds are typically several meters in diameter and up to 1.5 m high. In between these mounds, there is a clear depression in the middle of the study area that is fed by the creeks to the West and the South.

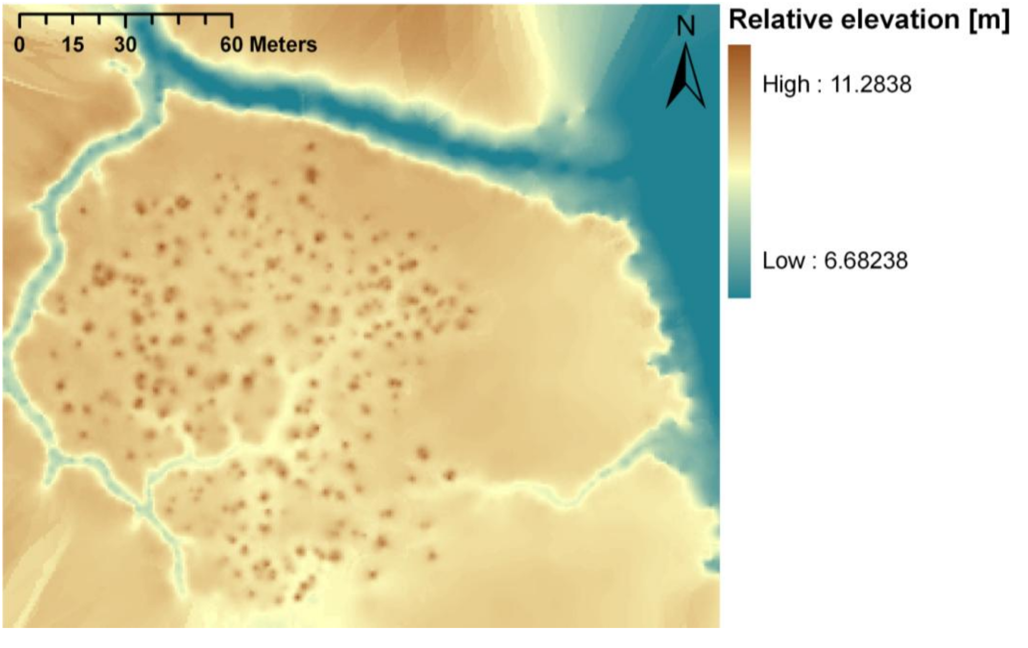

Figure 4 Elevation map of the study area

Vegetation in the study area (figure 5) shows a characteristic distribution dependent on the elevation and distance to the forest fringe. The forest fringe facing the Kantang river is covered in dense Rizophora vegetation (44 trees per 225 m^2). Directly behind this fringe, a less dense forest cover is found consisting of a mix of Rizophora, Avicennia, Sonneratia, Bruguiera and Xylocarpus trees of different ages. The density in this zone is 42 trees per plot, but the significant difference is that the number of Rizophora trees is half of the number in the fringing plot, causing a significant reduce in the number of roots and thus of biomass in the plot. Along the main creeks in the study area the same mix of trees is observed (37 trees in a plot) with a dense understory consisting of Acanthus shrubs. Rizophora trees are dominant in the part of the study area that is covered in mud mounds. These trees are taller than the fringing ones along the river but their density is lower as well with only 16 trees per plot.

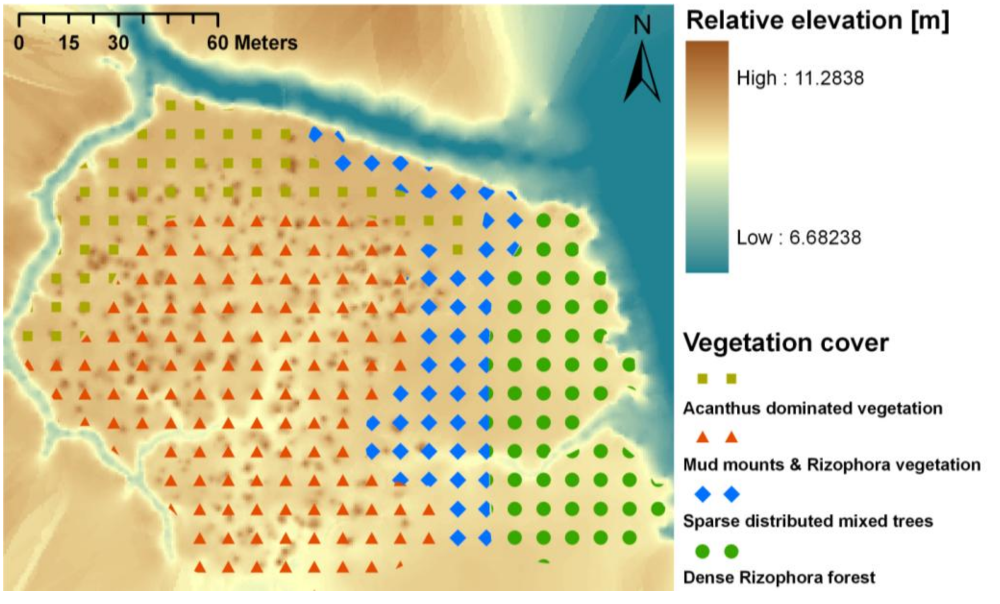

Figure 5 Vegetation cover in the study area

4.2 *Flow velocities*

Flow velocity measurements have been plotted against water depth at 5 grid points (figure 6). The plots for the three separate creeks show similar shapes. With increasing water depths due to tidal inundation, flow velocities also increase gradually. At water levels of around 9.8 m, flow velocities display a sudden increase, as a result of overbank flow. The larger area of the mangrove forest starts inundating at this time demanding an increasing volume of water that is supplied by the creeks, resulting in the sudden acceleration of creek flow. This shape for the creeks is also encountered during flood in front of the mangrove fringe. Next, the velocity profiles are not symmetric over the entire tidal cycle. During ebb flow velocities tend to have higher maximum flow velocities and maintain higher flow velocities for a longer duration (Wolanski et al., 1992). This phenomenon has already been identified as self-scouring of tidal creeks (Mazda et al., 2007). The Western creek shows an irregularity in its flow profile that can be explained by the presence of a fallen tree across the creek banks just downstream of N5. 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 in water level is encountered in the velocity profile. Without this obstructing tree the profile would have been similar to that of the other creeks.

Maximum flow velocities range between 0.05-0.3 m/s during flood and between 0.1-0.3 m/s during ebb for the main creek at K3. At the back of the study area at N5 flow velocities range between 0.05-0.2 m/s during flood and between 0.1-0.3 m/s during ebb. The third smaller creek present in the creek catchment shows velocity ranges between 0.025-0.15 m/s during flood and 0.025-0.16 m/s during ebb at P1. The creek flow velocities are of the same order of magnitude and the difference in velocity ranges is easily explained by the size of the creeks. The main creek (K3) is the largest and deepest and has therefore the largest velocity range, since bottom friction is less dominant. The main creek is followed with a smaller velocity range by the smaller Western creek (N5) and the smallest Southern creek (P1) also has the smallest velocity range.

At the seaside of the creek catchment velocity profiles were measured just in front of the creek catchment (N0) and on top of the mangrove fringe (N1). In front of the mangroves, in contrast to the creek flow, velocities keep increasing at ebb due to the influence of the discharging Kantang River. The velocity range for N0 in front of the fringe is of the same order of magnitude as in the creeks and is 0.05-0.24 m/s during flood and 0.05-0.12 m/s during ebb. At the fringe however, maximum flow velocities are significantly lower, with a velocity range between 0-0.04 m/s at flood and between 0-0.065 m/s at ebb. This is due to both the much shallower water depths over the forest fringe and the increased roughness caused by the presence of the dense Rizophora vegetation on the mangrove fringe.

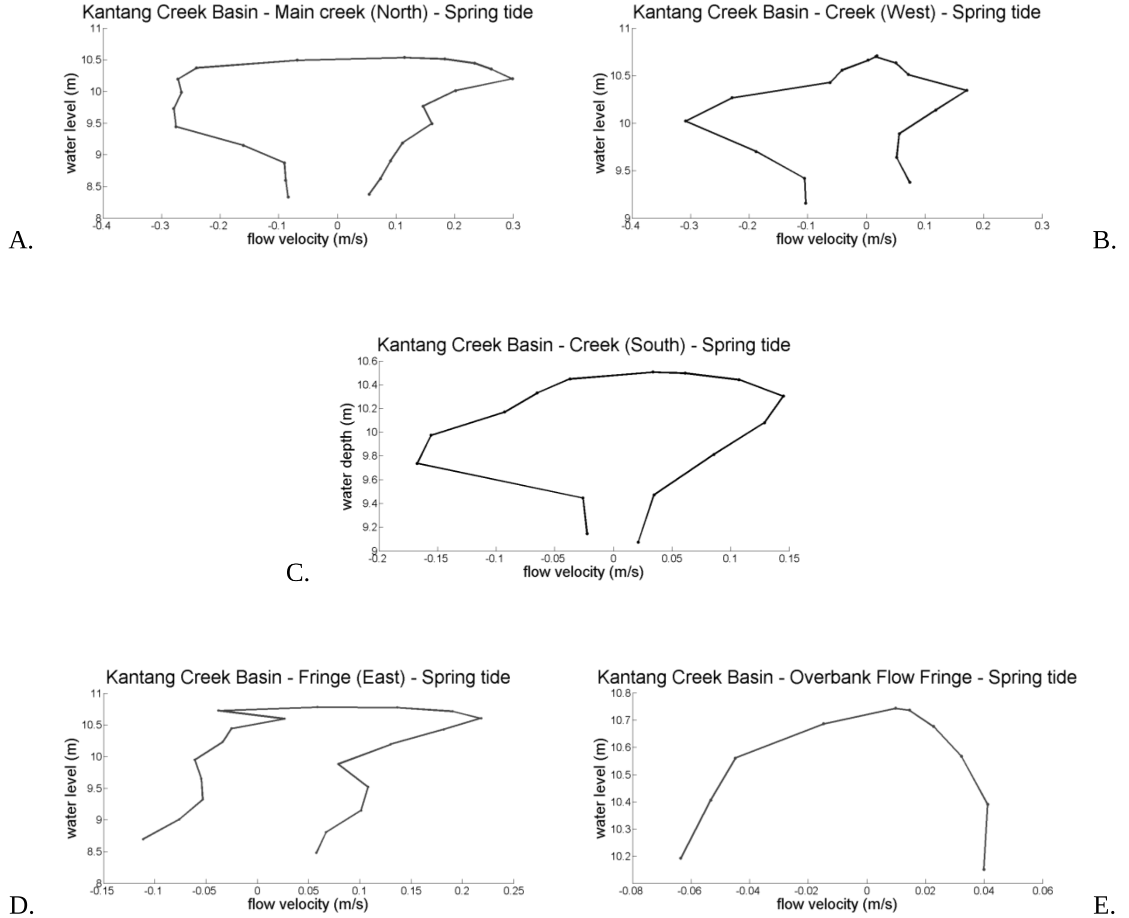

Figure 6 Creek catchment velocity profiles during one spring tidal cycle. Flow velocity is plotted against water depth, to relate tidal inundation to flow velocities. Positive velocities are measurements during flood, directed into the study area (e.g. into the creek and from the creek into the forest) and negative velocities are measurements during ebb directed out of the study area. A: Velocity profile at K3 (the main creek) B: Velocity profile at N5 (back creek) C: Velocity profile at P1 (small side creek) D: Velocity profile at N0 (in front of the fringe) E: Velocity profile at N1 (mangrove fringe)

4.3 *Suspended sediment concentration*

SSC's were measured on two occasions during spring tides and averaged to gain insight into the distribution of SSC's over the study area (figure 7). A clear difference can be observed in the concentrations at the two different elevations from the surface. Larger concentrations are encountered at 7 cm from the bed than at 25 cm from the bed. At 7 cm from the bed the SSC's vary from 0.38 g/L to 1.68 g/L and at 25 cm from the bed the SSC varies from 0.21 g/L to 1.16 g/L. Dropping concentrations with increasing water levels are attributed to higher near-bed flow velocities when the mangrove forest just starts filling up. At the initial stages of tidal filling only a thin film of water propagates into and through the forest with a relatively high speed. As can be seen in figure 6E, flow velocities within the forest decrease with increasing water levels.

At the fringe grid points (L1, M1, N1, O1, Q1) and grid points N3 and Q3 the differences between the two measuring heights are smallest compared to elsewhere in the creek catchment. The grid points N3 and Q3 together with the fringe grid points also exhibit the largest SSC in the creek catchment. These points are located at the lowest elevations in the creek catchment, with N3 and Q3 located at the end of a creek arm. For the highest elevations, encountered at the grid points on the main creek bank (L2, L3, and L4), at 30 meters from the fringe (M2, N2 and O2) and in the back of the catchment (M4, N4, O4 and Q4) the SSC's are lowest.

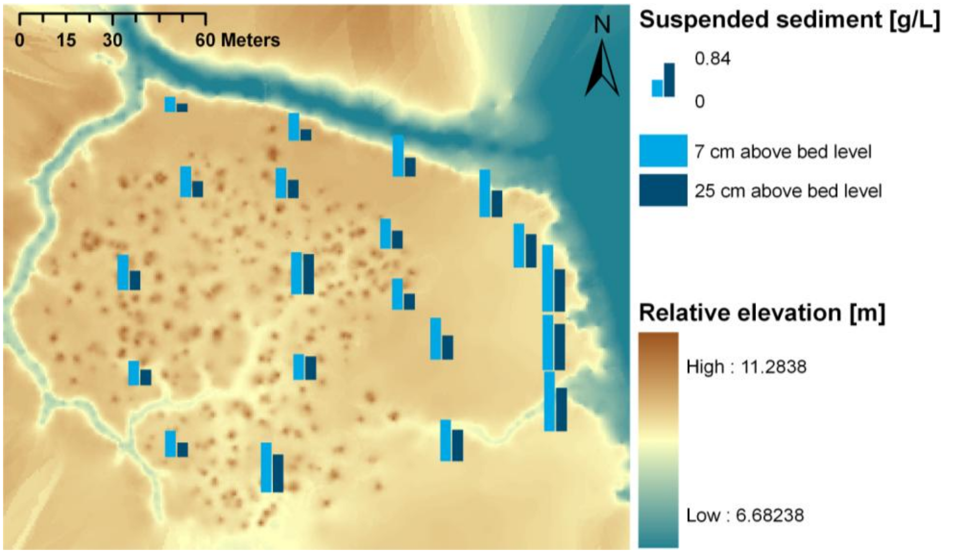

Figure 7 Suspended sediment concentrations (in g/L) at all elevated grid points measured at 7 cm (light blue) and 25 cm (dark blue) above bed level. Suspended sediment concentrations are averaged over 2 spring tides.

4.4 *Sediment deposition rates*

Whenever overbank tides inundate the creek catchment, sediments are being deposited. The sediment deposition pattern as measured at the grid points is shown in figure 8. Some patterns can be distinguished in the sedimentation rates throughout the creek catchment. At the fringe grid points (L1, M1, N1, O1, Q1) higher sedimentation rates are found than at the area approximately 30 meters behind the fringe (M2, N2, O2, Q2). The range of sedimentation rates on the fringe is 131-178 g/m^2 while the sedimentation rates behind the fringe range between 61-127 g/m2. The fringe has a lower elevation than the area behind it. High flow velocities are entering the fringe with large SSC's as observed from figure 6D and 7. Due to the reduction in flow velocities over the fringe (figure 6D, 6E) high sedimentation rates are observed at the fringe. This results in lower SSC's directly behind the mangrove fringe (figure 7) and thus in lower sediment deposition rates.

At the creek bank (L2, L3, L4) relatively low sedimentation rates were measured. The sedimentation rates at the creek bank range between 50-66 g/m^2. The creek bank is a higher elevated area in the creek catchment. At the high water levels for which the creek bank inundates large flow velocities are present in the creek itself. The creek bank then starts flowing with the creek (i.e. flow directions over the bank are parallel to flow directions in the creek) and higher flow velocities will be present at the bank than further in the back of the catchment area. These higher flow velocities cause the sediment to remain suspended. Higher SSC's together with the found low sedimentation rates corroborate the high flow velocities at the bank. The sandy substrate observed at the creek bank is another indication for the high flow velocities, since the characteristic fine bed material does not settle on these banks.

Figure 8 also indicates a large supply of sediments into the center of the catchment through the smaller creeks. This is since most sediments entering the catchment through the fringe at the seaside are already deposited at the fringe and SSC's over the Northern creek bank are limited and directed parallel to this main creek. The elevation chart shows the intrusion of the creek into the catchment with large SSC's at the low lying area (figure 7). The creek inundates the catchment and provides sediments to the entire area. At the ends of the creek arms, relatively large sedimentation rates are measured. So apparently sediments are transported through the entire catchment by the creeks and at the turning of the tides they settle down. Sedimentation rates at the center and back of the creek catchment (M3, N3, O3, Q3, M4, N4, O4, Q4) have a range of 83-331 g/m^2. Variations in these deposition rates can partly be explained by local bed topography, with lower deposition rates at higher elevated measurement locations. However, this relation does not hold for deposition rates at M3, M4, N3 and N4. Deposition at these locations is much higher and may be caused by trapping of the sediments in the central area of the creek catchment enclosed by the banks of the outer creeks.

Links between sediment deposition rates and vegetation patterns are harder to describe. At the seaside fringe of the creek catchment the sedimentation rates are directly linked to the strong decrease in flow velocities, which in turn is caused by the dense vegetation present at this location. For the back of the creek catchment however, linking of sediment deposition rates and mangrove vegetation is not unambiguous.

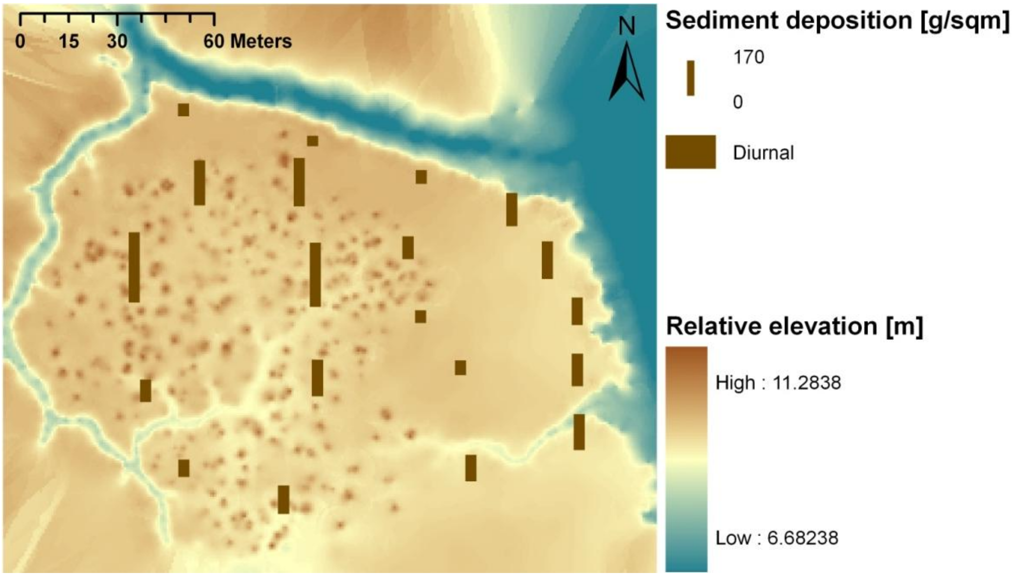

Figure 8 Sediment deposition rates (in g/m^2) at all elevated grid points measured. Sediment deposition rates are averaged over 2 spring tides.

5 DISCUSSION

Flow velocities observed in this field campaign (maximum creek flow of order 0.2-0.3 m/s and overbank flows over the forest fringe of order 0.05 m/s) are comparable to velocities measured in mangroves in other parts of the world. Victor et al. (2006) found flow velocities of the same order (0.4 m/s in creeks, 0.08 m/s in mangroves) for a mangrove area in Pohnpei, Micronesia. For the mangroves in Gazi Bay, Kenya, Kitheka (1996) found maximum flow velocities (0.6 m/s in creeks and <0.1 m/s in mangroves) comparable to the results presented above. Wolanski (1992) studied mangroves along Hinchinbrook Channel, Australia, and also came across flow velocities in the mangroves of order 0.3 m/s. However, he found higher creek flow velocities reaching up to 1.6 m/s. In contrast, Anthony (2004) presents measurements from Sherbro Bay, Sierra Leone, with creek velocities of order 0.5 m/s but relatively high flow velocities over the mangrove banks of order 0.1 m/s. All in all, however, observed flow velocities in this study are well in line with general observations in mangroves.

Observed suspended sediment concentrations within the study area range from 0.21 g/L to 1.16 g/L at 25 cm above the substrate. These values are up to one order larger than observations in Adame et al. (2010) which are of order 0.12 g/L and in Van Santen et al. (2007) who observed average SSC values of 0.03 g/L and maxima reaching up to 0.6 g/L. These differences can be attributed to the measurement method for

SSC applied in this study. Other studies applied instantaneous SSC measurements, either by optical backscatter sensors (Van Santen et al., 2007) or bottles being opened and filled at a certain water depth and retrieved immediately (Adame et al., 2010). These instantaneous measurements were not feasible within this study. Nonetheless, differences in SSC measurements over the study area will still exhibit comparable spatial differences to those instantaneous measurements since all bottles have been out in the field for the same time span (i.e. one day).

Sediment deposition rates measured in the current study range from 50-331 g/m^2/day and these rates are clearly related to elevation and distance to the mangrove fringe and creeks. Furukawa et al. (1997) found similar rates ranging from 300 g/m^2/day at the creek edges to 100 g/m^{2-}/day and about 0 g/m^2/day at respectively 50 m and 200 m away from the creek edge. Van Santen et al. (2007) on the other hand found sedimentation rates gradually increasing from 0.5-2.5 g/cm^2/yr in the densely vegetated back mangrove to 40-70 g/cm^2/yr on the bare mudflat in front of the mangroves. Linear extrapolation of the observed values in the study area results in deposition rates of 1.8-12 g/cm^2/yr. These are comparable to Van Santen et al.'s observations in dense and moderately dense mangroves, which is a proper description for the forest in our study area. In these previous studies negative sediment deposition gradients with increasing distance from creeks (Furukawa et al., 1997) and increasing distance from the forest fringe (Van Santen et al., 2007) have been observed separately. This paper shows the combined effect of these two sediment suppliers. Deposition rates are decreasing perpendicular to the forest fringe, but larger deposition rates are found again in the back of the forest that is being fed by the creeks. Sediment deposition also does not show a clear relation with distances to the creek (e.g. the very low deposition rates directly along the main creeks), but depends mainly on local elevation. So sediment dynamics in this complex mangrove environment do not show a straightforward relation to distances to the forest fringe or creeks as suggested in these previous studies.

In order to get a better understanding of sediment fluxes through the forest, additional information will be needed on flow velocities at different locations within the study area and on the variation of SSC's at these locations over an entire spring-neap tidal cycle. These fluxes should then be compared to sediment deposition rates over a spring-neap tidal cycle. This should give a better understanding on how deposition and erosion during spring tides differ from their neap tide equivalents and can shed a light on longer-term accretion within mangroves (which will probably show that linear extrapolation of diurnal accretion rates as applied above overestimates annual accretion). These data are available and will be presented in an upcoming paper.

6 CONCLUSION

For the supply of sediments, mangroves depend in large on the presence of a creek system. Flow velocities are reduced quickly by the vegetation over the forest fringe, resulting in high sediment deposition rates at the fringe. Little sediment is thus carried into the forest over the forest fringe. In the center of the creek catchment high SSC's with high deposition rates are found indicating a supply of sediment to this area. The only alternative routing into the forest is through the mangrove creeks. Along the main creek of the creek catchment, however, low suspended sediment concentrations are found over the banks and flow parallel to the main creek. Moreover, deposition rates on the creek bank are low. Altogether, this indicates that the main supply of sediments into a mangrove creek catchment occurs through a system of smaller creeks (starting at the fringe and branching off the main creek) penetrating deep into the mangrove forest. The sediment routing found in this study is different from previous studies where sediment supply into the forest was either related to the sea-side fringe or the creek-fringe. This study shows that smaller creek branches play a significant role in sediment input in mangroves.

A more quantitative analysis of the sediment dynamics in a mangrove creek catchment, including flow velocities and directions within the creek catchment and sediment concentration changes over time, is pending. Data for this quantitative analysis is available and will be presented in a future paper.

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