Papers

Experiments on wave motion and suspended sediment concentration at Nang Hai, Can Gio mangrove forest, Southern Vietnam

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Abstract

Biogeochemical and trophodynamic processes as well as hydrodynamic factors play a major role in the structure and function of mangrove ecosystems. This study outlines field experiments on wave motion and suspended sediment concentration carried out at Nang Hai, Can Gio mangrove forest, Southern Vietnam. Pressure sensors were used to measure sea surface elevation, and Optical Backscatter Sensors (OBS) were applied to detect infrared (IR) radiation scattered from suspended particles in order to measure turbidity and suspended sediment concentrations.

The experimental results indicate that most of the energy is dissipated inside the mangrove forest as a result of wave-trunk interactions and wave breaking. The suspended sediment concentration depends on wave intensity and tidal current velocity. Wave action is one of the main factors forcing sediment transport and coastal erosion at the study site; even the wave field at the study site is not so strong. The establishment of mangrove vegetation can encourage the deposition of sediment, or at least the retention of the flood-tide sediment influx.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

1. Introduction

Mangroves are very important ecosystems at the boundary between terrestrial and marine environments in tropical and subtropical zones. Covering about 181 000 km^2 of the coastal areas in the tropics, mangroves are considered highly productive yet vulnerable to the impacts of nature and human beings. Mangroves have a beneficial effect on the surrounding environment in that they are an important food supply for humans, protect the land from erosion, facilitate alluvium deposition, and mitigate the effects of typhoons and floods. Mangroves are also important as breeding and nursery grounds for prawns, fish and other marine and terrestrial organisms. In addition, they are a source of timber for firewood, construction, etc. (Snedaker & Snedaker 1984, Tuan et al. 2002).

Biogeochemical and trophodynamic processes in mangrove forests, and the structure of such forests and their growth are intimately linked to water movements due to tides and waves (Massel et al. 1999). Numerous studies of the physical processes within mangrove forests have been made in the past. They have generally focused on riverine-type mangrove forests and tidally periodic processes (Wolanski et al. 1992, Furukawa & Wolanski 1996, Furukawa et al. 1997). However, studies of wave processes within the mangrove forests themselves are few. The significant attenuation of surface waves over relatively short distances was studied by Mazda et al. (1997a) and Massel et al. (1999), and a few experimental studies in mangrove forests have been conducted. In particular, field measurements were undertaken on the muddy coast of Thai Binh province, in the Tong King Delta, Vietnam (Mazda et al. 1997a). It was found that the rate of wave reduction varies with water depth and the age of the trees. Wave attenuation was greater where the trees were older. Moreover, the efficiency of mangroves in protecting the coast from wave-induced erosion depends on the mangrove species (Mazda et al. 1997b). However, these authors did not describe the mechanism of wave energy dissipation. These problems have recently been addressed by Massel et al. (1999), who developed a theoretical model for predicting the attenuation of wind-induced random surface waves in a mangrove forest of constant depth. Examples of numerical calculations as well as preliminary experimental results of wave attenuation through mangrove forests at Townsville (Australia) and Iriomote Island (Japan) were given. Both theoretical analysis and field experiments indicated that for shallow water depths, the combination of bottom friction with the effects of drag caused by mangrove roots and trunks produces a significant amount of attenuation over a relatively short distance.

This paper reports on the field experiments on wave motion and wave-induced suspended sediments recently carried out in the Can Gio mangrove forest, Southern Vietnam. The field observations provide data on wave parameters and suspended sediment concentration, as well as on bottom current velocity, topography and mangrove characteristics. The measurements and data analysis make it clear that wave motion is one of the main factors driving sediment transport and accumulation/erosion processes in the mangrove environment.

2. Experimental equipment and procedures

2.1. Study site

Can Gio mangrove forest, adjacent to Ho Chi Minh city (Saigon), South Vietnam, is the first Biosphere Reserve in Vietnam, and has a total area of 75 740 ha. (Fig. 1). The Can Gio area has a complex, convoluted network of rivers and creeks, where the Vam Co, Saigon and Dong Nai Rivers discharge into the sea. Can Gio lies in a recently formed, soft, silty delta with an irregular, semi-diurnal tidal regime. Tidal amplitudes range from about 2 m at mean tide to 4 m during spring tides. Maximum tidal amplitudes, in the range of 4.0–4.2 m, are the highest recorded in Vietnam. The climate of Can Gio is influenced mostly by the equatorial monsoons – a rainy season (from May to October) with prevailing south-westerly winds, and a dry season (from November to April) with prevailing north-easterlies, creating waves up to 2.0–2.3 m in height (Tuan et al. 2002).

The study site is at the mouth of the Dong Tranh estuary (Fig. 1). The Dong Tranh area is less affected by strong wind-induced waves, as it is sheltered by Capes Ly Nhon and Long Hoa either side of the estuary. This situation is conducive to the formation and growth of mangroves. As a result, only winds from SE to SSW can create direct waves propagating to Dong Tranh. The site chosen for the wave measurements was the Nang Hai mangrove forest, located between the Rach Trung and Khe Ca creeks. Nang Hai is only about 2.5 km distant from the Dong Tranh estuary and has a more direct influence on wave motion than the other sites. Nang Hai forest consists of mixed mangroves of *Avicenia* sp. and *Rhizophora* sp. in the first 100 meters; beyond this *Rhizophora* sp. are largely dominant. The field measurements were carried out for 16 days, during January and February 2005. The instrumentation transect (10°23.427N, 106°52.761E – 10°23.442N, 106°52.793E) was chosen parallel to the direction of wave propagation towards the forest (Fig. 1b). The topography of the study site was measured at 2 m intervals along the 88 m long instrumentation transect with a YA-28X theodolite. The zero reference level was chosen as the bottom level at Station 2 (ST2).

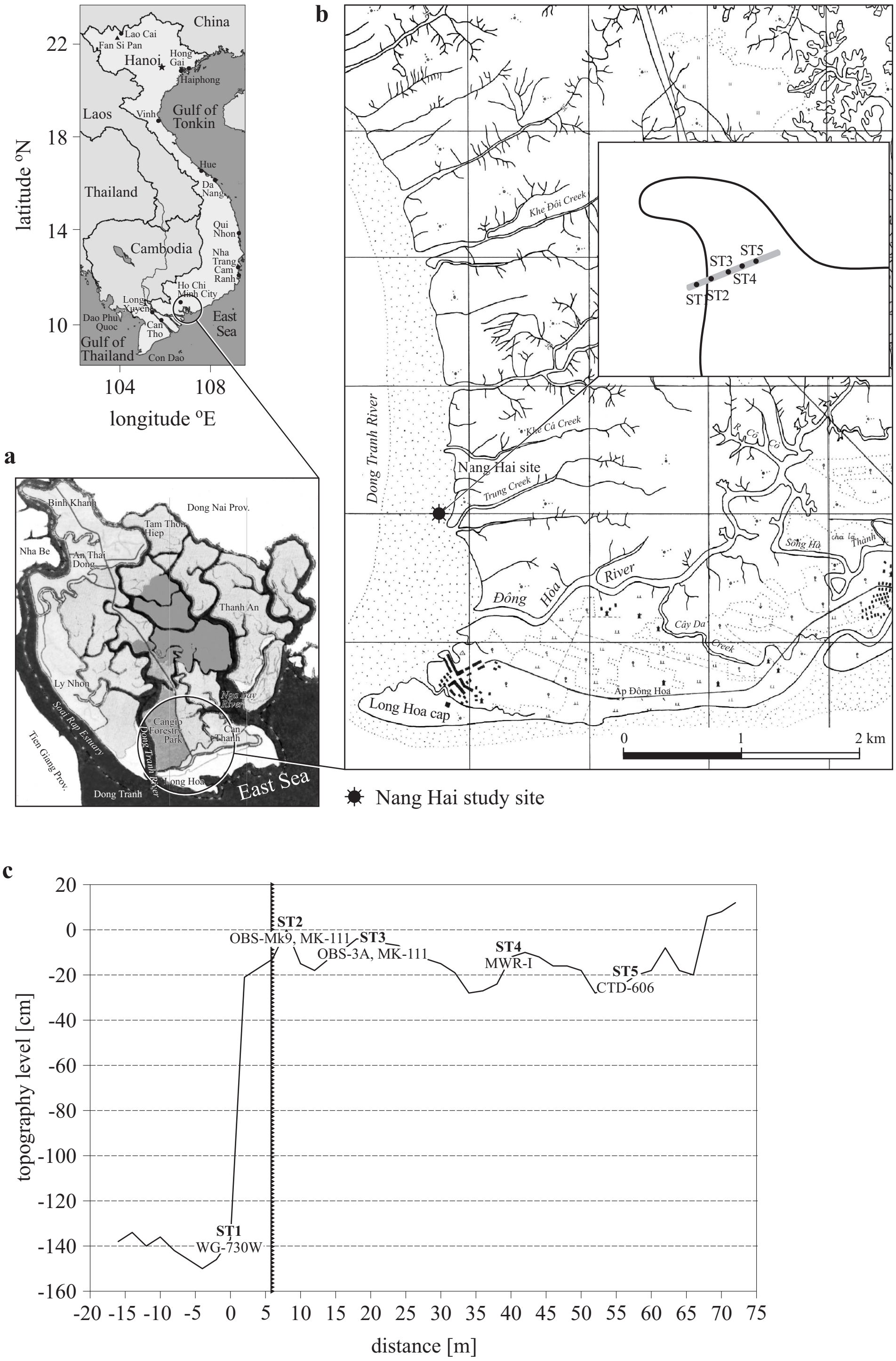


Fig. 1. Location of the experimental area. Can Gio mangrove Biosphere Reserve, Ho Chi Minh, Vietnam (a); Nang Hai study site and transect of stations (b); Instrumentation layout on 30 January 2005 at the Nang Hai site (c)

2.2. Data collection and methods

2.2.1. Instrument layout

To determine the surface wave propagation within the mangrove forest and the induced sediment transport, wave instruments and the instruments measuring suspended sediment concentrations (SSC) were deployed along a transect from the edge of the mangroves for a distance of about 80 m into the forest (Fig. 1c). All the instruments were cleaned daily to prevent errors due to mud adhering to the sensors. Additionally, other factors such as bottom current velocity, grain size distribution, bottom topography, and the characteristics of the mangrove trees (circumferences of trunks and roots, density of the forest) were determined.

2.2.2. Wave measurement

Pressure sensors were used to measure sea surface elevation, and time series were analyzed over periods from 20 to 30 minutes with a sampling frequency of 2–5 Hz. Pressure sensors were mounted under water at a fixed position to measure the variations in the height of the water column passing above them.

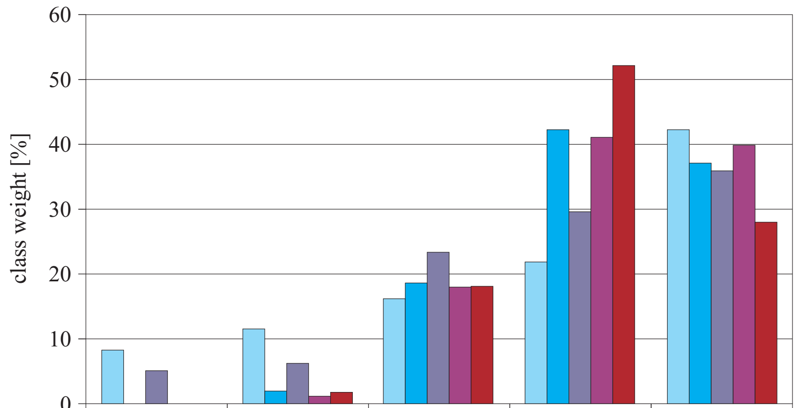
Various types of instruments were used to measure the waves: a WG-730W wave gauge (Valeport Co.), an MWR-I wave gauge (Sanyo Sokki Co.), an OBS-3A (D&A Co.) and a CTD-606 (Valeport Co.), as shown in Fig. 1c. At Station ST1, 5 m in front of the mangroves, the WG-730W sensor was mounted 0.1 m above the sea bed. The sampling frequency was 4 Hz, and 2048 wave burst samples were recorded at 30 minute intervals. The other instruments were spaced out along the transect through the mangroves at ST3, ST4 and ST5: the MWR-I was installed with a burst of 5 Hz and 6000 samples every 30 minutes, the CTD pressure sensor (CTD-606, Valeport Co.) was installed at a sampling frequency of 4 Hz, and the OBS-3A optical backscattering sensor was deployed to record the pressure with a frequency of 2 Hz. The positions of these pressure sensors in the mangroves were changed in response to water levels and wave heights during the field measurements. Fig. 1c shows the instrumentation layout on 30 January 2005.

2.2.3. Measurement of suspended sediment concentration (SSC)

As Optical Backscattering Sensors (OBS) are able to detect infrared (IR) radiation scattered from suspended particles, they are used to measure turbidity and suspended sediment concentrations. In this experiment, two OBS were installed in the mangrove forest (Fig. 1c): an OBS-3A (D&A Co.) with 0.5-second sampling intervals 20 m from the mangrove edge

(ST3), and a self-cleaning OBS-Mk9 (James Cook University, Australia) 8 m from the mangrove edge (ST2) recording every minute with a 30-min wiper time. Both sensors were calibrated in the standard laboratory way using sediments sampled at the study site (Ridd et al. 2001). Two MK 111-2035 (General Oceanics Inc.) current meters were positioned adjacent to the OBS sensors to measure the current velocities every half-hour.

At 5 stations along the transect sediment samples were taken to analyze the grain size distribution (Fig. 2). Soft and silty sediments with a size distribution from very fine sand to fine clay are common at the Nang Hai site. Bottom sediments contain between 20% and 52% of very fine silt and clay ($< 5\ \mu$m). Under high shear stress, silts and clays will remain in suspension and will tend not to be transported as bedload. Therefore, measurement of the suspended sediment concentration (SSC) is required to calculate the induced sediment transport in mangroves (Rijn 1989, Mehta & Li 2003).



	0.25 - 0.1	0.1 - 0.05	0.05 - 0.01	0.01 - 0.005	< 0.005
ST1 [%]	8.21	11.52	16.13	21.88	42.26
ST2 [%]	0	1.98	18.60	42.23	37.19
ST3 [%]	5.09	6.15	23.36	29.51	35.89
ST4 [%]	0	1.19	18.00	41.03	39.8
ST5 [%]	0	1.77	18.16	52.07	28.00

grain size [mm]

Fig. 2. Grain size distribution at the Nang Hai site

3. Results and discussion

3.1. Wave data analysis

Before analysis, the wave data were edited to remove the spikes due to instrument malfunctioning. Because of the tidal motion, spurious trends, or low frequency components with a wavelength longer than the recorded length, had to be removed. Moreover, as this study concentrated on the highest-energy part of the spectrum, high-frequency components with negligible energy had first to be filtered out (Bendat & Piersol 1986, Hughes 1993, Massel 1996). Time domain statistics were extracted from the time series records, and individual waves were determined by zero-downcrossing. Wave height was taken to be the total vertical distance between the wave crest (highest elevation of the wave) and the wave trough (lowest elevation of the wave).

Figs 3a, b, c show the significant wave heights at stations along the transect. The ranges of wave heights give the maximum, mean and minimum values from the observed data. The recording time of the wave motion was selected to provide a chosen water depth. The water depth at ST1 varied from 1.90 m (Fig. 3a), 2.10 m (Fig. 3b) to 2.50 m (Fig. 3c) as a result of tidal motion. The water depth of 2.50 m at ST1 was practically the highest water level in the Nang Hai mangroves and was recorded only during the high spring tides in January 2005. Therefore, wave height data for a water depth of 2.50 m were sparse: only 4 data series were collected at water depth h_{ST1} = 2.50 m, but 10 data series for $h_{\mathrm{ST1}} = 2.10$ m and 11 for $h_{\mathrm{ST1}} = 1.90$ m. In general, the wave height H_{ST1} at ST1 was about 0.35–0.4 m. The wave height decreased very quickly over relatively small distances, especially in shallower waters. About 50%–70% of the wave energy was dissipated within only 20 m in the mangrove forest when the water at ST1 was 1.90 m or 2.10 m deep, while the wave height fell by about 50% over a distance of 40 m when the water was 2.50 m deep. After this abrupt fall, wave height then continued to decrease only slightly. Theoretical models indicate that wave breaking and interactions between the waves and the mangrove vegetation are the dominant mechanisms of energy dissipation as waves propagate into the mangroves. After most of the waves have broken, the further slight decrease in wave height is due mainly to wave-trunk interaction (Hong Phuoc in preparation).

The wave heights at particular stations are random variables that follow certain probability laws. As the water depth strongly influenced the wave motion, Glukhovskiy's distribution for wave height for a finite water depth was applied (Massel 1996). Fig. 4 illustrates a comparison of experimental data with the Glukhovskiy distribution for wave records at the edge of the mangroves (Fig. 4a) and 20 m from the mangrove edge (Fig. 4b). In general, the distribution of wave heights does follow a Glukhovskiy distribution. If the water depth decreases, the distribution becomes narrow and more symmetrical, because high waves disappear as a result of wave breaking, and

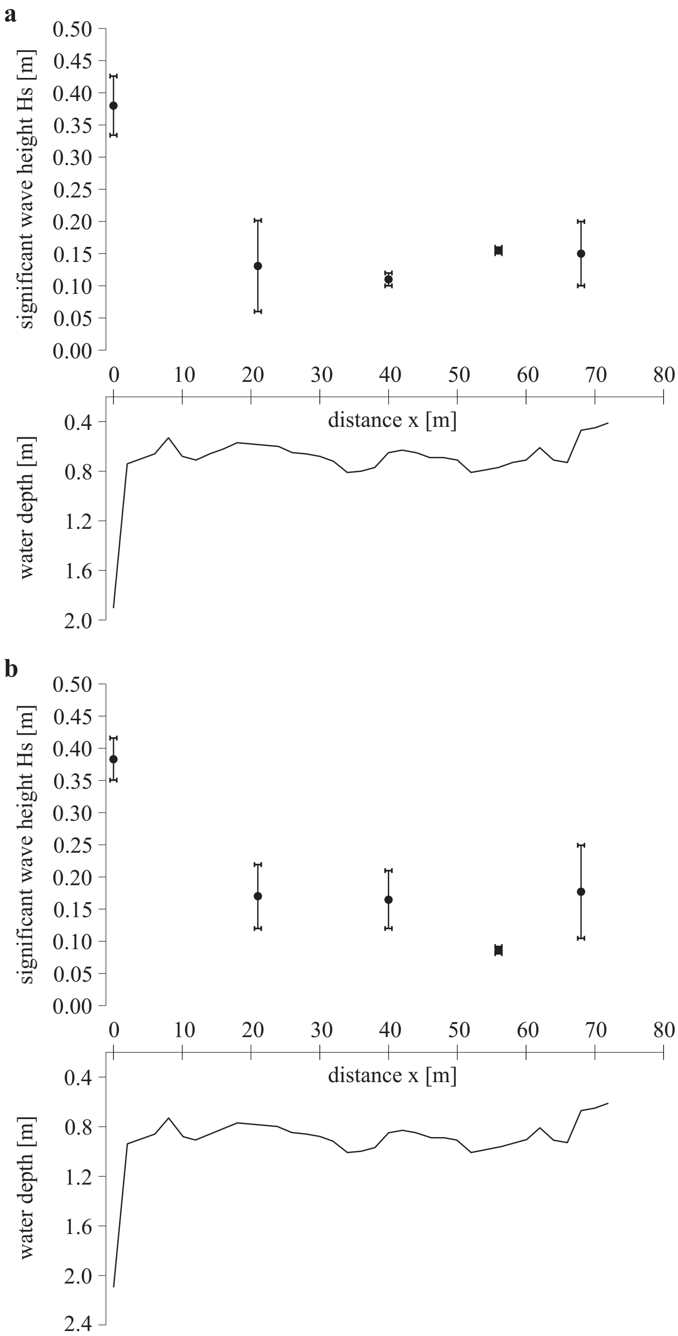


Fig. 3. Experimental wave height attenuation with varying water depth at the Nang Hai mangrove site: $h = 1.90$ m (a), $h = 2.10$ m (b), $h = 2.5$ m (c). The filled circles denote mean values and the horizontal bars indicate the range of wave height changes

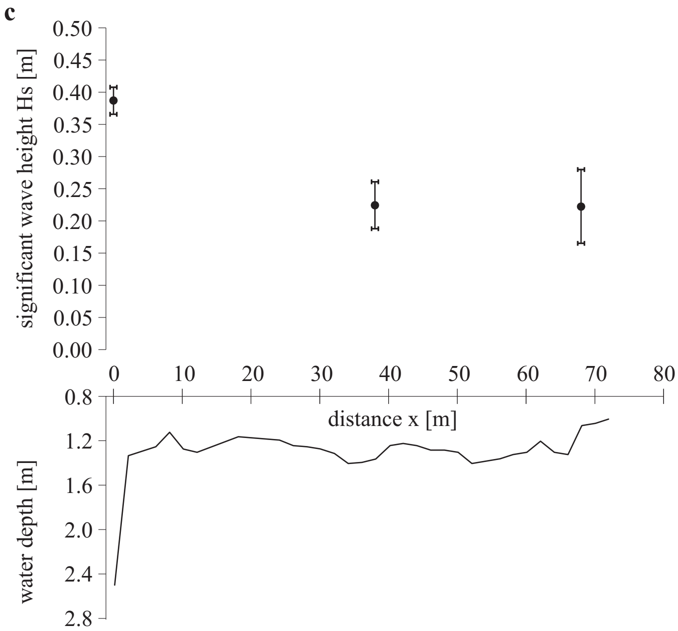


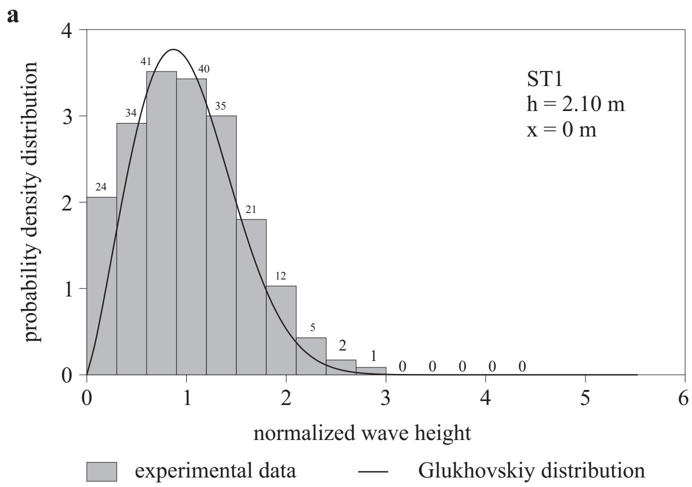
Fig. 3. (*continued*)

small waves attenuate because of their interaction with roots and trunks. Moreover, the most probable wave height shifts towards lower values.

The wave spectrum presents the distribution of wave energy as a function of frequency. The Blackman-Turkey method was used to estimate frequency spectra. Fig. 5 gives the spectral energy density at ST1 and ST3 (40 m inside the mangroves). These spectra were obtained at high tide, when $h_{\mathrm{ST1}} = 2.60$ m. They indicate that energy is strongly dissipated within the mangrove forest and in the shallower water zone, where water depth h_{ST3} = 1.35 m; the spectra have 2 peaks, one in the lower frequency part and other in the higher frequency part. This can be explained by the nonlinear interaction mechanisms in shallow waters.

3.2. Suspended sediment concentration (SSC) analysis

Fig. 6 shows suspended sediment concentrations for 6 days, corresponding to tides measured at the offshore station in the Dong Tranh estuary, about 1.6 km from the study site (Fig. 6a). At ST2, the highest water level was about 0.65 m. The half-hourly maximum velocities at ST2 in the mangroves are shown in Fig. 6b. It can be seen that the SSC changes in accordance with current velocities (Fig. 6c).



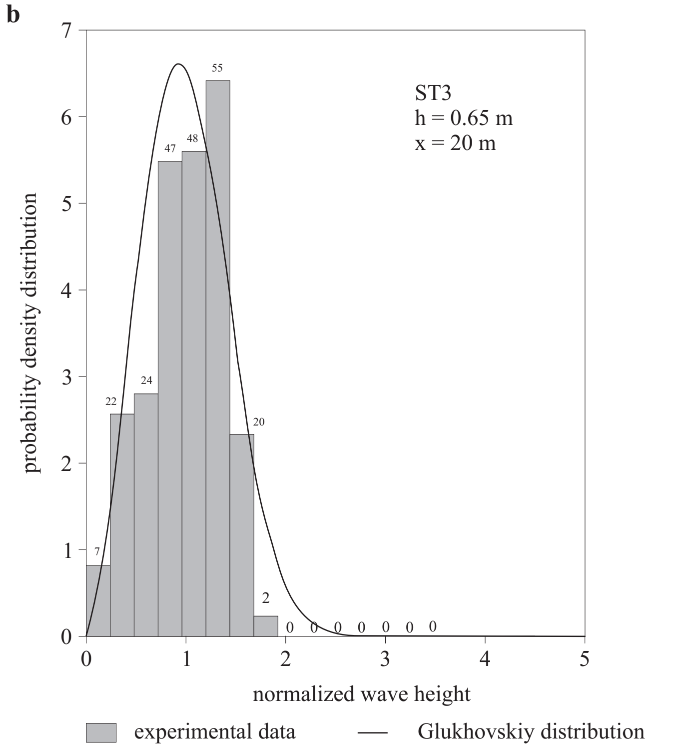


Fig. 4. Comparison of the Glukhovskiy's probability density function for wave height with experimental data at ST1 (a) and ST3 (b) on 01 February 2005 at 19:00

Fig. 7 shows the detailed changes in SSC at ST2 in one tidal cycle when the water level $h_{\max} \approx 0.65$ m for high waves (Fig. 7a) and weak waves (Fig. 7b). When waves were weak ($H_{\max\,\mathrm{ST2}} = 0.10$ m), the velocity was

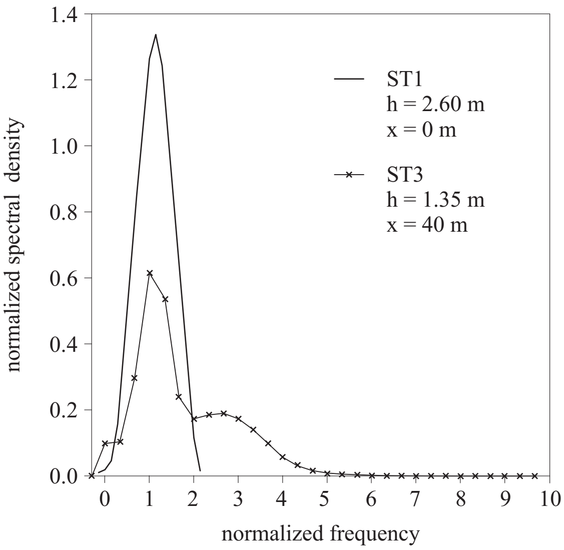


Fig. 5. Wave spectrum at ST1 and ST3 on 11 January 2005 at 00:00

low ($\approx$ 0.12 m s^{-1}) and the SSC was also low, about 0.1 kg m^{-3}. For high waves ($H_{\text{max ST2}} = 0.60$ m) with a high velocity up to 0.45 m s^{-1}, the SSC increased rapidly to 0.3 kg m^{-3}. The changes in high SSCs are chaotic and irregular, and independent of tides. Meanwhile, low SSCs change only slightly in response to tidal levels; SSCs were higher during the ebb and the flow, but decreased at the crest of the tide when the tidal current is almost zero. The comparison shows that high waves play a more dominant role on SSC than tidal currents, especially when the water level is low enough.

As a wave propagates into the mangrove forest over shallower depths, most of the wave energy will dissipate not only because of trunk-wave interaction but also because of depth-controlled wave breaking. Fig. 8 shows the suspended sediment concentration measured in January 2005 during the high spring tide. For a high water level, say $h_{\text{max at ST2}} = 1.10$ m, when the wave was high enough ($H_{\text{max}} \approx 0.6$ m), the tidal regime was mainly responsible for the changes in SSC. Concentration is higher during the ebb and the flow, and decreases when the tide crest appears (Fig. 8a). The influence of wave motion is demonstrated by the high amplitude of SSC fluctuations and the sudden increase when the water level is lower (Fig. 8b). This means that wave action strongly influences SSCs in shallower waters, where waves break and enhance sediment suspension.

A mangrove forest can be considered an effective buffer zone against erosion processes. This can be demonstrated by comparing SSC values at two different points (stations ST2 and ST3) in the mangrove forest (Fig. 9).

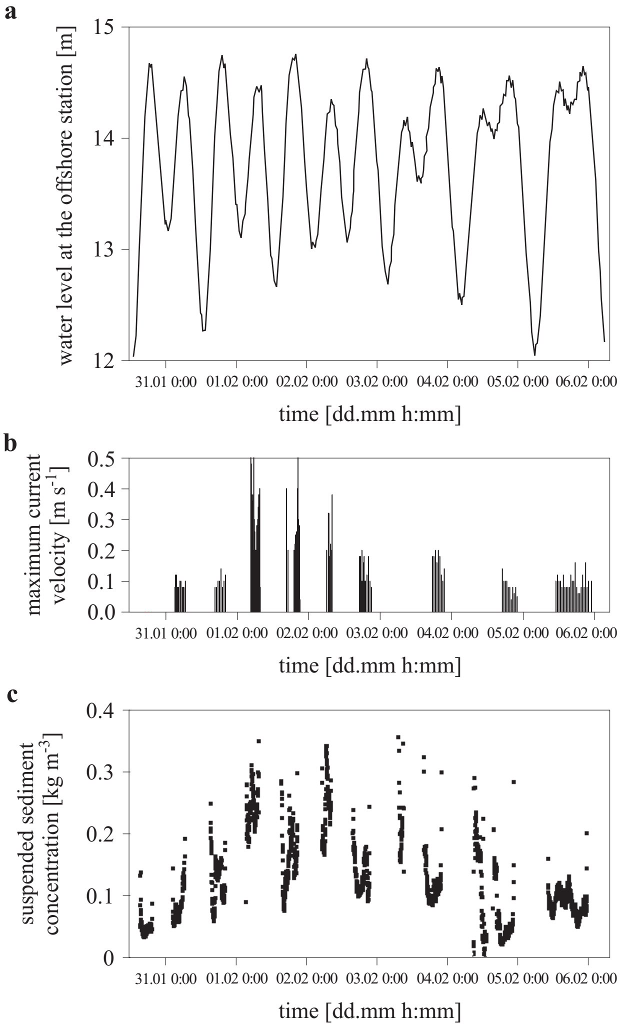


Fig. 6. Suspended sediment concentration during a 6-day experiment. Water level at the offshore station in the Dong Tranh estuary (a); maximum current velocity at ST2 (b); suspended sediment concentration at ST2 (c)

ST2 and ST3 were respectively located 8 and 20 m from the edge of the forest. Obviously, the stronger the wave action, the higher the SSC. When waves were weak ($H_{\text{max in ST1}} \approx 0.1$ m), the SSC at both stations were low, about 0.06–0.07 kg m^{-3}, and the SSC at ST2 was only slightly higher than at ST3. On the other hand, when waves were stronger ($H_{\text{max in ST1}} \approx 0.6$ m), the SSC was much higher: about 0.23 kg m^{-3} at ST2 and 0.19 kg m^{-3} at ST3. The lower concentrations at the more distant station demonstrate that wave energy decreases as waves propagate in the mangrove forest and

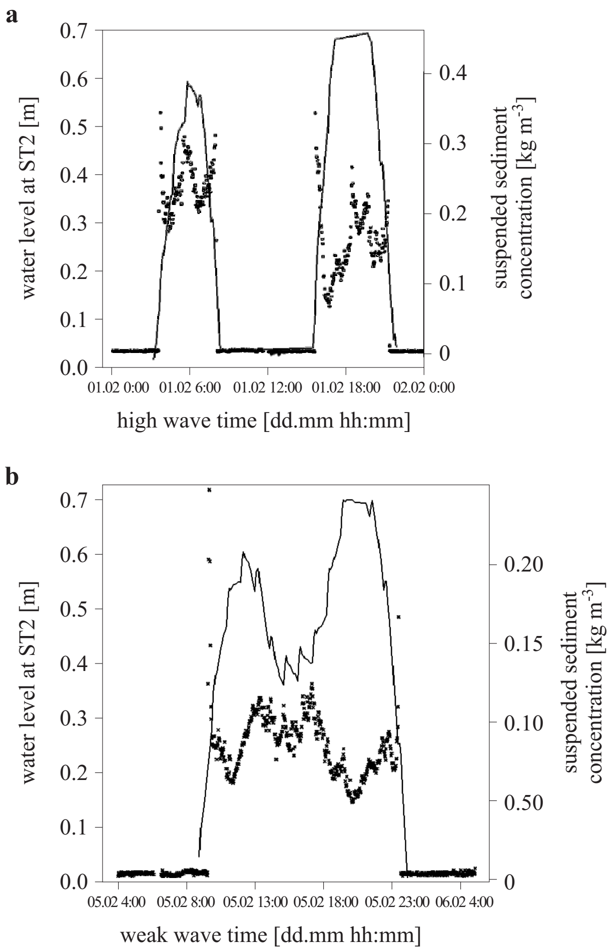


Fig. 7. Comparison of suspended sediment concentration in one tidal cycle in the case of high waves (a) and weak waves (b)

that mangrove vegetation can encourage the retention of sediment influx due to waves or flood tides. The 20-minute record shown in Fig. 9 corresponds to the time when the influence of wave motion and tidal currents were dominant.

3.3. Erosion at the study site

The north-east monsoons can generate high waves propagating directly towards the Nang Hai site. Nevertheless, these experiments have shown that besides tidal currents, wave action can make a significant contribution to the increase in SSC in mangroves and to accelerate the movement of suspended sediments. Furthermore, when water levels in the mangroves are low, wave

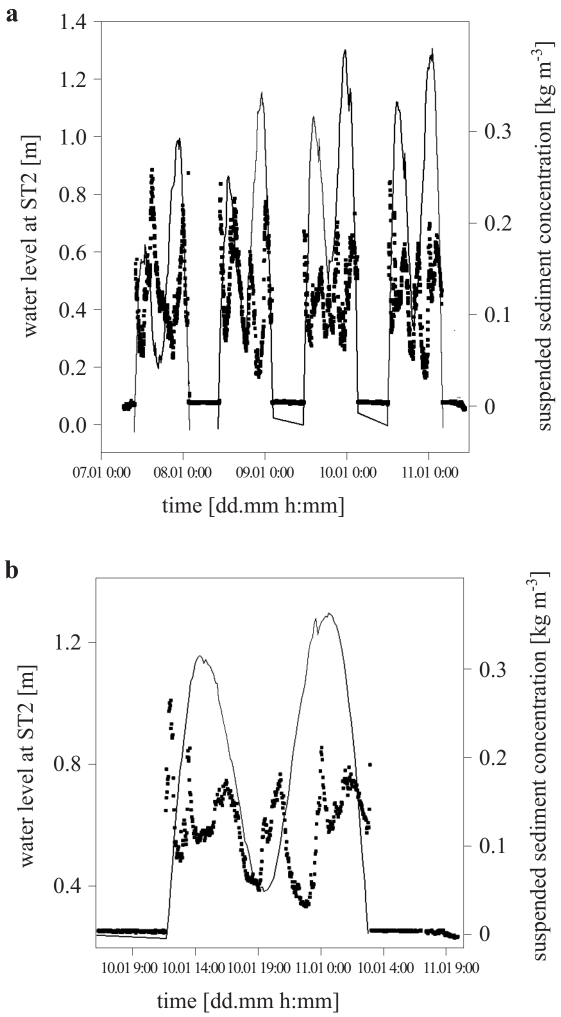


Fig. 8. Suspended sediment concentration for the high wave case: high spring tide in January 2005 (a), one tidal cycle (b)

action is more likely to affect SSC than tides. Generally, water levels at Nang Hai are rather low. Fig. 10 illustrates the predicted maximum water level in 2005 at the Can Gio open-sea station. The annual water level maximum occurs in January and almost all tidal peaks are lower than 4.0 m. When the water level at the open-sea station reaches about 3.25 m, there will be hardly any water in the Nang Hai mangroves. Similarly, when there are 4.0 m of water at the open-sea station, the water level at ST2 in the Nang Hai mangroves is about 0.75 m. Theory shows that when the water level at ST2 is about 0.75 m and if there is a higher wave, say of about 0.4 m, then

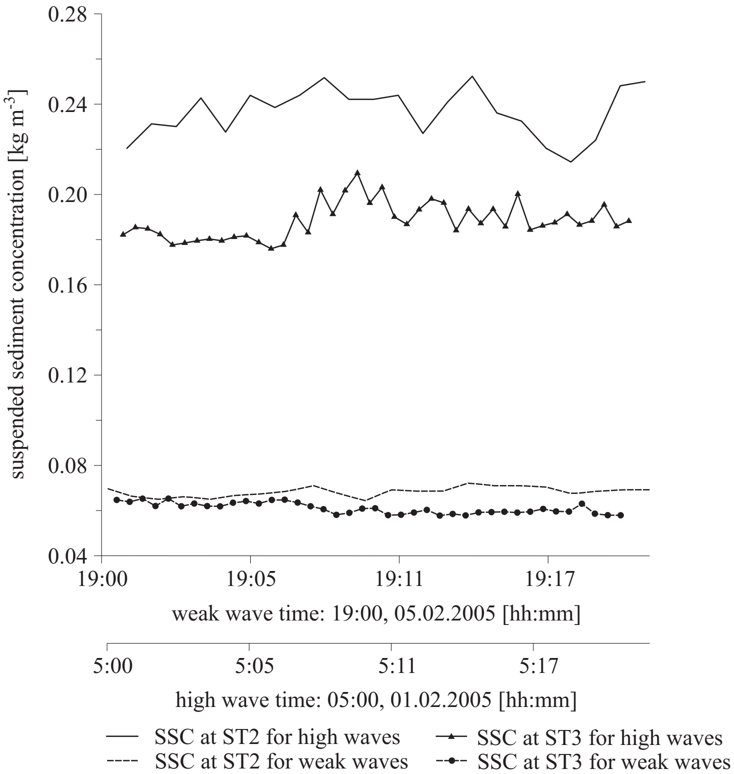


Fig. 9. Comparison of suspended sediment concentrations at ST2 and ST3 in the case of weak and high wave action

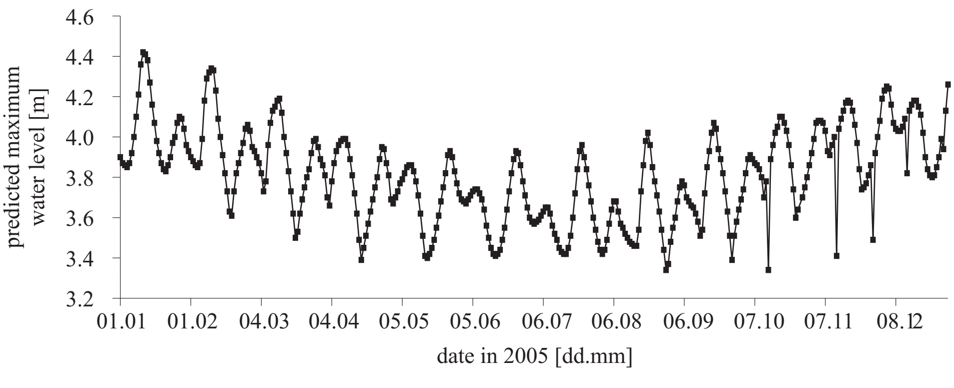


Fig. 10. Predicted maximum open-sea water level off Can Gio in 2005. (Source from Southern Regional Hydro-Meteorological Center, Vietnam)

almost all the waves will dissipate just beyond the mangrove edge (Hong Phuoc in prep.). Therefore, wave energy dissipation can cause movement of suspended sediment at the mangrove boundary itself.

Furthermore, waves will not be strong in the rainy season (from May to October), since the monsoon is from the SW. Fig. 10 also shows that annual water levels are lowest from May to October, which is equivalent to very shallow water or no water at all at the Nang Hai site.

Fig. 11 shows how the topography at Nang Hai changes during the year. Obviously, the rate of erosion changed rapidly, especially at the mangrove edge. Only in one year, the mangrove boundary shifted inwards about 3 m and this is the trend. Within the mangrove forest, erosion and accumulation along the transect were probably due mainly to current flows from neighbouring creeks. These results agree with the assessment of Mazda et al. (2002) of the coastal erosion in Long Hoa village, where the land has been eroded at a rate of approximately 50 m year^{-1} since the early 20th century.

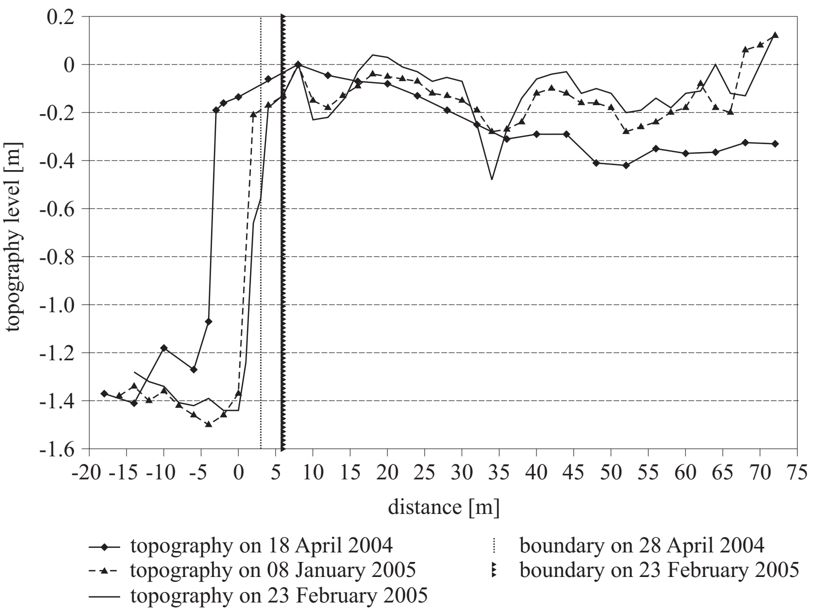


Fig. 11. Changes of topography at the Nang Hai site, Can Gio mangroves, in 1 year

4. Summary and conclusions

The Can Gio area has a complex convoluted network of rivers and creeks, with a irregular, semi-diurnal tidal regime, and is influenced by the equatorial monsoons. Therefore, river flows, rainfalls, tidal currents and wave action are the main factors forcing the movement of suspended sediments. Field measurements carried out at the Nang Hai site indicate that most of the energy dissipated within the mangrove forest is due mainly to wave-trunk interactions and wave breaking. Suspended sediment concentrations depend on the wave intensity and tidal current velocity. The results show that wave action is one of the main factors inducing sediment transport and erosion processes at Nang Hai; even the wave field in the Dong Tranh estuary is not so strong. Furthermore, the results also demonstrate that mangrove vegetation can encourage the deposition of sediment, or at least the retention of the flood-tide sediment influx. A comparison of the theoretical model with the experimental data as well as the determination of wave and tide-induced sediment transport in the mangrove forest will be presented in a separate paper, which is in preparation.

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