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HYDRODYNAMICS OF THE BANGRONG MANGROVE FOREST, PHUKET THAILAND

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ABSTRACT

Mangrove forests play a crucial role in transport processes between land and ocean. They trap, transform and modify solutes and particulates by physical, chemical and biological processes. Thus, the understanding of hydrodynamics in mangrove environments is crucial for assessing any possible impact on adjacent ecosystems. Forest bathymetry, meteorological data, salinity and water current profiles in the Bangrong mangrove forest, Thailand, were monitored during several tidal periods in the dry and wet seasons. The Bangrong creeks are partially well mixed with transient stratification. The salinity is significantly lower in the wet than the dry season due to variations in precipitation. A salinity maximum zone occurred in the upper reaches during the dry season impeding the mixing of water between the creek and coastal waters. Tidal currents were strong (up to 0.7 m^2 s^{-1}) and asymmetric as a result of a large tidal range (~2.5 m) and resistance of the dense mangrove vegetation. The ebb current was about ~15% stronger than the flood current with 5–30 minute delay of tidal phases between the outer and inner creek. A longitudinal diffusion coefficient, E, of 52 m^2 s^{-1} provided an estimated water residence time of about 2 days, which is in agreement with calculations based on evapotranspiration and mixing ratio.

INTRODUCTION

Mangrove forests are regarded as a transition zone between land and ocean. They act as filters for the exchange of suspended particles, nutrients and pollutants between these two systems (Tam and Wong, 1994; Furukawa *et al.*, 1997; Hagy *et al.*, 2000; Wattayakorn *et al.*, 2000). It is believed that mangrove environments promote primary productivity in the adjacent ocean by supplying important nutrients. Past studies have concluded that the amount of nutrient transport is difficult to quantify due to the heterogeneity and complexity of the system (Simpson *et al.*, 1997). However, reasonable estimates of nutrient mass transport can be provided through understanding hydrodynamics and material behavior in mangrove waterways.

Mangrove forest hydrodynamics is generally controlled by tides, mangrove vegetation and creek geometry (Hoguane *et al.*, 1999). Friction from dense mangrove vegetation causes tidal asymmetry, with strong and dominating ebb flow (Mazda *et al.*, 1995), which maintains deep self-scouring of the tidal channels (Wolanski *et al.*, 1980). Cross sectional current profiles of creeks usually show significant lateral or vertical variations due to channel geometry and bathymetry (Valle-Levinson and Atkinson, 1999). These variations in water velocity cause transverse and vertical shear stress, which are important for the mixing of creek water (Uncle *et al.*, 1985). The residence time of water in mangrove forests is highly dependent on forest topography, size, type and thus hydrodynamics. It can vary from few days in small fringe forests exposed to large tidal variations like the Klong Ngao in Thailand (Wattayakorn *et al.*, 1990) to more than a month in large fringe mangrove forests in Australia (Wolanski *et al.*, 1990).

This paper aims to describe the hydrodynamics in the Bangrong mangrove forest. Salinity distributions are discussed in relation to mangrove geometry and meteorological data. Current velocities at different tidal stages during spring and neap periods were compared. Residence time of the system was then calculated based on estimated longitudinal diffusion coefficient.

METHODS

Study site

The Bangrong mangrove forest is a 2.5 km^2 fringe forest, located on the northeast coast of Phuket Island (8° 03′ N and 98° 25′ E, Fig. 1). The creek area is 0.4 km^2 and consists largely of a 3 km long main creek. The area receives no river discharges and the source of freshwater originates from direct precipitation and run-off from land. The climate in the area is monsoonal with a wet season from May to November and a dry season from December to April. The tide in the area is semi-diurnal with 1.85 m mean tidal range; 0.83 m mean neap tide and 2.27 m mean spring tide (Sojisuporn, pers. comm.). The dominant mangrove species are *Rhizophora apiculata*, *Ceriops tagal*, *Xylocarpus granatum* and *R. mucronata*.

Hydrography

The bathymetry of the main creek was determined with an echo sounder at 7 stations along

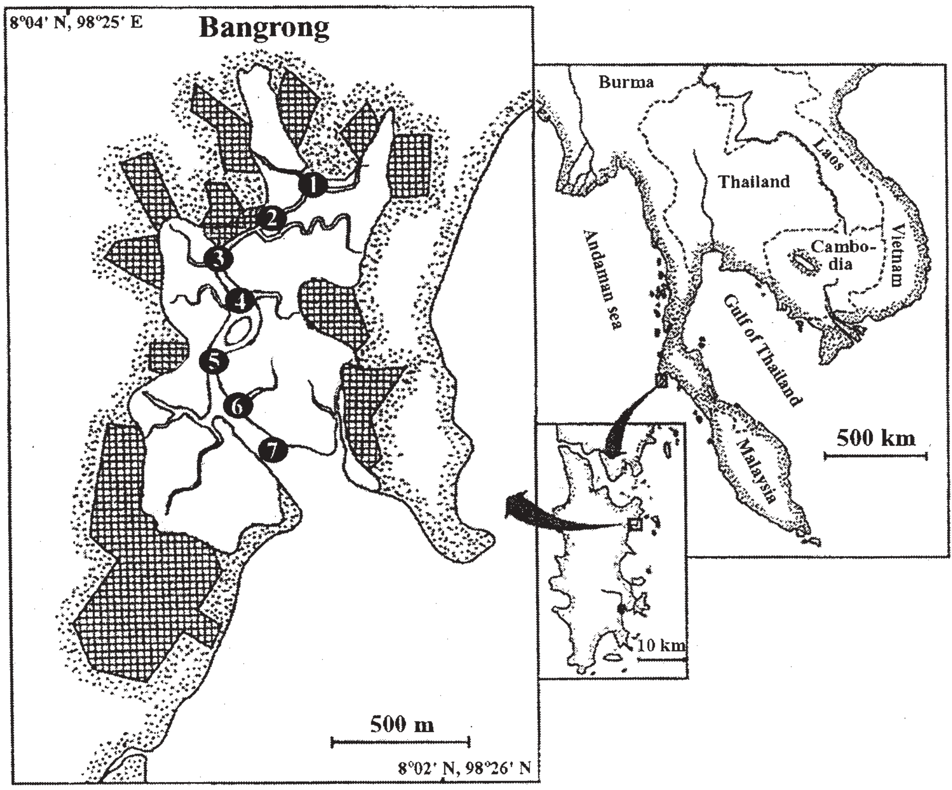

Figure 1 Map of the Bangrong mangrove estuary showing stations 1–7.

main creek. The topography of the mangrove was surveyed during low tide along the main creek bank using a Nikon theodolite model Total Station ATM A20LG. The height of the creek bank was measured at about 200 m intervals from the outer creek (sta. 7) to the inner creek (sta. 2).

Cross-section current profiles at station 5 (Fig. 1) were measured at 1.5 hr intervals (4 replicates each) for 25 hours on 3 occasions (23 Feb, 11 Mar and 16 Mar 1999) using RDI 300 kHz broadband Acoustic Doppler Current Profiler (ADCP). A metal wire was tied across the creek above highest high water. The ADCP, mounted on a floating unit, was then towed to the metal wire and dragged from side to side at a speed of 0.3 m s^{-1} (about 2.5 minutes per cross section). While the ADCP was deployed at station 5, two Oceanic propeller current meters model SD2000 were deployed 1 m below the water surface in the middle of the creek at stations 2 and 4. Current velocity at station 5 was also measured 1 and 2 m below the water surface by propeller current meters during spring tide (28 Jan 98) and neap tide (4 Feb 98).

Longitudinal salinity profiles along the length of the main creek were measured at high and low water both during spring and neap tide in the wet season (16 August 1996 and 4 October 1996) and the dry season (18 December 2000 and 25 December 2000) using a TOA multi-parameters probe model WQC-22A. The profiles were made at 20 cm intervals from surface to bottom at the outer station first and then at every 200 m to the inner station. In addition, a routine monitoring program was assigned to measure salinity 1 m below water surface, every month during high and low water at all stations.

Finally, time-series data of water level and salinity were collected simultaneously recording at 5-minute intervals at stations 2 and 7, in both the dry season (2–20 Mar 2000) and wet season (24 Aug–5 Sep 2000), using a water quality checker model Sonde4 and SBE19.

Meteorological data

Monthly air temperature, evaporation, precipitation, wind speed and wind direction from year 1996–2000 were obtained from the Phuket meteorological station located about 15 km northwest of the study site.

RESULTS

Bathymetry

The mouth of the main creek (sta.7) was wide (~100 m) and shallow (~3 m deep during the highest high water) except for a narrow channel (~4 m deep) on the eastern side (Fig. 2). The creek narrowed at the inner stations (~60 m wide at sta. 4, 5 and ~20 m wide at sta. 1–3) with the deepest part (~7 m) at sta. 4 near the junction of two branches of the main creek surrounding a small

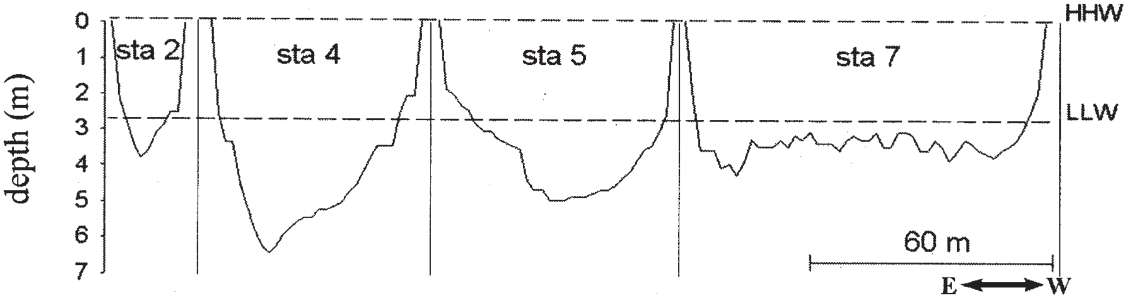

Figure 2 Cross-section bathymetry in the main creek at stations 2, 4, 5 and 7; HHW = highest high water; LLW = lowest low water.

island (Fig. 2). There were several small tributaries along the main creek and most of them were connected with shrimp farms. The mangrove forest between stations 2 and 3 had been cut to provide space for new shrimp farms. The banks in the inner creek (sta. 2) were elevated about 70 cm above those in the outer creek (sta.7) giving a slope of 0.30 m km^{-1}.

Meteorological data

The weather in the area is monsoonal, the wind direction in the dry season (Northeast monsoon) is ~90° North, with the maximum wind speeds of 11 ± 3 m s^{-1}. While in wet season (Southwest monsoon), the wind direction is ~270° North, with the maximum wind speeds of 14 ± 4 m s^{-1}. The average humidity was 82 ± 5 %. The monthly air temperature ranged from 24.7 to 30.2 °C, with an average of 27.8 °C (Fig. 3). The start of the wet season was defined by a monthly precipitation higher than 200 mm which occurred between April and June during the study period (1996–1999). The average monthly precipitation was 208 ± 148 mm (78 ± 88 mm in dry season and 315 ± 111 mm in wet season). The highest rainfall, 531 mm, occurred in August 1998. The average monthly evaporation was 130 ± 27 mm (151 ± 26 mm in dry season and 114 ± 19 mm in wet season). In the dry period, evaporation exceeds precipitation (Dec–April), while in wet period precipitation exceeds evaporation (May–Nov). It was noted that on some occasions during dry season (Feb–Apr 98) there was no precipitation at all.

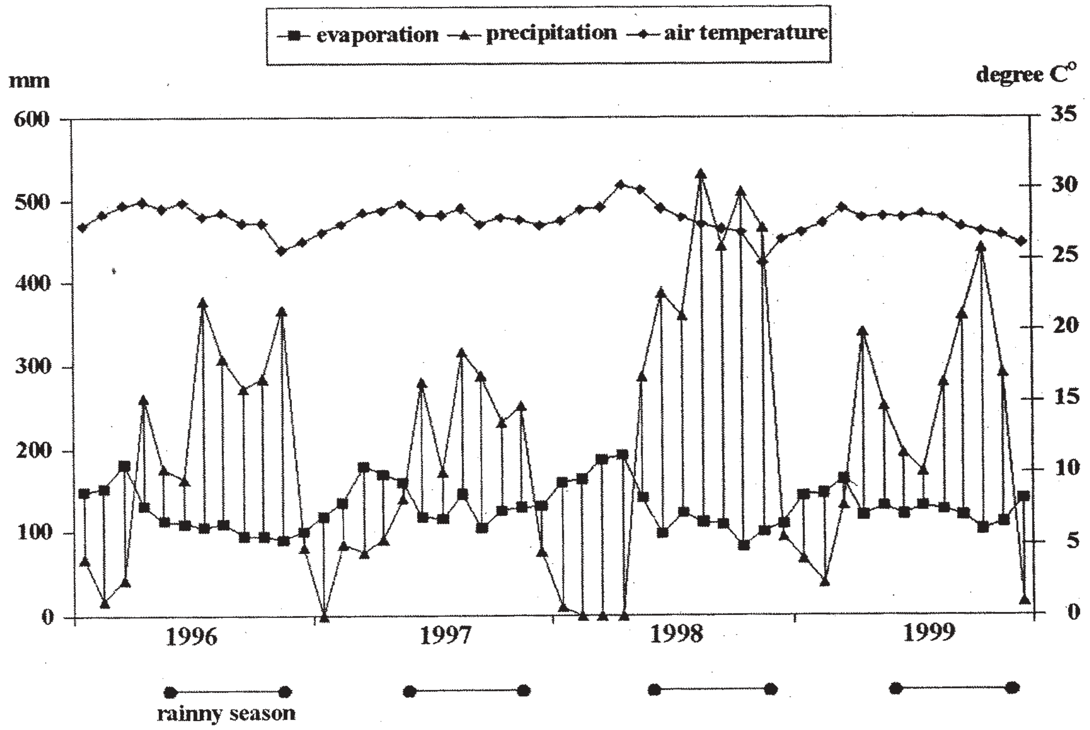

Figure 3 Time series of monthly evaporation (mm), monthly precipitation (mm) and monthly average air temperature (°C) from January 1996–December 1999. The vertical line denotes the difference between evaporation and precipitation.

Salinity distribution and profile

The average salinity at high and low tide were 28.0 ± 4.0 and 21.3 ± 4.5 PSU, respectively, in the wet season and 30.8 ± 1.8 and 29.1 ± 4.5 PSU, respectively, in the dry season. The lowest salinity (5 PSU) was experienced during a low tide in August 1998. The salinity was significantly different ($p<0.001$) between seasons and between tidal periods (high/low water). The salinity in the inner creek was always lower than in the outer creek during the wet season giving a gradient of ~2.2 PSU km^{-1} (Fig. 4). In contrast, the salinity in the inner creek was similar to or higher than that in the outer creek during the dry season (*e.g.*, 32.2 versus 31.8 PSU, March 1999) when evaporation caused the salinity in the inner part of the system to rise. Although the water in the creek was continuously mixed with oceanic water of constant salinity from Phang Nga Bay, salinity in the inner creek increased steadily from 32.2 to 33.2 PSU during a 10 day dry period in March 2000 (Fig. 5). The corresponding salinity increase in the outer creek was only 0.3 PSU during the same period.

The longitudinal salinity profiles in both wet and dry seasons showed that the Bangrong main creek acted as a partially well mixed tidal estuary. The buoyancy effect that hampered the mixing of fresh water in the headwater with incoming salt water was observed in both seasons. During low tide, the isohalines were inclined towards the ocean (Figs. 6a, 6c, 7a and 7c) but the water became vertically well mixed again at high tide (Figs. 6b, 6d, 7b and 7d). Although the mean salinity in general was influenced by the seasonal cycle with lowest salinity in the wet season (Fig. 4), the salinity at any specific time was closely linked to

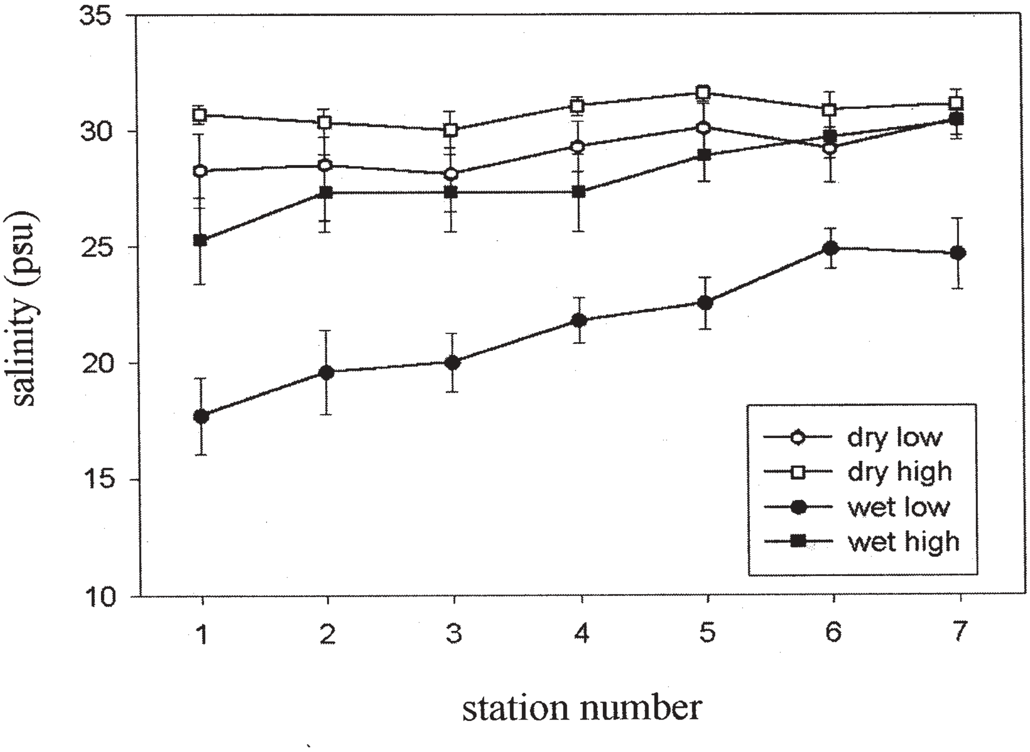

Figure 4 Salinity (Mean ± SE, n = 7–11) of the surface water, 1-m depth, at stations 1–7, during high and low tide in wet and dry seasons.

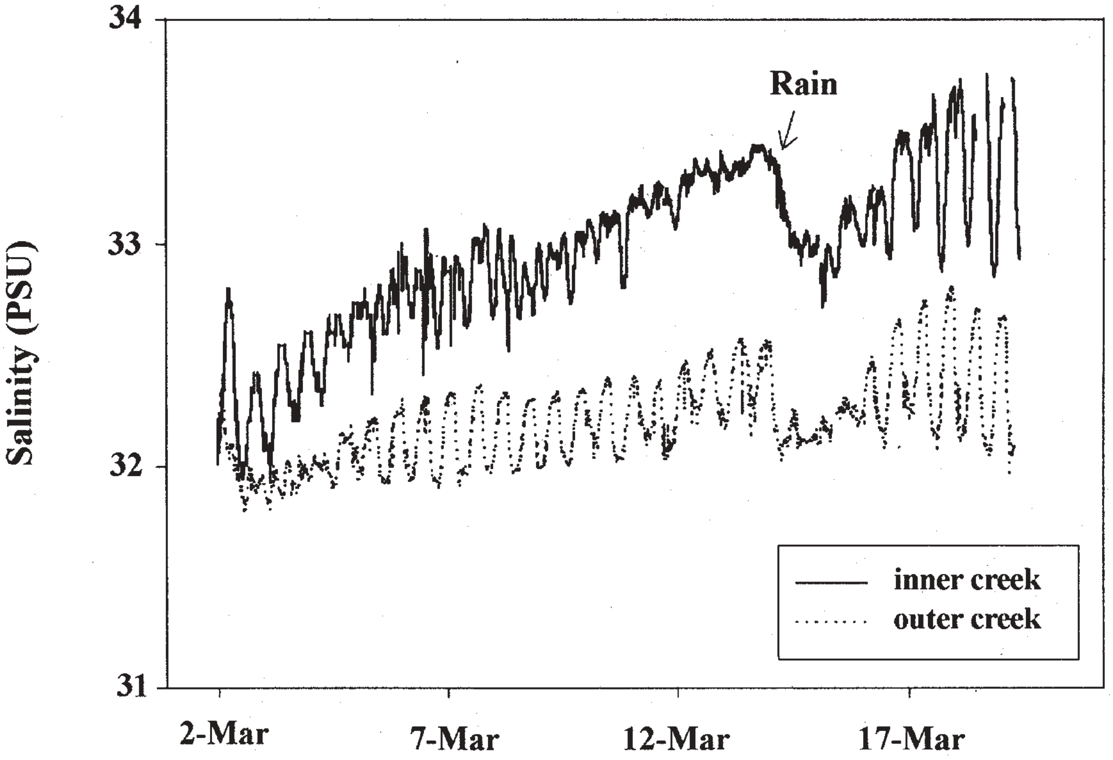

Figure 5 Time series of salinity at station 2 (inner creek) and station 7 (outer creek), from the 2nd –20th March 2000.

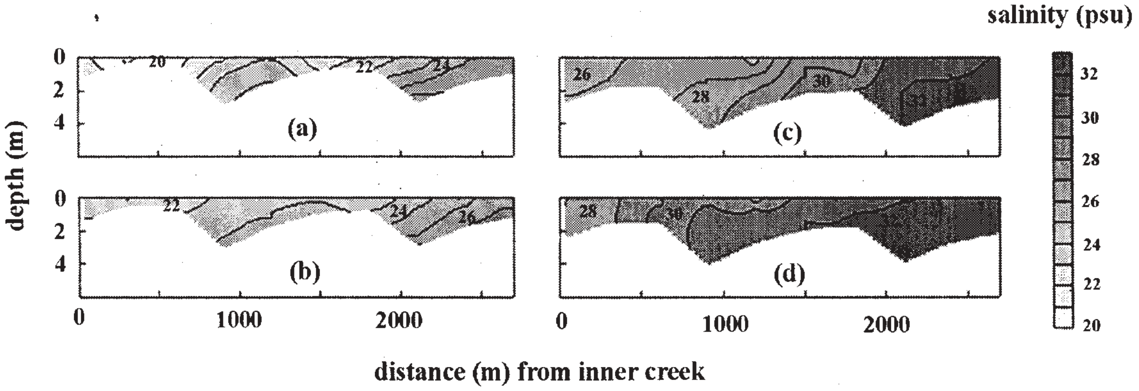

Figure 6 Longitudinal salinity profile during wet season; (a) neap low tide; (b) neap high tide; (c) spring low tide and (d) spring high tide.

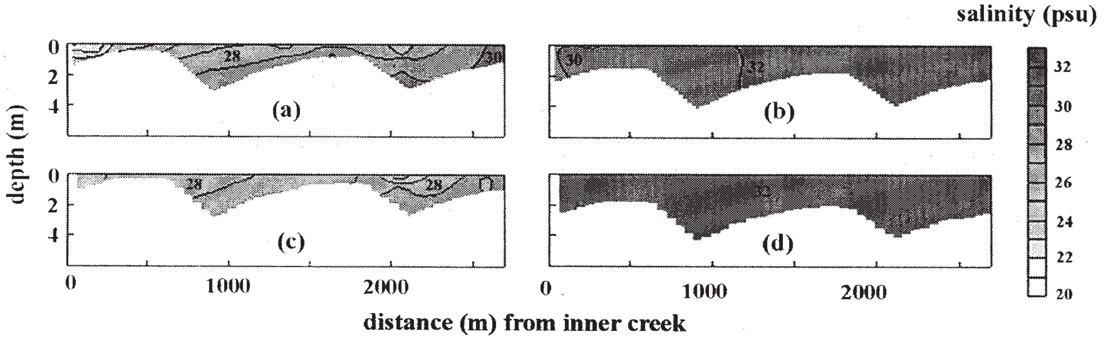

Figure 7 Longitudinal salinity profile during dry season; a) neap low tide; b) neap high tide; c) spring low tide and d) spring high tide.

rainfall during the preceding days with the highest correlation being obtained with the past 7-day rainfall period.

Water currents and discharges

The tidal current in the main creek was strong and asymmetric (Fig. 8). The peak ebb current was about 15% stronger than the peak flood current. The maximum current speed, 0.7 m s^{-1}, was recorded in the outer creek (sta. 5) during spring ebb tide on 16 Mar 1999; the current decreased to 0.6 and 0.3 m s^{-1} in the middle (sta. 4) and inner creek (sta. 2), respectively. There were 5–30 minutes tidal phase delays between the outer and inner creek (Fig. 9). The tidal amplitude decreased 5–10% in the inner creek when compared with the outer creek. The magnitude of the time lag and the amplitude decrease was positively related to the amplitude of the tidal range.

The maximum storage volume of water in the system was *ca.* 1.25 x 10^6 m^3, of which about 80% was in the swamp area. It should be noted that in this context the entire mangrove system is defined here as the area inside the boundary given by sta. 7. During the highest water level, the creek banks were covered by about 1 m of water. Thus, the determination of storage volume and water discharge is very dependent on the tidal amplitude. During neap tide periods, when the swamp was not flooded (<2 m tidal height) the discharge only originates from the creek (23–24 Feb 99 and 11–12 Mar 99, Fig. 10). However when water floods the swamp during spring tide, the discharge is substantially higher due to large storage capacity within the swamp area itself (16–17 Mar 99).

DISCUSSION

Hydrodynamics in the Bangrong mangrove area are modified by the mangrove forest as a result of friction created by the mangrove vegetation (Mazda *et al.*, 1995). The impact of the vegetation on physical parameters is evident as strong ebb current, asymmetry in flood and ebb tides and a time lag in a tidal phase between inner and outer creek. Similar conditions have been reported from other mangrove environments (Wattayakorn *et al.*, 1990 and Wolanski *et al.*, 1990).

Flushing time

When there is no precipitation and fresh water runoff during the dry season, flushing of water in the inner part of the mangrove creek is mainly due to tidal diffusion, which is controlled by the trapping effect in the mangrove swamp (Wolanski and Ridd, 1986). The tidally-average longitudinal diffusion coefficient, *E*, can be determined according to the model of Wolanski *et al.* (1990) of:

$$E = \varepsilon \mu^2 a_l \tau / 48(1+\varepsilon) \qquad (1)$$

where τ is duration of the tidal period (12.42 h for semi-diurnal tides); ε is the trap volume (vegetation

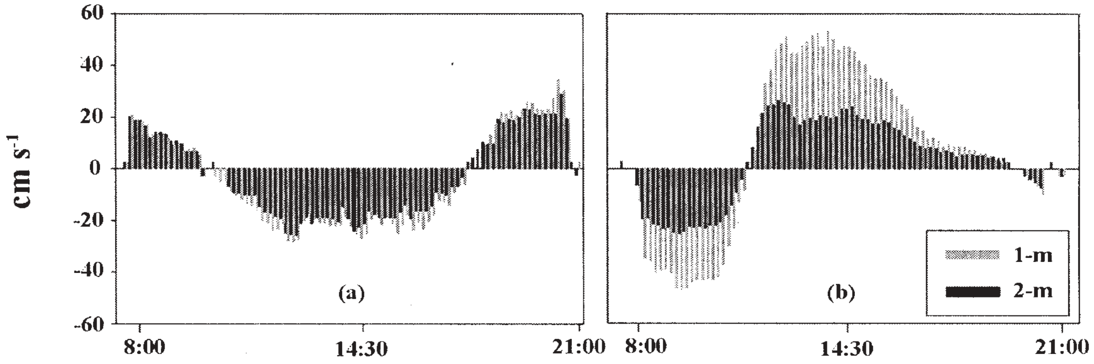

Figure 8 Current velocity at station 5 at 1 and 2 m below water surface during (a) neap tide, 4 Feb 98 and (b) spring tide, 28 Jan 98.

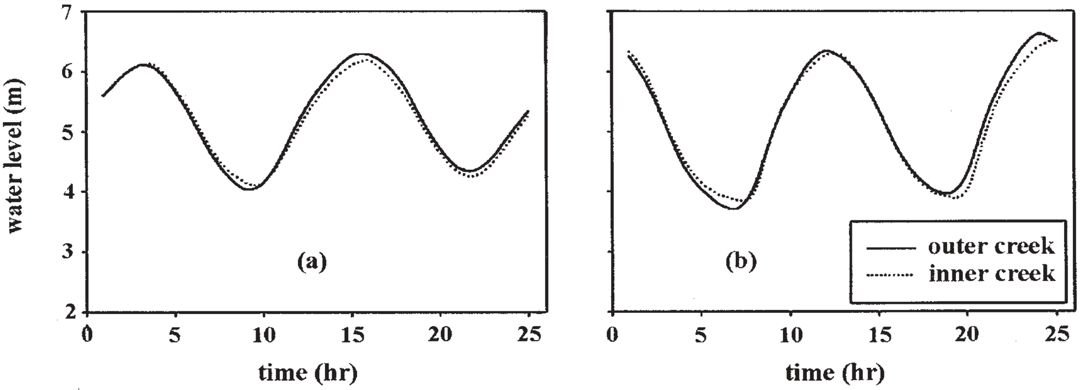

Figure 9 Comparison between water level at station 2 (inner creek) and station 7 (outer creek); (a) neap tide and (b) high tide.

swamp) to channel volume ratio; a_l is the immersion time ratio given as the fraction of a tidal cycle when the swamp is immersed and *m* is the peak flood tidal current. Based on the estimated values of $\varepsilon \sim 4$, $a_l \sim 0.2$, $\mu \sim 0.6$ m s^{-1}, the value of *E* is calculated to 52 m^2 s^{-1}. From the longitudinal diffusion coefficient, the residence time, *T*, of the water in the creek can be obtained according to:

$$T = l^2/E \qquad (2)$$

where *l* is the length of the system which is about 3 km for the Bangrong mangrove forest. Although the estimated value of *E* is crude and should only be considered a rough approximation (Wattayakorn *et al.*, 1990), the presently obtained $T = 2$ days is in close agreement with values of 1–2 days obtained by Kristensen and Suraswadi (unpubl.) from the system using production and concentration of ammonium. The water residence time can also be estimated from predicted and observed salinity changes. Without precipitation and freshwater runoff from land, evapotranspiration and mixing processes control salinity in the mangrove system. Evapotranspiration, which causes the salinity to increase, is counteracted by tidal mixing and dilution with water exchanged

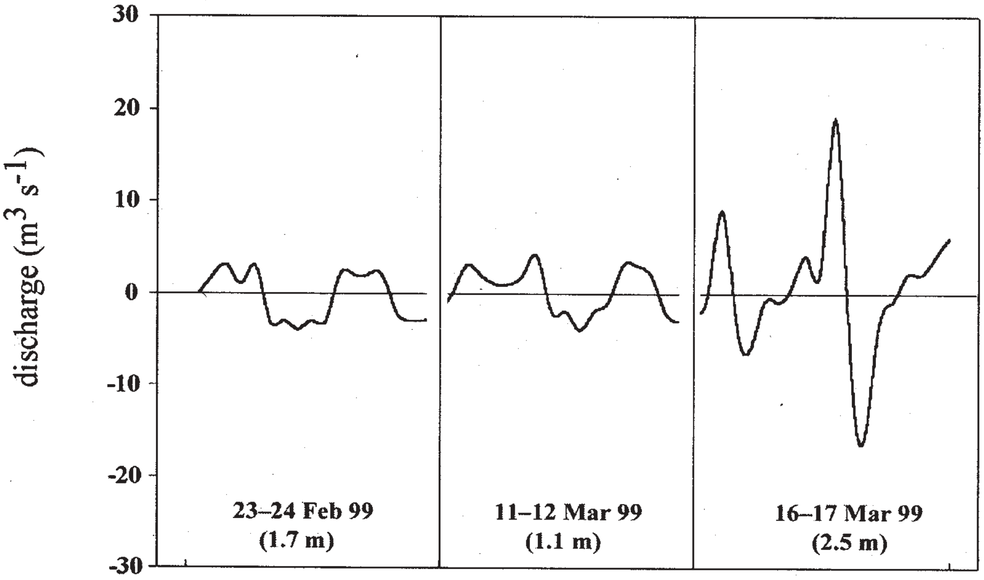

Figure 10 Discharged water measurement at the pier, station 5, during neap tide (11 Mar 99) spring tide (16 Mar 99) and in between (23 Feb 99); positive denotes ebbing tide, while negative denotes flooding tide.

across the outer boundary. Assuming no water mixing between mangrove water and the outer boundary water, the salinity in the mangrove system increases as the water evaporates. The predicted mean daily salinity change ΔS_p of the water mass affected by evapotranspiration can be calculated as:

$$\Delta S_p=[(V_s S_{init}) / (V_s-E_v A_b)] - S_{init} \qquad (3)$$

where Vs is the system volume; S_{init} is the average initial salinity when the system is completely mixed with oceanic water; E_v is the evapotranspiration rate and A_b is the basin area. When $V_S \sim 1.25 \times 10^6$ m^3, $A_b \sim 1.8 \times 10^6$ m^2, $S_{init} \sim 32.2$ PSU as found for Bangrong and $E_V \sim 0.5$ cm day^{-1} as found in other mangrove forests (Ridd *et al.*, 1990; Wattayakorn *et al.*, 1990; Hoguane *et al.*, 1999) a ΔS_p of 0.23 PSU is obtained.

When water mixes with the outer boundary water, the predicted salinity change, ΔS_p, clearly overestimates the observed value. The observed salinity change depends on the magnitude of the mixing process, *i.e.* the mixing ratio, M_x, which is the ratio between the observed and predicted salinity change. The mixing ratio can be calculated as:

$$M_x=\Delta S_{obs} / \Delta S_p \qquad (4)$$

where ΔS_{obs} is the average daily change of observed salinity (0.1 PSU). By applying these values, a mixing ratio of 0.43 is obtained, which implies that on average 43% of the mangrove water is exchanged daily. Thus, the residence time of the water in the system is then ~2.3 days which is close to the residence time obtained from the longitudinal diffusion coefficient.

During normal rainy periods in the wet season, the mangrove area receives ~0.2 $m^3 s^{-1}$ of fresh water, while during storm events this can increase to 2.5 $m^3 s^{-1}$ when runoff from land becomes significant. This input is substantial considering an average tidal discharge of 3 $m^3 s^{-1}$. For example, during one storm incident in August 1998, the salinity dropped to 5 PSU at station 5, which implies that the entire system was almost completely flushed by freshwater. Thus the residence time of water in the Bangrong mangrove forest varies considerably in space and time, ranging from few hours in the outer creek or during rainy periods to few days in the inner creek.

CONCLUSIONS

Bangrong is a small mangrove environment with a high fraction of pristine forest, although parts of the forest have been converted to shrimp farms. The salinity in the wet season is significantly lower than in the dry season due to variations in precipitation. A salinity maximum zone develops in the upper reaches during periods of no precipitation in the dry season. The Bangrong main creek is partially well mixed with a transient stratification during low tide, and becomes completely mixed during high tide. The tidal current in the main creek is strong (up to 0.7 m^2 s^{-1}) and asymmetric due to the large tidal range and dense mangrove vegetation. The ebb current is about 15% stronger than the flood current with a 5–30 minute delay of the tidal phases between the outer and inner creek. A tidally-average diffusion coefficient ($\dot{E}$ of 52 m^2 s^{-1}) can be calculated in dry periods when only tidal flushing of the inner creek occurs. As a consequence the residence time of water is estimated to be about 2 days, which is in agreement with calculations using evapotranspiration and the mixing ratios.

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