

## Sedimentation in mangrove forests

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### Abstract

The tidal currents in mangrove forests are impeded by the friction caused by the high vegetation density. The tidal currents are also complex comprising eddies, jets and stagnation zones. The sediment particles carried in suspension into the forest during tidal inundation are cohesive, mainly clay and fine silt, and form large flocs. These flocs remain in suspension as a result of the turbulence created by the flow around the vegetation. The intensity of sedimentation is largest for trees forming a complex matrix of roots such as *Rhizophora* sp. and smallest for single trees such as *Ceriops* sp. The flocs settle in the forest around slack high tide. At ebb tides the water currents are too small to re-entrain this sediment. Hence the inundation of coastal mangrove forests at tidal frequency works as a pump preferentially transporting fine, cohesive sediment from coastal waters to the mangroves. Mangroves are thus not just opportunistic trees colonising mud banks but actively contribute to the creation of mud banks.

### Introduction

Mangrove forests are a buffer zone between the coast and the ocean. One of their presumed important functions is to provide a mechanism for trapping sediment. Suspended sediment is introduced to coastal areas by river discharge, dumping of dredged material and resuspension of bottom sediment by waves and ships (Holeman, 1968; Laronne and Mosley, 1982; Wolanski, 1994). Mangrove forests are believed to be an important sink for suspended sediment (Woodroffe, 1992; Wolanski *et al.*, 1992; Furukawa *et al.*, 1996; Wolanski, 1994; Wolanski, 1995).

Most coastal mangrove forests are connected to the sea via a tidal creek. Sediment transport mechanisms in these creeks have been investigated in detail. These mechanisms are dominated by hydrodynamic processes, as opposed to biological processes which prevail further offshore (Ayukai and Wolanski, 1996), and include the asymmetry of the tidal currents, the baroclinic circulation and shear-induced destruction of flocs (Gibbs, 1985; Woodroffe, 1985; Dyer, 1986; Wolanski *et al.*,

1988; Wolanski, 1995; Wolanski *et al.*, 1995; Wolanski and Gibbs, 1995; Mazda *et al.*, 1995). Sediment transport mechanisms in mangrove forests have received little attention though observations suggest a net inflow of fine sediment in mangroves (Furukawa *et al.*, 1996). The flows through mangrove forests are sluggish as a result of the high vegetation density increasing friction (Wolanski *et al.*, 1980; Mazda *et al.*, 1995 and 1996). In these latter studies, only overall friction coefficients have been estimated by averaging spatially over several tens of roots, tree trunks and pneumatophores. There have been no previous studies of the details of these flows around the vegetation and their role in the process of sedimentation in mangroves.

It has never been clear whether mangroves create their own environments (mud banks) or whether they are simply opportunistic colonisers of mud banks generated by other geomorphological processes. From a detailed study of flows through a mangrove forests and the resulting sedimentation processes, we show that mangroves actively create their own ecosystems by trapping

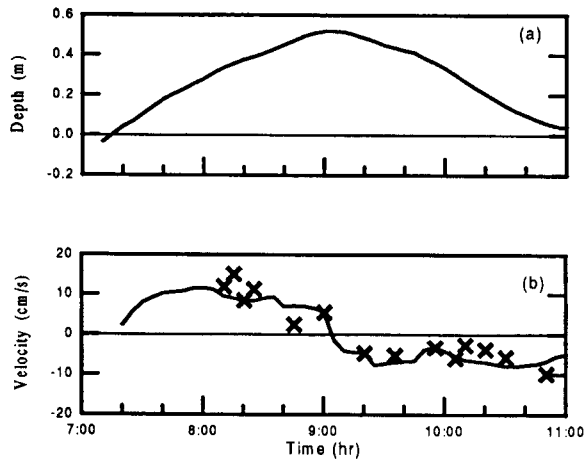


Fig. 1. Time series of (a) water depth and (b) observed (x) and numerically predicted (line) velocity at our study site in Cairns mangroves. Time is in hour on December 3, 1994.

sediment. The trapping mechanism is due to the high micro-turbulence created by the flow around the vegetation maintaining sediment in suspension at flood tidal currents. This sediment settles near the time of slack water high tide when turbulence vanishes. This sediment is not re-entrained by ebb tidal currents which are too sluggish because of the high vegetation density.

### Tidal pumping

Our study site was the mangroves along the Cairns boardwalk, in wet, tropical Australia (see details in Furukawa *et al.*, 1996). The area is populated by a fringe of *Rhizophora* sp. trees along the banks of the tidal creek and by *Ceriops* and *Avicennia* trees further inland. The width of the mangrove forest is about 150 m. Macro-tides prevail, peaking at 3.5 m peak to trough, during which water depth never exceeds 1 m in the mangroves.

The water currents in the mangrove forest were controlled by the tides. Water spilled over from the tidal creek to inundate the forest at flood tide, this water drained back in the tidal creek at ebb tide (Fig. 1). The currents through the forest were sluggish, seldom exceeding  $0.1 \text{ m s}^{-1}$ . The driving force for this flow is the water surface slope  $I$  (i.e. the slope of the water surface from the tidal creek into the forest, Fig. 2) and the retarding force is the friction. The total friction is the sum of that at the

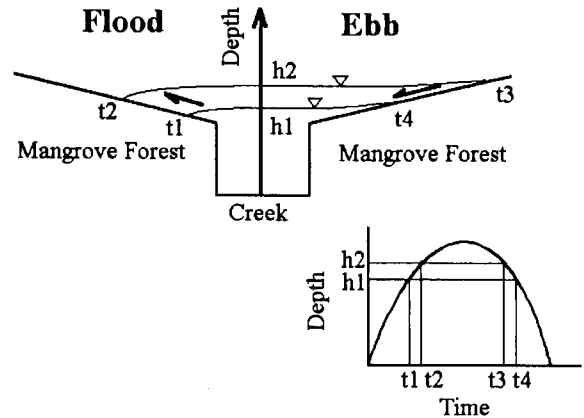


Fig. 2. Sketch of the water elevation in a tidal creek-mangrove swamp system at flood tide and ebb tide. The water surface slopes towards the creek at ebb tide but towards the mangroves at flood tide.

bottom and that caused by the flow around the tree trunks, roots and pneumatophores. These flows are complex, with eddies, jets and stagnation zones. Details of these micro-scale flows vanish if we average spatially over many roots, trunks and pneumatophores, so that only net currents remain. Inertia is negligible for these net currents because the flows are sluggish and the friction force balances the force created by the water surface slope. Thus

$$u = \frac{1}{n} h^{2/3} I^{1/2} \quad (1)$$

where  $u$  is the water velocity,  $n$  is the spatially-averaged Mannings friction coefficient,  $h$  is the water depth and  $I$  is the water surface slope.

The Mannings friction coefficient,  $n$ , is an important engineering parameter and has been the focus of much research by hydraulics engineers working with rivers and channels (e.g. Chow, 1959). Typical values of  $n$  for sandy channels are in the range 0.025-0.035. The value of  $n$  is believed to diminish for decreasing grain size of the sediment and indeed muddy estuaries can have an even smaller value of  $n$  ( $n=0.015$ ; see King and Wolanski, 1995; Lixian & Wolanski, 1996). Hence, if only bottom friction was important, at first glance the value of  $n$  should be  $<0.025$  in mangroves where the dominant sediment is mud. In fact that is not the case because flows around the vegetation increase friction. Wolanski *et al.* (1980)

and Wolanski *et al* (1992) found  $n=0.2-0.4$  from field observations and  $n=0.25$  from model studies in a heavily vegetated mangrove swamp at Hinchinbrook Island, Australia. Mangroves are as heavily vegetated as salt marshes and several authors have also reported a high value of the Mannings friction coefficient in such systems. Indeed, Burke and Stolzenbach (1983), Kjerfve *et al.* (1991) and Hosokawa and Furukawa (1994) modelled spatially-averaged flows through dense vegetation of *Spartina* salt marshes and deduced  $n=0.1-0.2$ .

Observed and predicted (assuming  $n=0.1$ ) currents at our study site compare favourably (Fig. 1). Thus the vegetation increases Mannings friction coefficient by a factor of at least 5, hence the friction force by a factor of at least 25, from that expected for non-vegetated surfaces. This effect in turn inhibits water flows and the small velocities, seldom exceeding  $0.1 \text{ m s}^{-1}$ , that result are unable to resuspend the fine cohesive sediment for which a peak velocity of  $0.3 \text{ m s}^{-1}$  is needed (Wolanski *et al.*, 1995). What causes a sediment pump is, as shown below, the high turbulence as a result of complex flows around the vegetation which maintaining sediment in suspension until settling occurs at high tide.

### Observed sedimentation rates

The net sedimentation rate at spring tides was measured at our study site on a transect from the bank of the tidal creek to the tidal limit in the mangrove forest. It decreases exponentially with distance,  $x$ , from the creek (Fig. 3).

This exponential decrease results from simple hydrodynamics. Sediment settles at a rate  $w_o C$ , where  $w_o$  is the settling velocity and  $C$  the suspended sediment concentration. The system is driven by the inflow of water from the creek, the water flowing into the mangroves at a velocity  $u$  over a depth  $h$ . At the creek bank the suspended sediment concentration is  $C_o$  and this is controlled by the dynamics of the tidal creek. The concentration of suspended sediment  $C$  in the waters in the mangroves decreases with distance from the creek because it progressively settles out, so that from continuity of sediment flux,

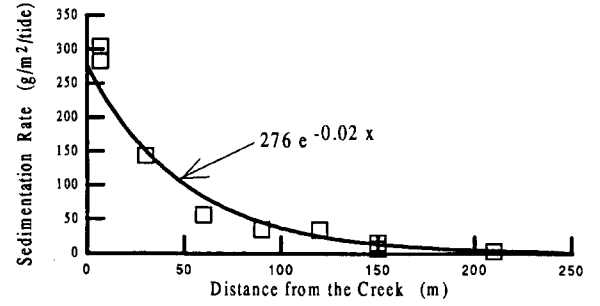


Fig. 3. Observed (□) and numerically predicted (line) sedimentation rates across the Cairns mangrove with distance from the tidal creek, for the spring tide of December 3, 1994.

$$C = C_o \exp \left[ -\frac{w_o x}{hu} \right] \quad (2)$$

where  $x$  = the distance into the mangrove forest from the tidal creek.

The sedimentation rate  $S$  is calculated from equation (2) as

$$S = -\frac{d(Chu)}{dx} = C_o w_o \exp \left[ -\frac{w_o x}{hu} \right] \quad (3)$$

and the predicted sedimentation rate matches the observations well (Fig. 3). The predicted sedimentation rate was calculated assuming from the field observations that  $h=0.4 \text{ m}$ ,  $u = 0.1 \text{ m s}^{-1}$ , and  $w_o = 0.0005 \text{ m s}^{-1}$ .

This simple model shows that nearly all the suspended sediment that entered the mangrove forest from the tidal creek, settled in the forest and was not re-entrained and exported at ebb tide.

It must be noted that we assume the sediment in the water column at point  $x$  is vertically well mixed by turbulence caused by mangrove roots and undulation of the bed. This assumption is justified by laboratory measurements for vertical velocity distribution in the *Spartina anglica* canopy which shows high complexity of the flow (Shi *et al.*, 1995). Woolnough *et al.* (1995) on the contrary, assume quiescent settlement, and get arc-tangential function for sedimentation rate for the salt marsh. The assumption of quiescent settlement has a risk of an over-estimate of settlement at the creek side and an under-estimate of settlement distant

from the creek for well mixed water. Thus, the selection of the settlement process is an important matter.

We show below that the high settling velocity of the suspended sediment is due to flocculation.

### Flocculation

The particle size distribution of the suspended sediment at the study site shows the sediment to be muddy silt, composed mainly of fine silt and clay (Fig. 5) with a mean diameter of 5.6  $\mu\text{m}$ , 40% by volume of the sediment being  $< 4 \mu\text{m}$  and 20% less than 2  $\mu\text{m}$ . If these sediment particles were not aggregated in flocs, their settling velocity as calculated by Stokes law would be around  $0.00008 \text{ m s}^{-1}$ .

This very low value of the settling velocity is however unrealistically low because in fact the sediment was flocculated. At our study sites, floc size was measured by two techniques, namely the special sampling slide - microscope technique of Gibbs and Konwar (1986) and in-situ micro-photographs. The latter technique samples less water and registers fewer flocs, can lead to loss of clarity particularly if flocs are packed too densely but has the advantage that it does not destroy flocs mechanically (Wells, 1989; Eisma *et al.*, 1990). Both techniques yielded similar results, which indicated that at least 99% of the suspended sediment was flocculated. The flocs in suspension at our study site (Fig. 4) had a loose structure, subdivided in zones of high and low density, and individual floc sizes varied between 30 and 300  $\mu\text{m}$ . Mean floc size was 100  $\mu\text{m}$  corresponding to a settling velocity of  $0.005 \text{ m s}^{-1}$  (Gibbs, 1985), this settling velocity is 100 times larger than that of the individual particles of clay and silt making up the floc.

Flocculation appears responsible for the rapid settling near high tide and the lower concentration in suspended sediment at ebb tide than at flood tide at our study site in the mangrove forest (Fig. 6). Most of the flocs settled within 30 min just prior to the high slack tide. The settlement removed preferentially (Fig. 6) the small particles ( $< 4 \mu\text{m}$ ), the largest (rare) particles ( $> 32 \mu\text{m}$ ) and all the large flocs ( $> 250 \mu\text{m}$ ) and over 90% of the large

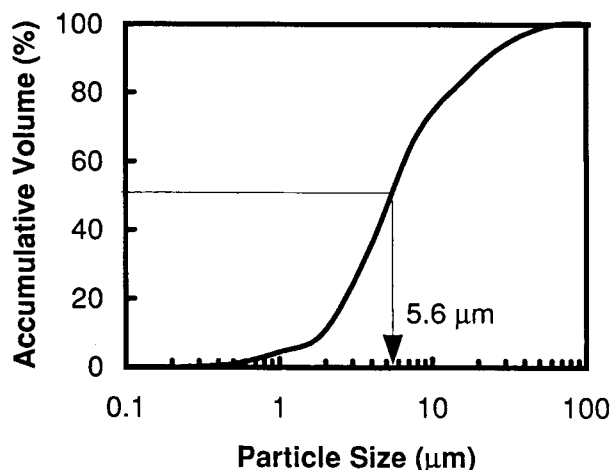


Fig. 4. Typical accumulative particle size distribution curve for suspended sediment in the water column at our study site.

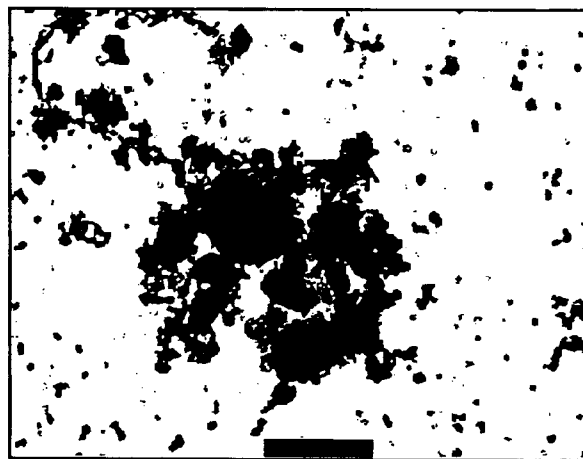


Fig. 5. Microphotograph of flocs in suspension in the water column at our study site in the mangroves. The bar represents 100  $\mu\text{m}$ . The darker areas in the flocs represent zones of high packing density of particles, the lighter areas zone of low packing density.

flocs ( $> 100 \mu\text{m}$ ). Thus preferential sedimentation of clay and fine silt occurred.

We show below that what maintained the flocs in suspension until near high tide was the high turbulence created by the water flow around tree trunks, roots and pneumatophores.

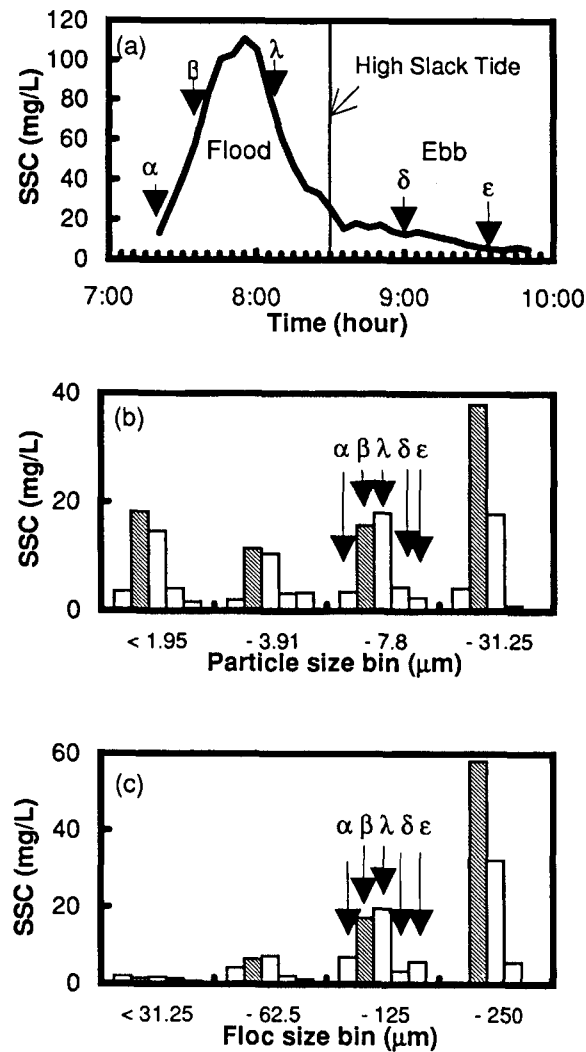


Fig. 6. (a) Time series plot of suspended sediment concentration (SSC) in the water column at our study site in the Cairns mangroves on December 2, 1994. (b) and (c) are respectively particle and floc size distributions for sampling times  $\alpha$ - $\epsilon$  (shown in Fig. 6a). The bin sizes for particle and flocs are different. The particle bin sizes are <1.95, 1.95-3.91, 3.91-7.8 and 7.8-31.25  $\mu\text{m}$ . The floc bin sizes are <31.25, 31.25-62.5, 62.5-125 and 125-250  $\mu\text{m}$ .

### Vegetation-induced turbulence

Observed flow patterns were visualised using downward-looking video cameras tracking small floats following the technique of Furukawa *et al.* (1996). The currents around the vegetation varied with the vegetation density. The simplest flows prevail around single tree trunks (e.g. *Ceriops* sp.)

and the most complex flows were found around the matrix of roots of *Rhizophora* sp.

Around *Ceriops* sp. (Fig. 7a) a wake was visible behind the tree. Such wakes are characterised by the Reynolds number

$$\text{Re} = \frac{UL}{\nu} \quad (4)$$

where  $U$  is the undisturbed velocity,  $L$  is the diameter of the tree trunk and  $\nu$  is the kinematic viscosity. For  $\text{Re} < 1$ , no bubble exist. A steady wake exist for  $\text{Re} < 100$ , but the water in the eddy is then nearly stagnant, while long wakes exist for  $\text{Re} = 100$ -400. Unsteady turbulent flows prevail for larger values of  $\text{Re}$ . Our data suggest  $\text{Re} = 100$ -400 in the field. Such flows are very turbulent with peak three-dimensional turbulent velocities of the same order as  $U$ . Indeed we visually observed zones of high upwelling and downwelling and other zones with high turbulence especially in the shear zones near the vegetation. This turbulence is sufficient to maintain the flocs in suspension.

For *Rhizophora* sp. the higher vegetation density generated more complex flows comprising jets, eddies and stagnation zones (Fig. 7b). Individual wakes behind roots interacted one with the other. Turbulence was intense in the region which the flow becomes jet, and sedimentation occurred preferentially in the stagnation zones.

The important parameter for calculating sedimentation rates in mangroves is the turbulent velocity. This was calculated using the numerical model of Furukawa and Wolanski (1996) for two-dimensional flows. The model *Rhizophora* root matrix comprised 19 roots each with a diameter of 0.04 m. Two undisturbed velocities  $U$  were chosen, 0.05 and 0.2  $\text{m s}^{-1}$ . The model is calibrated by its ability to reproduce mean flows obtained in the field (Fig. 7). The turbulent intensity is inferred from the model. For  $U = 0.05 \text{ m s}^{-1}$ , the turbulence is practically negligible and the wake effect is restricted to very small regions around each root (Fig. 8a). However for  $U = 0.2 \text{ m s}^{-1}$ , jet flows are formed, the jets are deflected by the vegetation to interact with each other, in agreement with observations (Fig. 7). The model predicts that in such conditions the turbulent intensity is 2-3 times larger than the mean velocity. This turbulence is three-

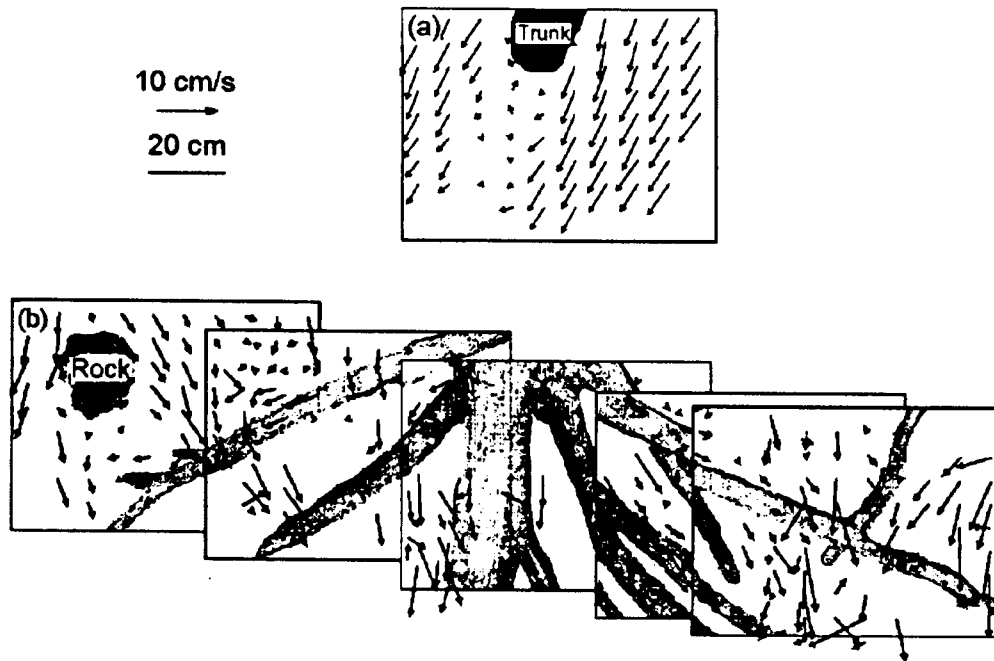


Fig. 7. Observed 1-min mean water velocities around mangroves for (a) *Ceriops* sp. and (b) *Rhizophora* sp. on December 3, 1994.

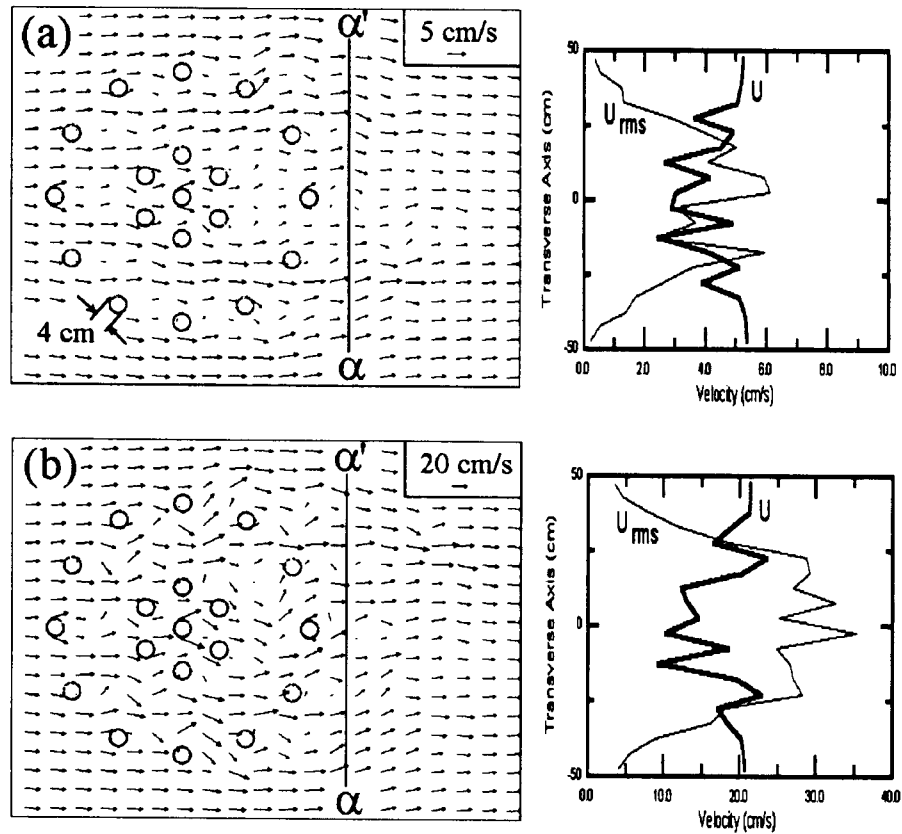


Fig. 8. (Left) Predicted horizontal velocities around a *Rhizophora* root matrix for an approach velocity of (a) 0.05 and (b) 0.2 m s<sup>-1</sup>. (Right) Mean velocity  $U$  and root mean squared velocity  $U_{rms}$  along the transect  $\alpha-\alpha'$  shown in the left figure. Note the stagnation zones and the jets interacting one with the other.

dimensional and is more than sufficient to keep the 100  $\mu\text{m}$  flocs in suspension.

## Conclusion

Mangrove forests are an important buffer between the sea and the land. They are not just passive colonisers of mud banks, but actively capture mud to create their own environments. The way they do this is to maintain high turbulence in the water flow through the forest; this high level of turbulence maintains in suspension the flocs of fine cohesive sediment which enter the forests at flood tide. Turbulent intensities are the largest for trees forming a complex matrix of roots such as *Rhizophora* sp. and smallest for single trees such as *Ceriops* sp. Sedimentation occurs when turbulence vanishes near slack high tide. The settled sediment is not re-entrained at ebb tide because the high vegetation density inhibits currents which are too sluggish to erode the sediment.

Mangroves actively pump fine, cohesive sediment from the tidal creeks and the coastal ocean. Mangroves are thus an important sink for fine sediment from rivers and coastal waters. While the biological role of mangroves in the biological food chain of coastal waters has been well documented (Robertson and Alongi, 1992), mangroves appear also to have an important physical effect. The removal of mangroves may increase water turbidity and hence decrease primary productivity by planktonic algae in tidal creeks and coastal waters surrounding mangrove ecosystem.

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