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Fine sediment trapping in two mangrove-fringed estuaries exposed to contrasting land-use intensity, Palau, Micronesia

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Abstract

A comparative study was undertaken of the fate of fine sediment in the Ngerikiil and Ngerdorch mangrove-fringed estuaries in Babeldaob Island, Palau, Micronesia, in 2002. The mangroves comprised 3.8% of each catchment area, and in both systems, they trapped about 30% of the riverine sediment. Mangroves are important buffers protecting fringing coral reefs from excessive sedimentation. The sediment yield was significantly higher in the Ngerikiil River catchment (150 tons km^{-2} yr^{-1}) that has been extensively cleared and farmed, than in Ngerdorch River catchment (1.9 tons km^{-2} yr^{-1}) that was still relatively pristine during the study period.

Introduction

Rates of soil erosion are rapidly increasing on many tropical islands as a result of land clearing and poor land use practices. Increased erosion is threatening estuaries and coastal coral reefs (Dubinsky and Stambler 1996; Meade 1996; Edinger et al. 1998; Wolanski and Spagnol 2000; Fortes 2001; McCook et al. 2001; Wolanski et al. 2003). Golbuu et al. (2003) reported that soil erosion is presently affecting the Ngerikiil River, its estuary and its fringing coral reefs in Airai Bay, Babeldaob Island, Palau, Micronesia (7°22′N, 134°34′E; Figure 1). There are no pre-development data on soil erosion rates in the area to help assess the changes in sediment yield during the recent peak development period. However, local residents attribute the recent increased erosion in the catchment, the reported rapid siltation of the estuary, and the die-off of coral reefs in Airai Bay to unplanned development activities in the catchment including forest and mangrove clearing, land grading, road construction, farming and housing development.

The Ngerdorch River drains a 39 km^2 mountainous catchment located northeast and adjacent to the Ngerikiil River catchment (Figure 1 and Table 1). These two catchments have similar geology, topography and rainfall (USDI 1997), as well as an identical tidal range within their estuaries. Both rivers flow into coral-fringed lagoons through mangrove swamps, which comprises 3.8% of each catchment area and fringe the whole length of the estuary to the tidal excursion limit.

In 2000, the ‘Babeldaob Compact Road’ (a 52-mile road around Babeldaob) and the ‘Capital Relocation’ (a new capital building in Melekeok) projects were initiated. A portion of the Compact road runs through the Ngerdorch catchment and the new Capital Building is being constructed on one hillside of the catchment. These developments will lead to large-scale land

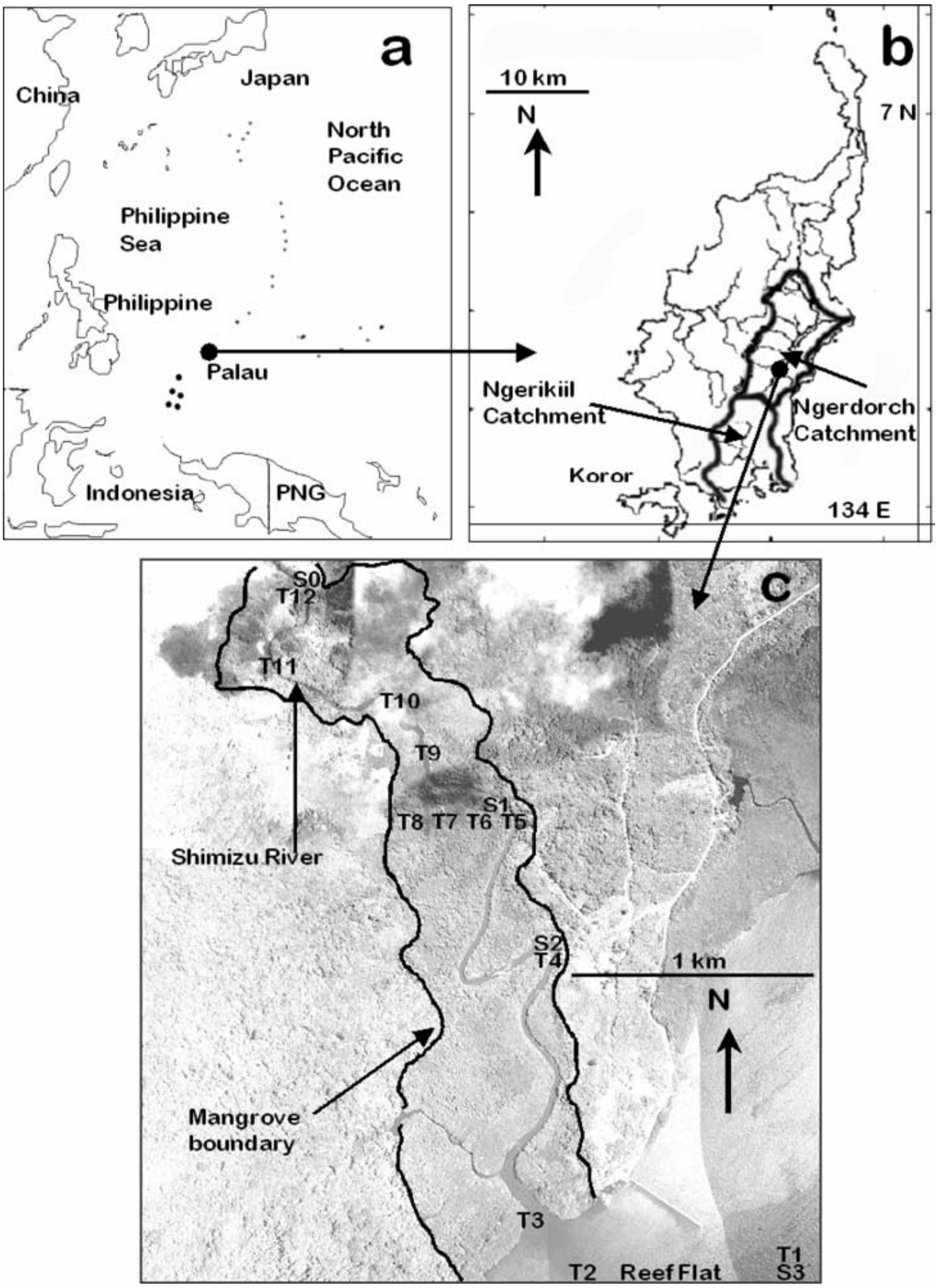

Figure 1. (a and b) Map of the Ngerdorch and Ngerikiil River catchments, Babeldaob Island, Palau, Micronesia. (c) Ngerdorch estuary showing the sampling sites described in the text. Abbreviations are T1, T2 ... = location of sediment traps and S0, S1... = locations of moored instruments.

clearing and an anticipated increase in soil erosion in the near future. In 2002, the Ngerdorch River catchment was still relatively pristine, being largely forested with only three small farms within the catchment while the Ngerikiil catchment has experienced significant housing and farming developments during the last few years.

Table 1. Characteristics of the Ngerikiil and Ngerdorch river catchments, Palau.

	Ngerdorch	Ngerikiil[a]
Catchment size (km^2)	39	19
Mean estuarine SSC ($mg\ l^{-1}$)	19	500
Peak estuarine SSC ($mg\ l^{-1}$)	160	>1500
Mangrove area/catchment area	3.8%	3.8%
Trapping in mangrove	28–44%	15–30%
Sediment yield (tons $km^{-2}\ yr^{-1}$)	1.9	>150

[a] *Source*: Golbuu et al. (2003).

To assess the human impact on soil erosion rates, we undertook a field study to quantify and compare the riverine sediment load and role of mangroves in determining the fate of fine sediment in the two tropical estuaries. Observations showed that (1) the Ngerdorch catchment is relatively pristine with mature vegetation, extensive ground cover and forested river banks; (2) the Ngerikiil catchment has been heavily impacted by poor land use practices resulting in elevated rates of soil erosion; and (3) mangroves comprises 3.8% of each catchment area. Based on these observations, we expected the following: (1) the sediment load in Ngerdorch River will be less than in Ngerikiil River and (2) the holding capacity of the mangroves will be the same for both estuaries.

Methods

Four oceanographic moorings were deployed at stations S1–S3 (Figure 1) from September to October 2003. These stations formed an along-channel transect. Salinity, temperature and suspended sediment concentration (SSC) were measured at stations S1 (at 1 m above the bottom at 4 m depth) and S3 (at 2 m below the surface at 6 m depth), using self-logging Analite nephelometers, Dataflow salinometers and an YSI self-logging CTD-cum nephelometer. The instruments were attached onto 1 m long steel star pickets (rebar) driven into the substratum. The Analite nephelometers and YSI instrument were equipped with wipers that cleaned the sensor every 30 and 10 min, respectively. The instruments logged data at 10 min intervals. The data were sampled at 0.5 s intervals and averaged over 1 min for all sensors except the YSI, which logged data continuously without averaging. The nephelometers were calibrated *in-situ* using water samples brought to the laboratory and filtered on 0.45 μm filters, which were dried at 60 °C in a drying oven for 24 h and weighed.

At station S2, at 6 m depth, the vertical profile at 0.5 m intervals of horizontal currents was measured at 5 min intervals using a bottom-mounted RDI Workhorse ADCP. In addition, the vertical profile of salinity, temperature and SSC were measured at stations S0–S3 with a ship-born YSI CTD profiler-cum nephelometer. These measurements were carried out daily following a flood event in October 2002 for one week and occasionally for the duration of the study. Salinity is expressed in psu, which for our study sites is practically equivalent to ppt.

Single, bottom-mounted sediment traps, with a diameter of 5.08 cm, were mounted at the edge of the mangroves on the river bank between stations S0 and S3 and in the mangroves along a transect perpendicular to the river bank at 10, 20 and 30 m from station S1. The sediment traps were deployed on 12 October 2002 and recovered 120 days later.

The National Weather Service provided daily rainfall data at Koror, located about 12 km southwest of study sites. The rainfall data were used to correlate sedimentation rate and SSC values.

Results

Semi-diurnal, meso-tides prevailed with a pronounced diurnal inequality, and a strong spring–neap tide cycle. The tidal range was about 2 m at spring tide and 1 m at neap tide. A salt wedge prevailed throughout the field study (Figure 2) and the isohalines were nearly horizontal. The brackish water plume lifted off the bottom between stations S0 and S1.

The SSC contour lines were not parallel to the isohalines; instead they sloped upwards toward the river mouth. A turbidity maximum zone existed near the lift-off point (Figure 2). Hence most of the suspended sediments fall out of suspension in the estuary before the plume exits the mouth of the estuary (Figure 2b). Some of that sediment may get re-suspended during incoming tides (Figure 2c) and may be brought back into the inner estuary and the mangroves.

The salinity in the salt wedge at site S1 fluctuated as a result of both the tides and the rainfall (Figure 3).

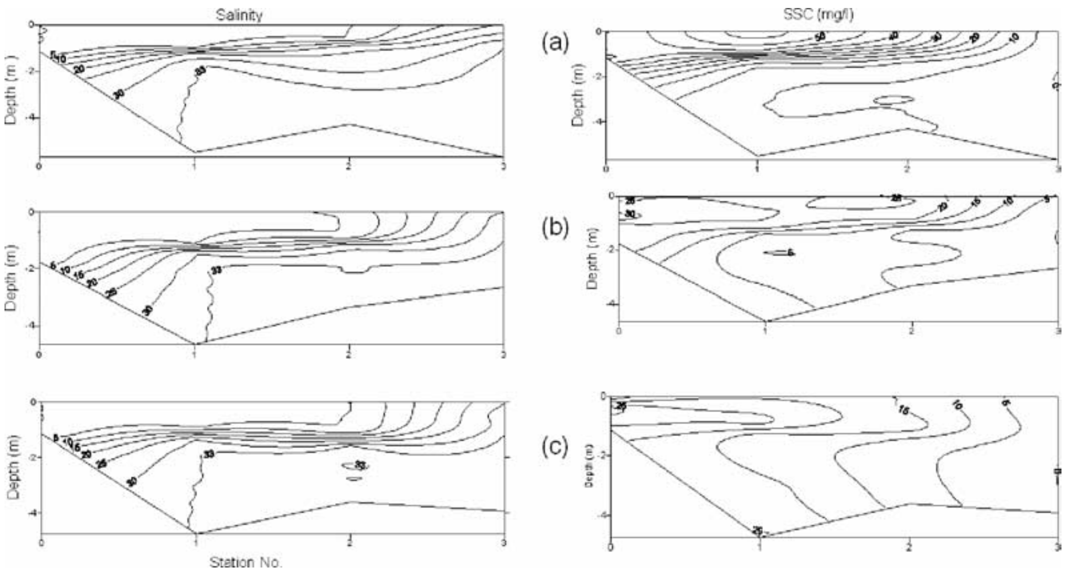

Figure 2. A long-channel distribution of salinity (ppt) and SSC (mg L^{-1}) in the Ngerdorch estuary during 17–19 October 2002. Station locations are shown in Figure 1.

The highest values of salinity were found at high tide, and the lowest values at low tides. The SSC values in the salt wedge at site S1 also fluctuated at the tidal frequency (Figure 3). They were the highest at high tide and following large rainfall events.

The low-frequency currents at site S2 in the estuary were predominantly landward in the salt wedge, and seaward in the brackish water plume near the surface (Figure 3). The currents also varied at the tidal frequency, though the tidal currents were usually smaller than the low-frequency currents.

During the field study, neither the freshwater plume nor the riverine fine sediments reached offshore waters (S3) in quantity, except once for about 20 min following a short river flood (Figure 3). The siltation rates in the mangroves were 65, 12 and 9 mg cm^{-2} day^{-1} at 10, 20 and 30 m inside the mangroves from the banks of the estuary. Hence most of the suspended sediments were deposited within 50 m of the edge of the river, in agreement with findings in other macro-tidal mangroves (Wolanski et al. 2001).

Discussion

The observations suggest a permanent freshwater inflow that formed a permanent salt wedge circulation in the estuary. The salt wedge exists as a result of the small tidal currents and the large depth of the estuary. The riverine fine sediment did not follow the freshwater flow. Instead, the suspended sediment settled out of the brackish, surface plume and was re-entrained towards the head of the estuary by the baroclinic currents in the salt wedge. A turbidity maximum zone prevailed near the plume lift-off point.

Occasional aerial observations (P. Colin, pers. comm.) suggest that the river plume was deflected alongshore, and this may explain why in our observations the river plume generally did not reach offshore waters (S3).

It was possible to estimate the freshwater flow rate, Q_f, from the classical two-layer estuarine equation (Pritchard and Burt 1951)

$$\frac{Q_f = Q_{in}}{[S_{out}/(S_{in} - S_{out})]},$$

where Q_f is the freshwater flow rate, Q_{in} is the inflow rate in the salt wedge, S_{in} is the salinity in the bottom layer and S_{out} is the salinity in the salt wedge. Q_{in} was calculated as follows:

$$Q_{in} = uA,$$

where u was the velocity in the salt wedge as measured by the ADCP and A was the cross-sectional

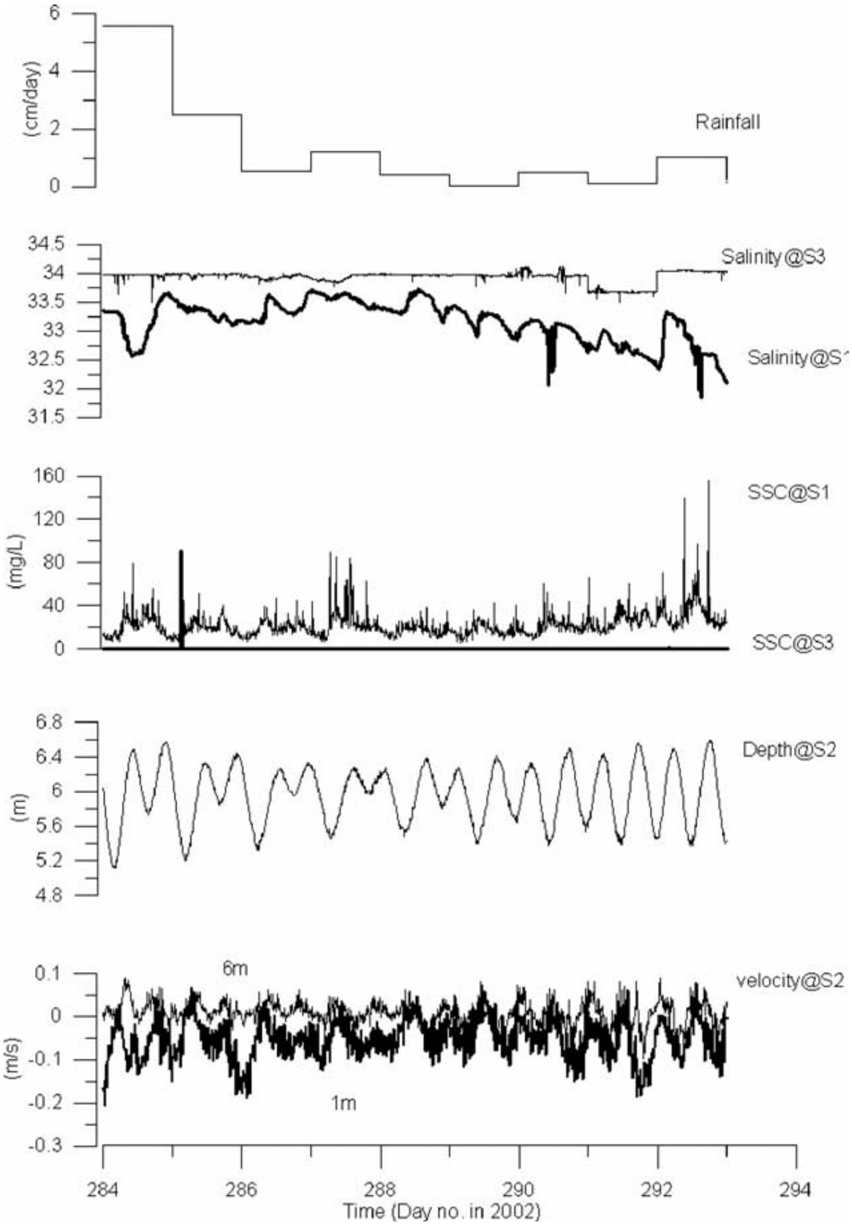

Figure 3. Time-series plot of daily rainfall, salinity and SSC in the salt wedge at site S1 and near the surface at site S3, and velocity (>0 if seaward; <0 if landward) in the brackish water plume and in the salt wedge at site 2. Station locations are shown in Figure 1.

area of the salt wedge. The brackish water outflow, Q_{out}, was calculated as:

$$Q_{out} = Q_f + Q_{in}.$$

The net fine sediment fluxes in the river, in the brackish water plume and in the salt wedge were then calculated as $Q_f C_f$, $Q_{out} C_{out}$ and $Q_{in} C_{in}$, where C_f, C_{out} and C_{in} were the SSC values in the river, the brackish water plume and the salt wedge, respectively. The latter values were taken from the daily CTD casts. The net estuarine sediment export, Q_{net}, was calculated as:

$$Q_{net} = Q_{out} - Q_{in}.$$

For the period of September–October 2002, the net fine sediment fluxes in the river and out of the estuary were 3.2 ± 1.915 and 2.3 ± 1.044 g s^{-1}, respectively. This suggests that the mangroves may trap about 0.9 g s^{-1}, i.e., about 28% of the riverine fine sediment inflow. However the possible error of this estimate is large. The sediment traps in the mangroves suggest a mean settling rate of 1.4 g s^{-1}, or about 44% of the riverine fine sediment flux. Interestingly, the mangroves trap a similar fraction of the fine sediment in the Ngerikiil estuary, although the riverine fine sediment yield in this estuary is 10–19 times higher (Table 1). In both the Ngerdorch and the Ngerikiil estuaries, the mangroves comprise about 3.8% of the catchment. This suggests that the sediment trapping efficiency of mangroves is a function of tidal dynamics in the mangrove wetlands, and not of riverine suspended sediment concentration.

The Ngerdorch estuary is still relatively pristine compared with Ngerikiil estuary (Table 1). In the context of the whole world, the Ngerdorch estuary is pristine compared with a similar sized river in Southeast Asia and Oceania (Milliman and Meade 1983) and of a small mountainous catchment with elevation <100 m in Oceania (Milliman and Syvitski 1992). The sediment yield in the Ngerdorch River (1.9 tons km^{-2} yr^{-1}) was slightly smaller than that (2.4 tons km^{-2} yr^{-1}) predicted by Milliman and Styvitski (1992).

Thus, mangroves play an important role in reducing coastal erosion (Mazda et al. 2002) and protecting fringing coral reefs from sedimentation. The Ngerdorch and Ngerikiil estuaries mangroves flood semi-diurnally, and they may trap up to 44% of the riverine fine sediment. As suggested by Golbuu et al. (2003) for the Ngerikiil River, this trapping efficiency, while helpful, is not sufficient to prevent degradation of coastal coral reefs from excessive sedimentation resulting from extensive land clearing and poor farming practices. Siltation of the Ngerdorch estuary and coral reef degradation in the lagoon waters is likely to occur if land clearing and poor farming practices are not regulated as they were the last few years in the Ngerikiil catchment.

Conclusion

The sediment yield in Ngerikiil watershed is 10–19 times higher than in the less developed Ngerdorch watershed. The implication is that while Ngerdorch watershed is still relatively pristine, coral reef conservation and management effort may not be possible without proper land management in the surrounding catchment.

The result of this study may have broad applications to coastal coral reef ecosystem worldwide. Sedimentation associated with poor land management has been identified as a dominant problem by the US Coral Reef Task Force. While physical and biological characteristics may vary among coral reef sites, the outcome of poor land use will be the same: accumulation of sediment that will prevent coral larval recruitment and recovery of corals (Golbuu et. al. 2003).

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