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Sedimentation in mangroves and coral reefs in a wet tropical island, Pohnpei, Micronesia

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Abstract

A six-month-long study was conducted of the fate of turbid river plumes from the Enipein watershed in Pohnpei, Federated States of Micronesia. Pohnpei is one of the wettest places on earth, with a mean annual rainfall exceeding 4 m in the lowlands and 8 m in the highlands. The river waters were clear of sediment except after major storms with rainfall exceeding 5 cm day^{-1}. Following a storm, the river plume spread in the mangrove fringed estuary and in the coral reef lagoon. The waters were highly stratified in temperature, salinity, and suspended sediment concentration. The brackish water was flushed out in four days, while the suspended sediment all settled out in the estuary, in the mangroves, and in the lagoon including on the coral reefs, in less than one day. The mean rate of sedimentation exceeded 35 mg cm^{-2} d^{-1} both over the mangroves and on the adjacent coral reefs. While this leads to no detrimental effects on the mangroves, sediment smothers corals and leads to substantial coral mortality in the lagoon. The mud is not flushed out from the lagoon because there are no strong currents from waves or tides. This high sedimentation rate is attributable to poor farming and land-use practices on the upland areas.

Keywords: watersheds; river plume; sediment; coral reefs; sedimentation; mangroves; Pohnpei

1. Introduction

Deforestation and poor land-use practices result in increased soil erosion in many tropical, populated islands where there is already a high pressure on both the land and the marine resources. This increased erosion is threatening estuaries and fringing coral reefs (Dubinsky and Stumbler, 1996; Meade, 1996; Edinger et al., 1998; Wolanski and Spagnol, 2000; Fortes, 2001; McCook et al., 2001). Very few studies have been conducted in Micronesia to date that have documented the effects of soil erosion on coral reefs (Wolanski et al., 2003; Golbuu et al., 2003; Victor et al., 2004). Coral reefs in Micronesia are among some of the most diverse and intact coral reefs in the world (Wallace, 1999; Veron, 2000).

To effectively address the problem of coral reef degradation resulting from land-based activities, scientific data that would convince the community and the policy makers to intervene are required. This has been successfully done in the Ngerikiil River catchment, Palau, where scientific data were used to convince stakeholders and policy makers that specific actions were necessary to reduce the negative effects of soil erosion on mangroves and coral reefs, including replanting trees along the river banks and halting mangrove clearing.

Soil erosion is currently one of the biggest threats to coral reefs in Pohnpei, Federated States of Micronesia (Fig. 1). Much of the erosion and associated sedimentation results

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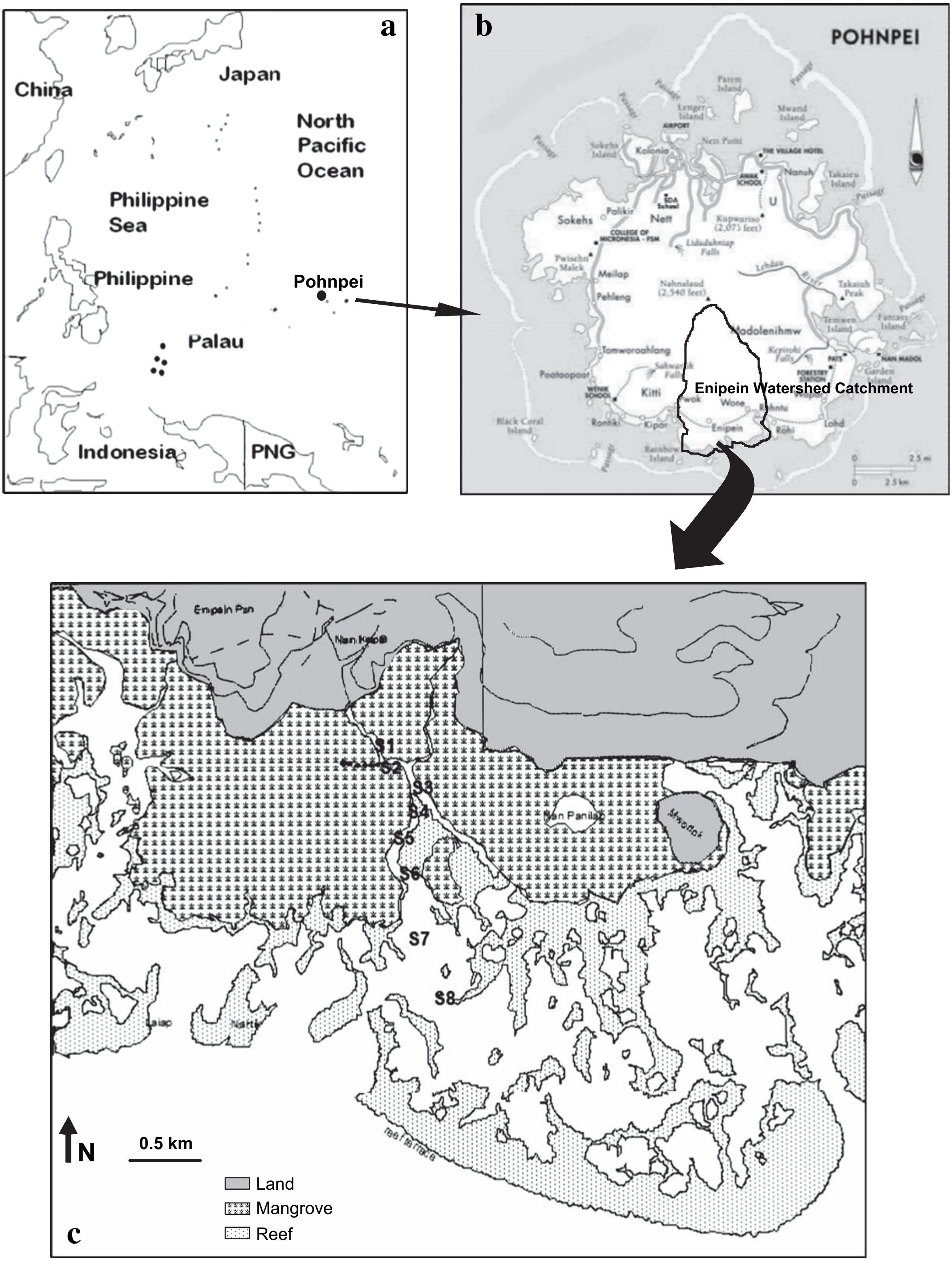

Fig. 1. Map showing location of Pohnpei, the Enipein River catchment, and the study sites as mentioned in the text. The unlabeled sites in the mangroves are named S2M1–S2M5 in Table 1. S2M5 was located 250 m in the mangrove.

from poor farming practices, especially the planting of sakau, *Piper methysticum*, a traditional as well as commercial crop, which provides income for 80% of people living in the village of Enipein. The Enipein River is a mountainous catchment situated in the South of Pohnpei (6°48.3′ N, 158°13.4′ E) with an area of approximately 27.2 km^2 (Fig. 1). The river flows into a coral lagoon with a mangrove swamp that fringes the entire length of the estuary. The average annual rainfall in

Fig. 2. Photo of a landslide in Pehleng, about 5 km west of the study area. Photo taken on September 16, 2004, a day after the landslide.

the highest point of the island is 8.2 m whereas in the lowlands, it is 4 m (Lander and Khosrowpana, 2004). The catchment is home to many of Pohnpei's 110 endemic plants and 13 endemic birds. However, with a rapidly growing human population, the Enipein watershed is threatened. Large areas of native forest have been cleared for housing and agricultural activities, particularly, sakau plantations. In the upland areas, this deforestation often results in landslides causing massive soil erosion (Fig. 2). Such landslides have already been responsible for a number of deaths of villagers.

No study has ever been conducted in the island to examine the impact of soil erosion on coastal and offshore coral reefs. Many residents attribute coral reef die-offs and the decline of fisheries resources to sedimentation. To assess the impact of poor land-use practices on soil erosion, a field study was undertaken to quantify the riverine sediment load, the dynamics of the fine sediment, and the role of mangroves in mediating sedimentation onto coral reefs in the Enipein estuary and lagoon.

2. Methods

Five oceanographic moorings were deployed at stations S1, S3, S6, S7 and S8 (Fig. 1) from August to September 2004. These stations formed an along-channel transect. Salinity, temperature and suspended sediment concentration (SSC) were measured at stations S1 (at 0.5 m above the bottom and at 0.5 m below the surface in 2.5 m depth of water) and S3, S6 and S7 (at 0.5 m above the bottom in 2.5, 3, and 5 m depths of water, respectively), using self-logging Analite nephelometers, Dataflow salinometers, and a YSI self-logging CTD-cum nephelometer. The instruments were attached onto a 2-inch steel pipe driven into the substratum. The Analite nephelometers and YSI instrument were equipped with wipers that cleaned the sensor every 30 min 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. At station S3, in 2.5 m depth of water, the vertical profile at 0.5 m intervals of horizontal currents was measured at 5 min intervals using a bottom-mounted RDI Workhorse Acoustic Doppler Current Profiler (ADCP). At station S8, the horizontal current was also measured at 5 min interval using a Sontek Acoustic Doppler Profiler (ADP). In addition, the vertical profiles of salinity, temperature and SSC were measured at stations S1, S3, S6, S7 and S8 with a ship-borne YSI CTD profiler-cum nephelometer.

CTD casts were taken along a transect between S1 and S8 once a week during the six months of the study. In addition, CTD casts were taken daily for four to five days following floods on three occasions during the study period.

Double, bottom-mounted sediment traps, with a diameter of 5.08 cm, were mounted along a transect between stations S1 and S8. In addition, a second set of traps was deployed in the mangroves along a transect perpendicular to the river bank at 0, 25, 50 100, 150 and 200 m from station S2. All of these traps were deployed for a period of one month, after which they were replaced with new traps. The traps were maintained for six months.

3. Results

3.1. Rainfall

Rainfall was intense during the six-month study (Fig. 3), and these conditions are typical of Pohnpei throughout the

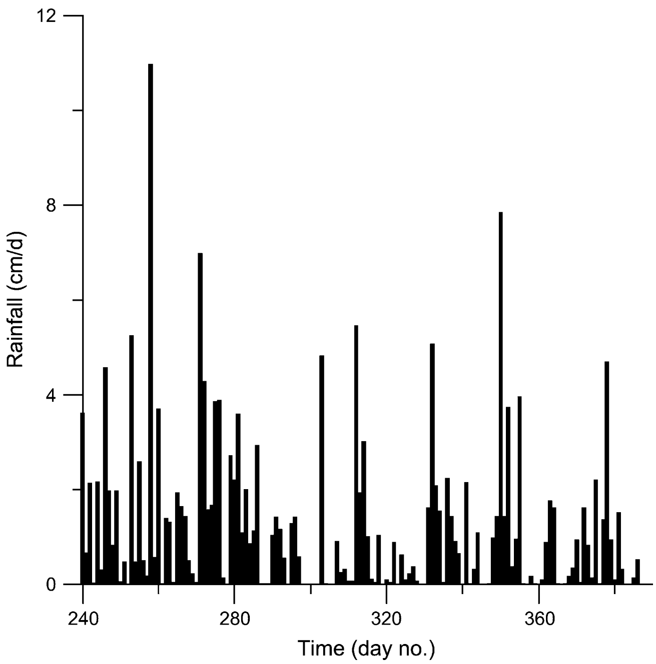

Fig. 3. Time-series plot of daily rainfall (cm d^{-1}) during the study period. Time is in day number from January 1, 2004.

year. Mean rainfall was 36.8 cm $month^{-1}$ with minimum and maximum values of 24.1 and 61.5 cm $month^{-1}$, respectively (Table 1). Peak daily rainfall was 10.9 cm d^{-1}. There were 21 rainless days, i.e. 86% of the days had rain.

3.2. Moored instruments

Semi-diurnal, meso-tides prevailed, with a pronounced diurnal inequality, and a strong spring–neap cycle; the tidal range was about 1.5 m at spring tide and 0.5 m at neap tide (Fig. 4).

River floods were short-lived and resulted from intense rainfall within the catchment. During non-flood conditions, the salinity at station 1, located in the upper estuary, was about 32. During a flood event, it fluctuated between 5 and 30 at low and high tide (Fig. 4) during which time the temperature varied between 26 and 30 °C. The currents in the estuary had a strong barotropic component driven by the tides, and a baroclinic component driven by the river runoff. During a flood event, the near-surface current velocity fluctuated between 0.4 m s^{-1} at ebb tide and −0.3 m s^{-1} at flood tide (Fig. 4). The near-bottom velocity also was tidally asymmetric. Outside of flood events, the velocity was symmetric at flood and ebb tide with a mean velocity of −0.016 m s^{-1}. At site 8, in the lagoon, the velocity fluctuated between ± 0.08 m s^{-1}. The salinity at site 7, located in the lagoon, also fluctuated at the tidal frequency, but was of shorter duration than that landward at site 3. The fluctuations were also of lesser amplitude as the salinity varied between 30.4 and 32 (Fig. 4). During a flood event, the suspended sediment concentration (SSC) at site 7 also fluctuated at the tidal frequency, peaking at 100 mg l^{-1} during low tide and 5 mg l^{-1} during high tide. Outside of flood events, the SSC at site 7 was less than 5 mg l^{-1}.

The sediment trap data showed both temporal and spatial differences in sedimentation (Table 1). Sedimentation rates decreased with increasing distance from the land into the mangroves. They also decreased within the estuary and in the lagoon with increasing distance from the river. Monthly sedimentation rates correlated weakly, but not significantly, with peak rainfall for that month, and did not correlate with monthly rainfall. There was no significant effect of distance into the mangrove on the level of sedimentation in the mangroves. However, much of the suspended sediment was deposited within the first 25 m from the edge of the mangrove in agreement with findings from other micro-tidal mangroves (Wolanski et al., 2001; Victor et al., 2004).

Table 1
Monthly sedimentation rates at the 13 sites, monthly rainfall, and maximum daily rainfall during the study period August 2004–January 2005

Site	Rate (mg cm^{-2} d^{-1})						
	August	September	October	November	December	January	Average
S1	57.4	91.1	82.5	144.4	113.3	76.7	94.2
S2	54.5	57.5	75.3	31.8	56.7	58.2	55.7
S3	73.5	60.1	95.5	123.9	85.7	81.5	86.7
S4	54.9	66.5	55.2	73.5	73.6	49.2	62.2
S5	63.8	50.1	44.1	62.6	53.5	50.4	54.1
S6	69.2	69.0	57.2	62.1	88.1	52.7	66.4
S7	40.3	41.1	34.1	36.6	36.4	37.3	37.7
S8	44.4	36.6	34.6	30.5	30.6	35.1	35.3
S2M1	36.5	38.4	34.1	37.7	29.7	37.4	35.6
S2M2	26.0	38.1	29.1	65.8	31.3	36.3	37.8
S2M3	34.9	46.2	39.6	34.9	35.3	38.1	38.2
S2M4	30.5	49.7	33.1	32.5		37.3	36.6
S2M5	32.0	44.0	31.9	28.9	25.3	38.1	33.4
Average	47.5	53.0	49.7	58.9	55.0	48.3	52.1
S.D.							23.4
Total rainfall (cm $month^{-1}$)	N/A	61.5	37	27.2	34.3	24.1	36.8
Maximum rainfall (cm d^{-1})	N/A	10.9	4.8	5.4	7.8	4.7	6.72

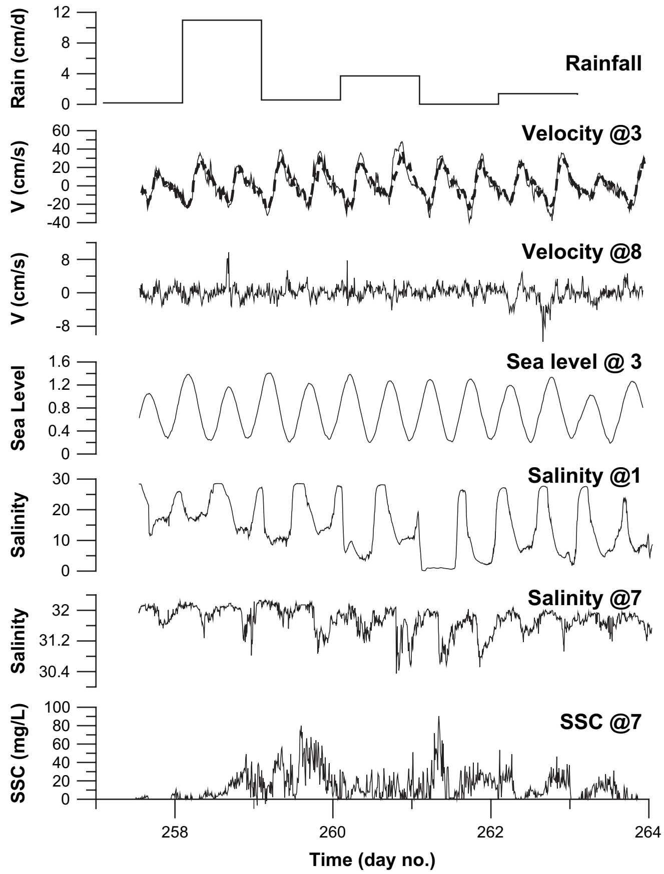

Fig. 4. Time-series plot during the flood of 15 September 2004 of daily rainfall, near-surface (line) and near-bottom velocity (–) at site 3 (positive values indicate seaward flow), velocity at site 8, sea level, salinity at sites 1 and 7, and suspended sediment concentration (SSC) at site 7. This is the same flood that generated landslides at various locations in Pohnpei (see Fig. 2); there are no data on landslides in the Enipein River catchment.

3.3. Ship-borne observations

Fig. 5 shows the salinity and SSC data from the CTD transects between stations S1 and S8 following the river flood of December 2004. On day 1, the river plume had spread throughout the lagoon, and the isohalines sloped upward towards the ocean. The waters in the lagoon and in the lower estuary were highly stratified. At station S1, in the upper estuary, salinity was vertically uniform at about 5. The SSC was about 10 mg l^{-1} at the surface and 7 mg l^{-1} at the bottom, indicating that the riverine sediment was dropping out of suspension from the sediment-laden river plume. While the brackish water plume extended across the lagoon, the suspended sediment plume only extended half way into the lagoon to station S7. On day 2, much of the brackish water plume was still in the lagoon and in the estuary, and most of the suspended sediment had disappeared. On day 3, brackish water was flushed out of the lagoon, and the water remained substantially free of suspended sediment. On day 4, oceanic water has re-entered the estuary and by day 5 the estuary was back at its steady-state, while water in the lagoon remained at high salinity and substantially free of suspended sediment. Similar results were found following other river floods during the study period.

A negative correlation was found (Fig. 6) between the SSC and the salinity at site S1, in the upper estuary.

4. Discussion

Pohnpei is one of the wettest places on earth and this study may be the first one on estuarine dynamics in such an environment. Some of the results are quite novel. Because there are no dry and wet seasons, the river is perennial. Because of the high rainfall, the vegetation is thick and to the inexperienced eye it may appear to be so, even when farmed on steep hills. This permanent vegetation prevents significant soil erosion during 'benign' conditions (rain $< \sim 4$ cm d^{-1}). Erosion, however, is significant following intense rainfall (rain > 4 cm d^{-1}), especially if storms generate landslides on farmed slopes (Fig. 2). Thus, riverine sediment is only imported in quantity into the estuary during major river floods, a finding also reflected by the inverse correlation between salinity and SSC (Fig. 6). Such river floods – and the resulting riverine sediment flux – occur one to three times each month throughout the year. This situation is thus quite different from the one in other islands in Micronesia where 30–50% of the annual riverine sediment flux may occur in one day following the first heavy rainfall after several months of dry weather (Rongo, 2005).

During such floods, the river plumes extend well into the lagoon and they take four days to be flushed out. The riverine sediment disappears, however, much faster, in less than one day (Fig. 5). This indicates that it drops out of suspension within the estuary, in the mangroves, and in the lagoon, including coral reefs. This rapid settling of the riverine sediment from the river plumes is a result of the river plumes being thin (<2 m thick) and is consistent with findings elsewhere in Micronesia (Golbuu et al., 2003; Wolanski et al., 2003; Victor et al., 2004).

The lagoon is densely packed with patch reefs. This makes the water circulation patterns very complex. Swift currents (0.4 m s^{-1}) are restricted to channels such as reef passages and the estuary, while small (<0.08 m s^{-1}) currents prevail elsewhere (Fig. 4). The lagoon is also well sheltered from oceanic swells and even from large, local, wind-driven waves. Thus no resuspension is observed in the lagoon, except on the upper reef flats. The lagoon and the mangroves are therefore a deposition area for riverine sediment after it has been spread by swift tidal currents within the estuary (Furukawa et al., 1997).

Sedimentation occurs at all sites (Table 1). The estuary itself is silting at a rate of about 78 mg cm^{-2} d^{-1}. The mangroves and the lagoon are silting at a mean rate of about 36 mg cm^{-2} d^{-1}, with measurable spatial gradients. From these data, the impact of the plumes can be extrapolated, and these predictions are shown in Fig. 7. These data suggest that 20% of the riverine sediment may settle in the estuary itself, 40% in the lagoon and 40% in the mangroves.

The high sedimentation rate within the estuary suggests that it may be silting up. This situation may be similar to that of the Negrikiil Estuary in Palau (Golbuu et al., 2003). That estuary

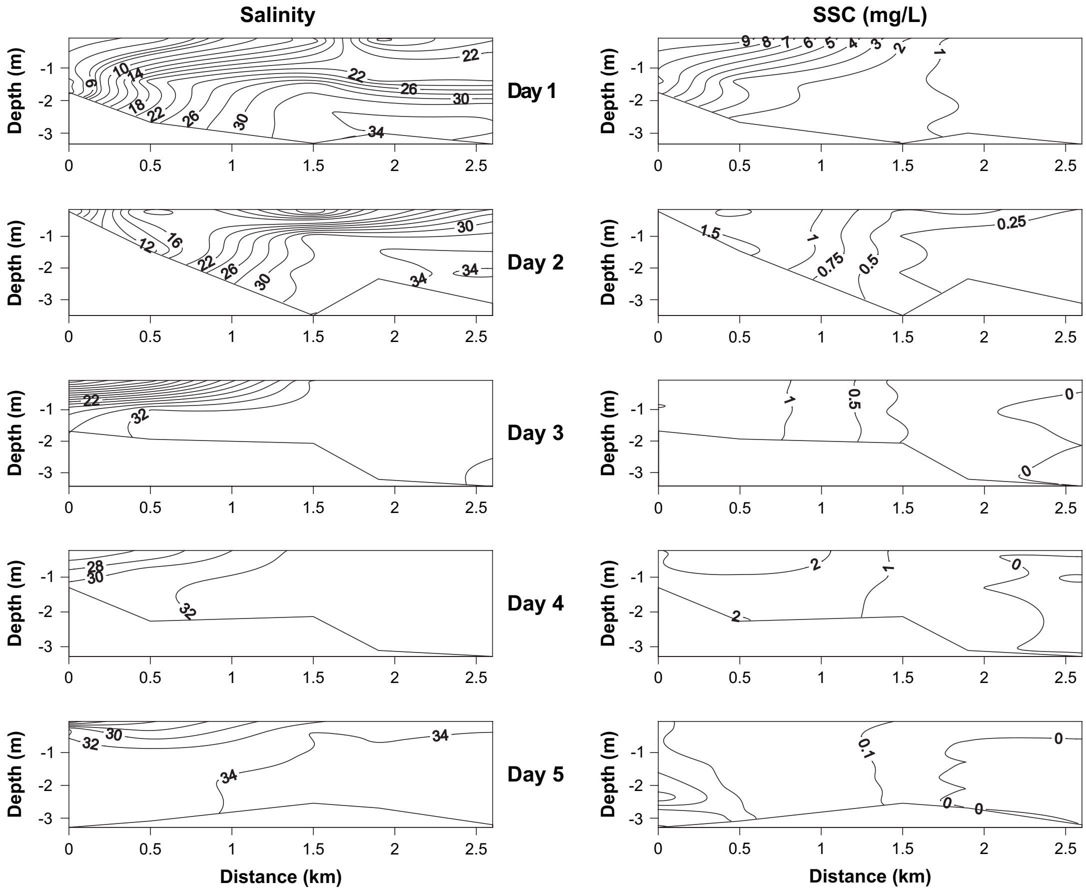

Fig. 5. Daily, along-channel distribution between sites 1 and 8 of (left) salinity and (right) suspended sediment concentration (SSC) from December 17, 2004 (day 1) to December 21, 2004 (day 5). *X*-axis is the distance between stations from station S1 where S1 = 0 km, S3 = 0.5 km, S6 = 1.5 km, S7 = 1.9 km, and S8 = 2.6 km.

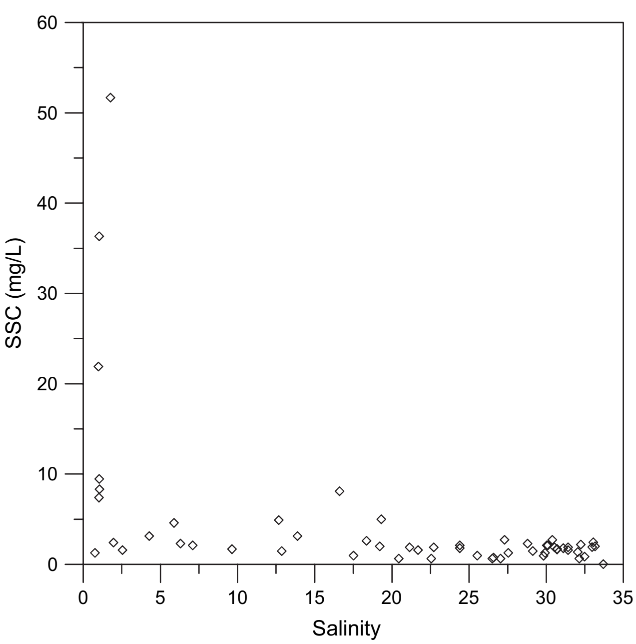

Fig. 6. Scatter plot of suspended solid concentration (SSC) versus salinity at site 1 during the study period.

has been filled with silt following land clearing in the catchment. At low tide, much of the estuary was navigable in the past but much of it is now exposed. This may become the fate of the Enipein Estuary.

This sedimentation rate is similar to that (~20 mg cm^{-2} d^{-1}) observed in mangroves of the heavily impacted Ngerikiil River catchment in Palau, Micronesia (Golbuu et al., 2003), and much higher than that (~2 mg cm^{-2} d^{-1}) in the pristine Ngerdorch River catchment in Palau (Victor et al., 2004). It is also much higher than that (2–5 mg cm^{-2} d^{-1}) in ocean-fronting, river-free mangroves in Australia (Furukawa et al., 1997; Wolanski et al., 1998). A similarly high sedimentation rate is observed over coral reefs in the lagoon. No resuspension mechanism exists in the lagoon to flush out this sediment. Indeed visual underwater observations reveal the accumulation of mud up to site 8; much of the reef was found to be dead in the study area in 2004 (Victor and Golbuu, pers. obs.). In the absence of resuspension that can flush out the sediment, these sedimentation rates (35 mg cm^{-2} d^{-1}) are stressful to adult corals (Fabricius, 2005). They are lethal to juvenile corals when accompanied by marine snow (Fabricius et al., 2003), which is abundant in the lagoon (Victor and Golbuu, pers. obs.). Thus the coral larvae arriving from more pristine reefs are unable to settle and thrive on these

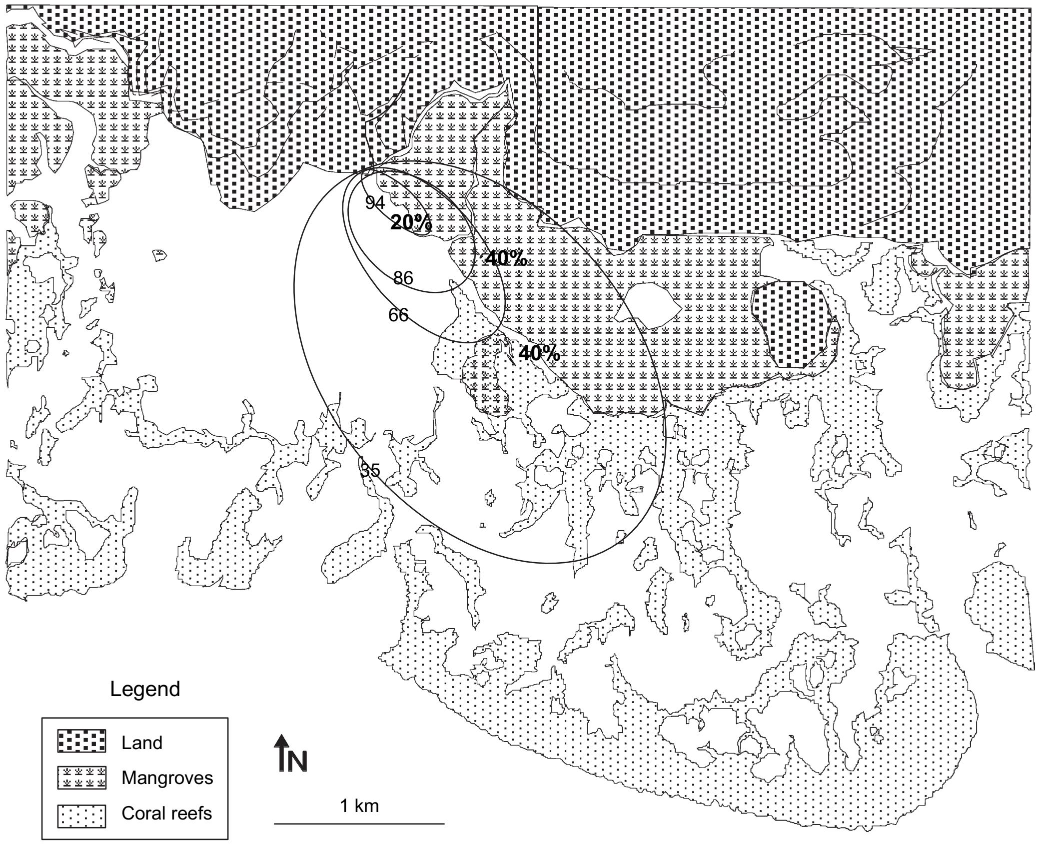

Fig. 7. A sketch of the sedimentation plume (mg cm^{-2} d^{-1}) in the Enipein river estuary and coastal waters, and the estimated partitioning of the riverine sediment flux between siltation in the estuary (20%), in the mangroves (40%) and in the lagoon and its coral reefs (40%). These values may be slightly over-estimated because some sediment may escape to the ocean during the first ebb tide during a river flood by out-flowing tidal currents through the outer reef passage.

lagoons impacted by the river plume; coral populations thus may not recover as long as poor land practices continue.

5. Conclusion

The Enipein Estuary, the mangrove and the coral reefs are silting as a result of poor land management in the catchment. This sedimentation rate is high compared to those in the other Micronesian islands. While no detrimental impact was observed in the mangroves, silt deposition within the estuary and reefs smothers adult corals, kills juvenile corals, and can prevent larval settlement. Thus, coral reefs will continue to degrade. The findings of this study are applicable to all of the coastal coral reefs in Pohnpei because they are all impacted by river runoff. This study suggests that the whole reef ecosystem of Pohnpei may collapse if poor land-use practices are not corrected.

Pohnpei has both democratically elected and traditional/hereditary leaders that govern and have direct responsibilities for policy development and implementation. In islands where traditional leadership still exists, long-term, generational impacts of activities are often considered in the development of environmental policies. An effective community-based organization exists in Pohnpei, the Conservation Society of Pohnpei, and serves to help disseminate results of this and related studies to community leaders. Efforts aimed at implementing best farming practices on sakau farming in the upland rainforests are underway, and the data generated in this study will be used to help support wise resource usage and management efforts.

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