



## Trapping of fine sediment in a semi-enclosed bay, Palau, Micronesia

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### Abstract

Airai Bay, Palau, is a small (3 km<sup>2</sup>), semi-enclosed, mangrove-fringed, meso-tidal, coral lagoon on the southeast coast of Palau. It drains a small catchment area (26 km<sup>2</sup>) of highly erodible soils in an area with high annual rainfall (3.7 m). River floods are short-lived and the sediment load is very large, with suspended fine sediment concentration exceeding 1500 mg l<sup>-1</sup>. The resulting river plume is about 2 m thick. The brackish water residence time is about 7 days; during this period the plume remains a distinct surface feature even after river runoff has ceased. About 98% of the riverine fine sediment settles in Airai Bay, of which about 15–30% is deposited in the mangroves during river floods. This mud remains trapped in Airai Bay because the bay is protected from ocean swells and the tidal currents and locally generated wind waves are too small to resuspend the mud in quantity. The mud is smothering coral reefs, creating a phase shift from coral to fleshy algae dominance, and is even changing habitats by creating mud banks. The persistence of Airai Bay marine resources may not be possible without improved soil erosion control in the river catchment.

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### 1. Introduction

Throughout the wet tropics of the world, rapid deforestation and poor land-use practices are resulting in huge increases in soil erosion (Meade, 1996), with resulting major environmental changes in estuaries (Wolanski & Spagnol, 2000). Some of the fine sediment reaches coastal waters where it can increase turbidity and even modify habitats by creating a muddy coast (Duke & Wolanski, 2001; Wolanski & Duke, 2002). This mud can also degrade coral reefs through a number of biological processes (see reviews in Fortes, 2001; McCook, Wolanski, & Spagnol, 2001; McManus, Meñez, Reyes, Vergara, & Ablan, 2000; Richmond, 1995). The degree of degradation is very much dependent on the fine sediment quantity and quality, the sedimentation rate, and the residence time of the mud

(Fabricius & Wolanski, 2000; Gilmore, 1999; Peters, Gassman, Firman, Richmond, & Power, 1997; Richmond, 1993, 1994a,b; Rogers, 1990; Sato, 1985). Unfortunately, while the dynamics of water circulation in lagoons is fairly well understood (Kjerfve, 1994), the dynamics of terrigenous mud in reefal waters are not (Healy, Wang, & Healy, 2002). This is largely due to the complex physical and biological processes controlling the transport and settlement of fine sediment in biologically rich waters (Asaeda & Wolanski, 2002; Ayukai & Wolanski, 1997; Fabricius, Wild, Wolanski, & Abele, 2003; Lick, Lick, & Ziegler, 1992; Logan, Passow, Alldredge, Grossart, & Simon, 1995). Therefore it remains difficult to quantify the biological impact of various land-use practices on coastal coral reefs.

Recently, environmental degradation by terrigenous mud has become a major local issue for the community living around Airai Bay (7°22'N, 134°34'E; Fig. 1), Palau, Micronesia. This bay is a semi-enclosed, coral reef lagoon about 3 km long and 1 km wide. The bay

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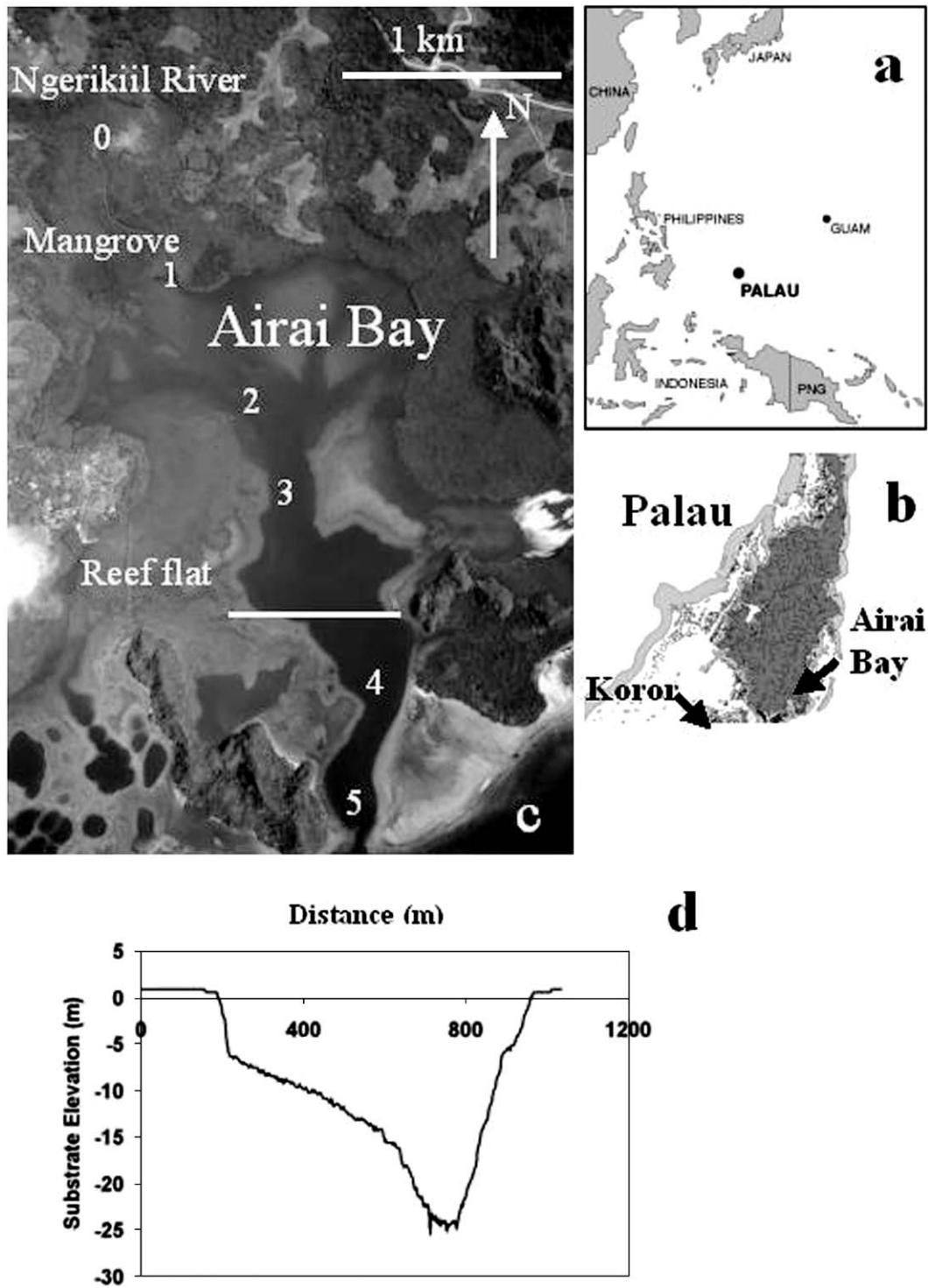


Fig. 1. Location maps of (a) Palau and (b) Airai Bay ( $7^{\circ}22'N$ ,  $134^{\circ}34'E$ ), (c) vertical aerial photograph of Airai Bay showing the channel, the reef flat, the mangroves and the location of stations 0–5. The straight line across Airai Bay shows the location of a cross-channel bathymetric transect. (d) Bathymetry (in m below lowest tide) along the cross-channel transect shown in (c).

comprises a coral-fringed channel, about 13 m deep at the mouth of the bay (near station 5; see Fig. 1) and about 3 m deep at station 2; at low spring tide this channel nearly emerges mid-way between stations 1 and 2. This channel is fringed by a coral reef flat that is

exposed for periods at low spring tide. A  $1 \text{ km}^2$  mangrove swamp exists at the northern end of Airai Bay on both sides of the Ngerikiil River estuary, which is muddy. The depth in the thalweg of the estuary decreases with increasing distance from the mouth

(station 1), and at low spring tide it is about 1 m at station 1, and 0.1 m at station 0. The Ngerikiil River catchment area is about 26 km<sup>2</sup> and the mean annual rainfall is 3.75 m. There are 3 months (February–April) of moderate rainfall and 9 months of heavy rainfall.

The land was relatively undisturbed until the 1970s. The 1963 USGS survey map shows Airai Bay as a deep drowned river channel with extensive coral patches. Construction of Koror airport, in the Ngerikiil River catchment, in 1978 and 1982, and extensive land clearing for agriculture in the lowlands of the catchment in the 1990s, have accelerated soil erosion, so that reddish-brown to dark brown fine sediment has filled the bottom of the channel and covered much of the patch reef habitat (USDI, 1997). Since 1997, the rate of land clearing has accelerated and this has been accompanied by poor land use practices that include the destruction of green belts along the banks of the Ngerikiil River. These activities generate intense soil erosion, made visually apparent by the zero visibility of the river water. In addition, the mangroves are being cleared, potentially negating their useful role as a sediment buffer as reported elsewhere (Duke & Wolanski, 2001; Wolanski et al., 2001). The artisanal fisheries in Airai Bay have since collapsed, and this is generating socio-economic problems (Noah Idechong and village leaders, personal communication). In 2002, we found that the reef was heavily overgrown with an algae mat, especially inshore of station 4. The algae trapped a large amount of fine sediment that was readily released as a muddy discharge when the algal mat was manually shaken or, in very shallow waters over the reef flat at low tide, stirred by the prevailing, small, locally generated wind waves.

To resolve the conflict between agriculture and fisheries, a management plan is warranted for the Ngerikiil River catchment and Airai Bay. Key parameters needed to develop this plan are the rate of flushing of water and fine sediment from Airai Bay, and the efficacy of the sediment buffer provided by the mangroves. There were no data available before this study to evaluate these parameters. To answer these questions a field study was carried out during 3 months in 2002.

## 2. Methods

Four oceanographic moorings were deployed at stations 1–4 (Fig. 1) from March to June 2002. These stations formed an along-bay transect following the channel. Salinity, temperature and suspended sediment concentration (SSC) were measured at stations 1, 2 and 4, using self-logging Analite nephelometers, DataFlow salinometers and a YSI self-logging CTD-cum nephelometer. The instruments were attached onto meter long steel star pickets (rebar) with 1.25 cm diameter 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 salinometers and nephelometers were deployed at nominal depths of about 1.5 m. At station 3, in the middle of the channel, the vertical profiles of horizontal currents were measured using a bottom-mounted Workhorse ADCP.

In addition, the vertical profile of salinity, temperature and SSC was measured at stations 1–5 from a ship-borne YSI CTD profiler-cum nephelometer. These measurements were carried out daily during 1 week, occasionally twice daily, following two local floods, one in March 2002 and one in May 2002.

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.

Double, bottom-mounted sediment traps, with a diameter of 5.08 cm, were mounted at the edge of the mangroves on the river bank at stations 0 and 1, and in the mangroves along a transect perpendicular to the river bank at 10, 20, 30, and 60 m from station 0. The traps were set on March 12, 2002 and recovered 51 days later. The National Weather Service provided daily rainfall data at Koror, located about 7 km away.

## 3. Results

### 3.1. Rainfall

Rainfall was moderate, usually less than 8 cm day<sup>-1</sup>, but twice during the study period it exceeded 12 cm day<sup>-1</sup> (Fig. 2). Although no data on river runoff were available because the river was not gauged, visual observations revealed that runoff was also intermittent, practically ceasing a day after a storm.

### 3.2. Moored instruments

#### 3.2.1. Synoptic distribution

Semi-diurnal, meso-tides prevailed, with a pronounced diurnal inequality, and a strong spring–neap cycle; the tidal range was about 2 m at spring tide and 1 m at neap tide (Figs. 2 and 3).

At station 1, located at the mouth of the estuary, the SSC fluctuated widely (Figs. 2 and 3). In the absence of runoff, it was less than 30 mg l<sup>-1</sup> at ebb tide and 50 mg l<sup>-1</sup> at rising tide, suggesting that fine sediment was imported from the bay and settled in the estuary and its fringing mangrove swamp. During a river flood, the waters were very turbid. SSC at two occasions exceeded 1500 mg l<sup>-1</sup> (the saturation limit for the nephelometer),

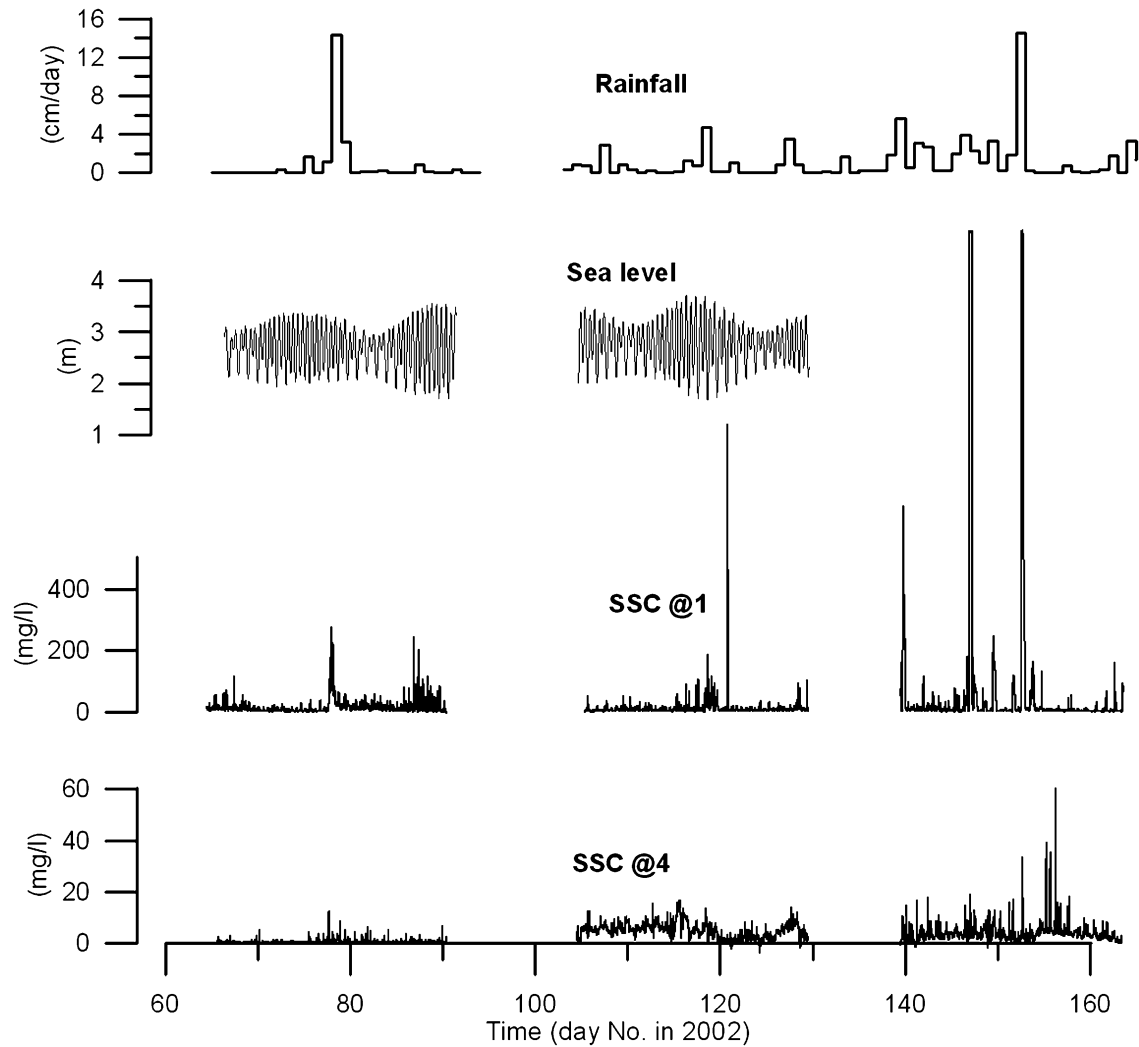


Fig. 2. Time-series plot of the daily rainfall ( $\text{cm day}^{-1}$ ), the sea level (m), and the SSC ( $\text{mg l}^{-1}$ ) at stations 1 and 4.

though commonly it peaked at  $200\text{--}800 \text{ mg l}^{-1}$ . This would typically last 1/2 day and would also vary tidally, with the SSC being higher at falling tide, when sediment-laden river water was exported, than at the rising tide, when oceanic water was imported. The high SSC events were all associated with river runoff because during such events the salinity always decreased (not shown). Minimum observed salinity was 12 during the study period.

At station 4, near the mouth of the bay, SSC values were much smaller, peaking at about  $60 \text{ mg l}^{-1}$ , but more commonly occurring at about  $20 \text{ mg l}^{-1}$  (Figs. 2 and 3). There was no clear correlation between the occurrence of high SSC events and low salinity events. Minimum observed salinity was 32.7.

### 3.2.2. River plume dynamics

Fig. 3 illustrates the dynamics of water and sediment following a river flood. Intense rainfall occurred on day

78 and was followed by dry conditions. At station 1, suspended sediment was exported in short pulses, preferentially at ebb tide. Indeed, SSC increased rapidly during the river flood at ebb tide and peaked at  $350 \text{ mg l}^{-1}$ . It rapidly decreased to  $30 \text{ mg l}^{-1}$  at the following rising tide, increased to  $50 \text{ mg l}^{-1}$  at ebb tide and remained low thereafter. Thus, it may be deduced that much of the sediment settled at rising tide within the estuary and fringing mangroves, and was not resuspended at the following ebb tide. At station 2, before the river flood, SSC fluctuated at the tidal frequency, peaking at about  $20 \text{ mg l}^{-1}$ . Because waters were shallow at low tide between stations 1 and 2, fine sediment was resuspended at tidal frequencies under the combined action of small, locally wind-generated waves and moderate tidal currents (peaking at  $0.15 \text{ m s}^{-1}$  at station 3; see Fig. 3). When the river plume intruded in Airai Bay in the late afternoon of day 78, as evidenced by a drop in salinity, it carried fine sediment, with an SSC peaking at about  $50 \text{ mg l}^{-1}$ .

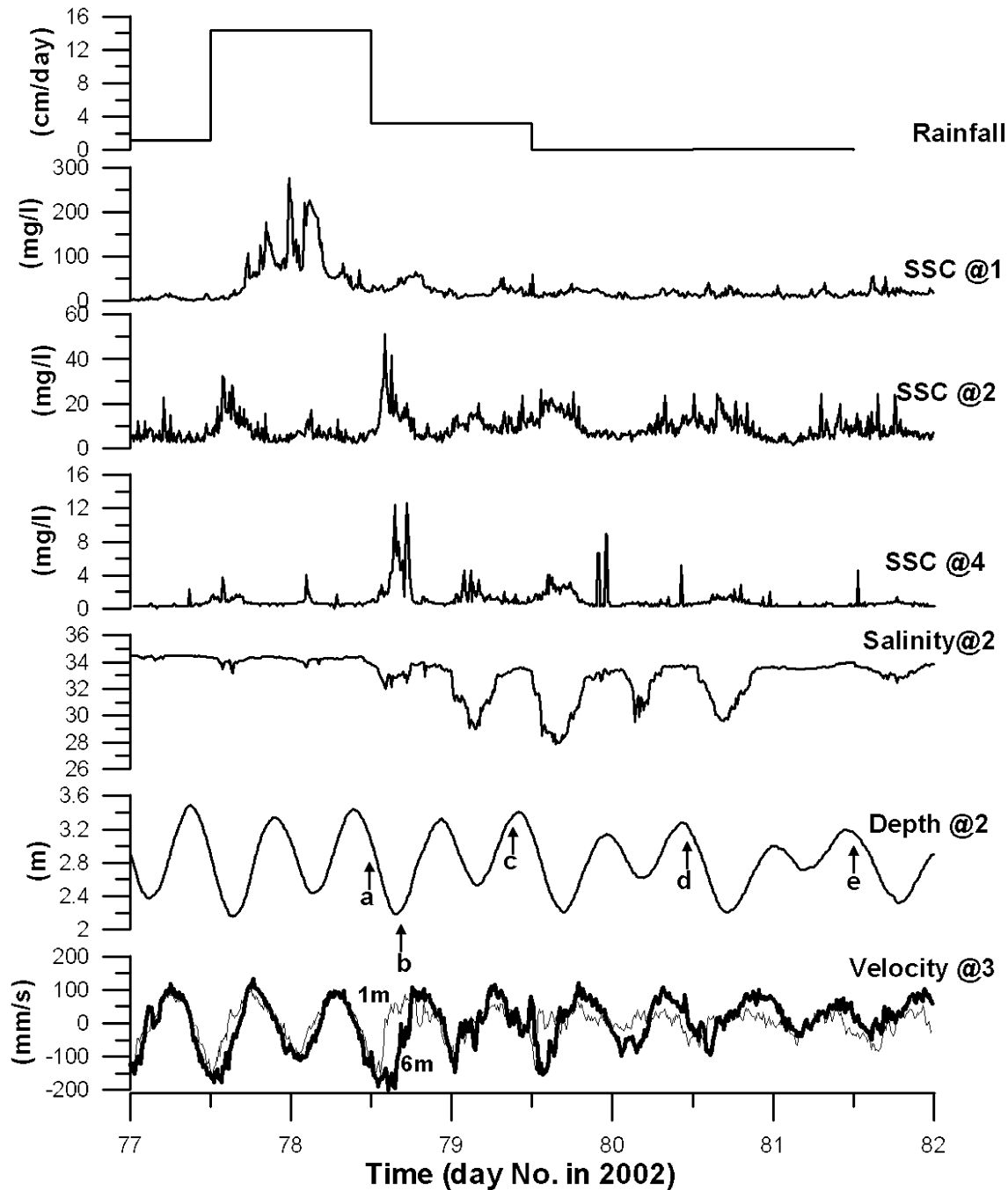


Fig. 3. Time-series plot following the storm of March 19, 2002, of the daily rainfall ( $\text{cm day}^{-1}$ ), the SSC ( $\text{mg l}^{-1}$ ) at stations 1, 2 and 4, the salinity at station 2, water depth (m) at station 2 and the along-channel velocity ( $\text{mm s}^{-1}$ ) at 1 and 6 m from the bottom at station 3. The velocity is positive if the water is flowing landward, negative if seaward. The letters a–e indicate CTD transects shown in Fig. 4.

About 1 h later, advected by currents peaking at  $0.15 \text{ m s}^{-1}$ , this sediment-laden brackish water reached station 4, near the mouth of the bay, with SSC peaking at  $12 \text{ mg l}^{-1}$ .

At station 2, in the early morning of day 79, at the next ebb tide, 12 h later, the river plume passed by stations 2 and 4 once more, evidenced by a salinity decrease to about 29 at station 2 and an SSC

peaking at 20 and  $4 \text{ mg l}^{-1}$  at, respectively, stations 2 and 4.

In the absence of runoff, the tidal currents in the channel at station 3 were tidally asymmetric, being larger at ebb tide than at rising tide ( $0.17 \text{ m s}^{-1}$  compared to  $0.12 \text{ m s}^{-1}$ , respectively). During the river flood, on day 78, the currents were measurably larger at the surface than at the bottom during ebb tide when the

river plume passed over that station; the currents were uniform with depth at rising tide when high salinity oceanic water intruded in the bay. For the next 3 days, there was a substantial vertical shear of the currents, with fresher, surface waters moving at  $0.1 \text{ m s}^{-1}$  over slower moving ( $0.05 \text{ m s}^{-1}$ ), more saline bottom waters.

For the next few days, the river plume was still present in the bay, though it was increasingly flushed out or diluted, as evidenced by increasing salinity. However

the plume by that time carried a negligible amount of suspended sediment, as evidenced by SSC values less than  $5 \text{ mg l}^{-1}$  at station 4.

3.3. Ship-born observations

Fig. 4 shows the salinity and SSC data from the CTD transects at stations 0–5, following the river flood of day 78. The timing of the observations is shown by the

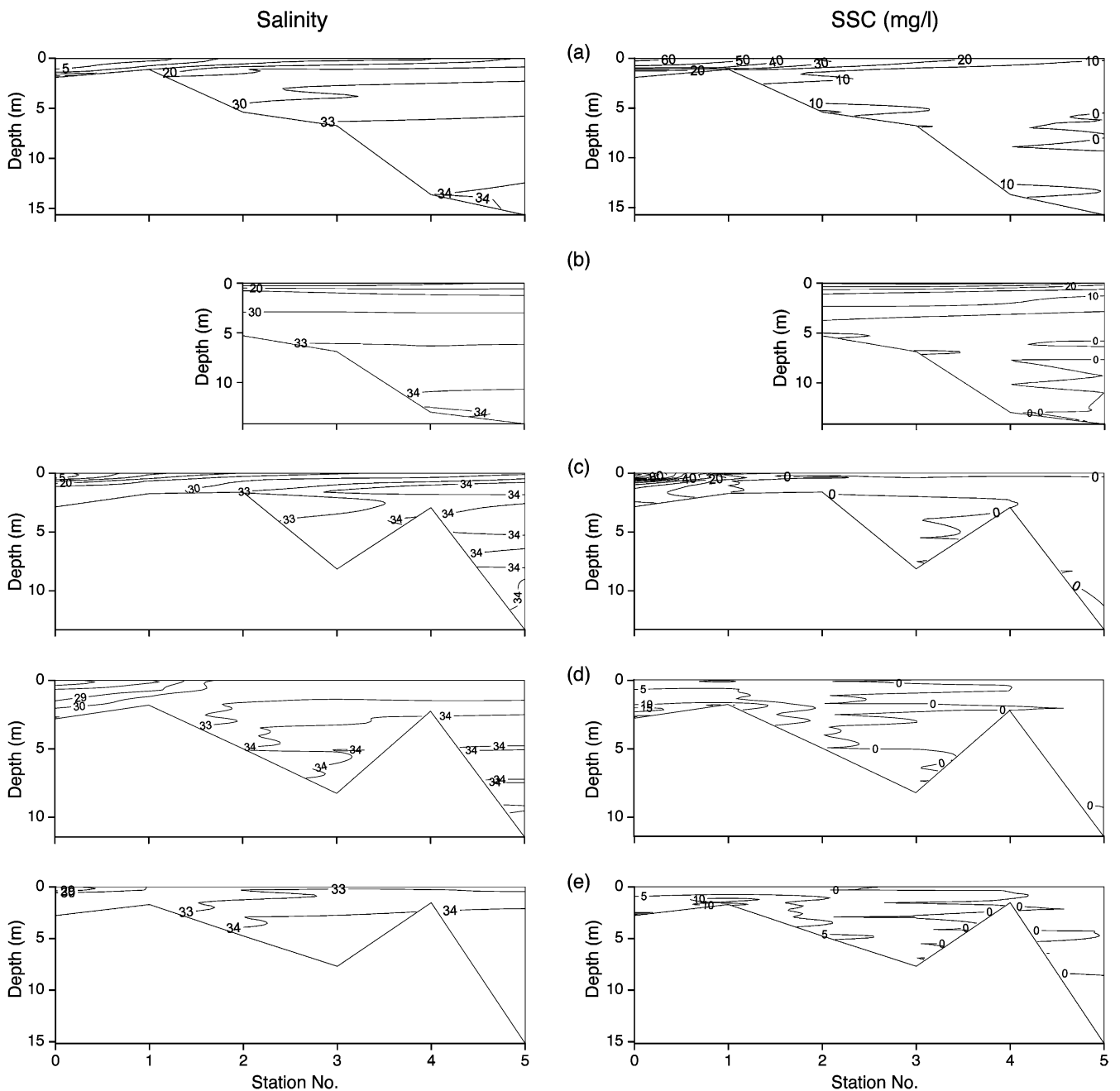


Fig. 4. Along-channel distribution of (left) the salinity and (right) the SSC ( $\text{mg l}^{-1}$ ) at sampling times a–e shown in Fig. 3. Occasionally only the top few meters were sampled at station 4. The location of stations 0–5 is shown in Fig. 1.

letters a–e in Fig. 3. Because the shallow water made access very difficult, the transects were all carried out near high tide except for transect b that was sampled at low tide.

Transect a was sampled at ebb tide, several hours after the peak of the river flood (see Fig. 3). The river plume had spread throughout Airai Bay, and the isohalines sloped upward towards the ocean. The waters were highly stratified. At station 0, in the estuary, salinity was about 5 at the surface and 15 at the bottom. The SSC was about  $60 \text{ mg l}^{-1}$  at the surface and  $20 \text{ mg l}^{-1}$  at the bottom, indicating that the riverine sediment was dropping out of suspension from the sediment-laden river plume. Maximum SSC values at station 1 were about  $50 \text{ mg l}^{-1}$ , compared to  $300 \text{ mg l}^{-1}$  7 h earlier (see Fig. 3) during the peak of the river flood. SSC were less than  $10 \text{ mg l}^{-1}$  at the surface, and  $5 \text{ mg l}^{-1}$  at 2 m depth, at the mouth of the bay. The iso-SSC lines sloped upwards towards the ocean.

Transect b was sampled a few hours later, near low tide. The river plume extended all along the channel and it carried suspended sediment at typically  $10\text{--}20 \text{ mg l}^{-1}$ .

Transect c was sampled a day later, and oceanic water had already started to enter Airai Bay along the bottom. Most of the fine sediment in suspension had already dropped out in Airai Bay, with an SSC less than  $2 \text{ mg l}^{-1}$  at stations 2–5. Only the estuary remained turbid. Over the following 4 days (transects d–e and two other transects sampled the following 2 days), brackish water was progressively flushed out of the bay and the estuary. During that time water remained clear in the bay and turbid in the estuary.

Similar processes were observed following the river flood of late May 2002.

#### 3.4. Sediment traps data

As summarized in Table 1, the sedimentation rate decreased by 30.5% between stations 0 and 1. Sediment also settled in the mangroves, with the sedimentation

rate decreasing with increasing distance from the riverbank.

#### 4. Discussion

Because of the small size of the river catchment and the episodic rainfall, the river floods are short-lived, typically lasting less than 12 h. Several such events were sampled in March–June, 2002. The dynamics of river runoff and suspended sediment fluctuated at time scales of hours, with the two dominant time scales being the semi-diurnal tidal period and the duration of the river flood.

The data show that a muddy river plume forms following a storm. The plume starts forming in the estuary, which becomes stratified. Fresher, more turbid, water is found on top. At the first ebb tide, this water leaves the estuary and spreads as a surface plume, typically 2 m thick, throughout Airai Bay. Some of that water is flushed out to the ocean through the channel. Much of the suspended fine sediment settles during the rising tide within the estuary and fringing mangroves, and is not resuspended at the following ebb tide. Fine suspended sediment also settles out rapidly in the bay. At the rising tide, oceanic water enters the bay preferentially at the bottom and fine suspended sediment settles out of the surface river plume and into the intruding oceanic water. This sediment is thus preferentially advected upstream in Airai Bay. At the following ebb tide, about 2% of the sediment remains in the surface plume, thus severely limiting seaward movement of sediments.

Freshwater and terrigenous fine sediment arrive in Airai Bay together, during a river flood, but their fate is different. Freshwater is flushed out of the bay in 5 days, while the bulk of the mud remains trapped in the bay following settlement at the first slack tide. Tidal currents and the small, locally wind-driven waves in Airai Bay do not resuspend this sediment, except near the coast and on the reef flat at low tide. This is evidenced by the lack of a correlation at station 4 between the occurrence of high SSC events and low salinity events at station 4; the low salinity events were due to the river plume while the high SSC events were due to the wind-driven waves resuspension.

It is possible to estimate the sediment budget for Airai Bay. The bulk of the sediment export from Airai Bay occurs during the first ebb tide after the river flood. The budget relies on estimating the flow rates of fresh water in the estuary and oceanic flows into the bay. The actual rates are unknown, but their relative values can be determined from the salinity data, since salinity is a conservative tracer. These flow rates were then multiplied by the observed SSC. The amount of sediment exported from the estuary into Airai Bay is estimated at

Table 1  
Sedimentation rate in the Ngerikiil River Estuary between March 12 and May 2, 2002

Station	Sedimentation rate ( $\text{g cm}^{-2}$ )	Description
M0	1.78	Mangrove edge near Station 0
M1	0.736	10 m inside mangroves near station 0
M2	0.343	20 m inside mangroves near station 0
M3	0.274	30 m inside mangroves near station 0
M5	0.203	50 m inside mangroves near station 0
N1	1.23	Mangrove edge near station 1

85% of the sediment flux at the head of the estuary (station 0), i.e. 15% of the riverine sediment settles in the estuary and fringing mangroves. Only 2% of that sediment appears to be exported from Airai Bay to the ocean.

This outwelling flux may be over-estimated. Indeed, a pulse of muddy, brackish water is exported at the first falling tide following runoff. As the tide reverses, most of the fine sediment settles and is not resuspended later on by tidal currents. Thus the export of terrigenous sediment is largely restricted to the first falling tide following a short-lived river flood. Assuming that on the average short-lived river floods occur equally during rising and falling tide, about 30% of the riverine sediment settles in the estuary and fringing mangroves, and about 1% is exported out of Airai Bay to the ocean.

Thus the mangrove swamp of Airai Bay is an important sediment buffer protecting the reef. This estimate is also supported by the sediment trap data showing, first, a 30.5% decrease in the sedimentation rate between stations 0 and 1 in the estuary, and, secondly, a sedimentation rate of  $2.0 \text{ g cm}^{-2} \text{ year}^{-1}$  in Ngerikiil Estuary mangroves. The  $1 \text{ km}^2$  mangrove swamp of the Ngerikiil River estuary may thus trap 20,000 tons of mud per year, assuming that the 51 days of data are representative of the rest of the year. This sedimentation rate is equivalent to about  $1 \text{ cm year}^{-1}$ , and is similar to that ( $\approx 0.3\text{--}1 \text{ cm year}^{-1}$ ) for Australian mangroves fringing muddy coastal waters (Brunskill, Zagorskis, & Pfitzner, 2002; Furukawa, Wolanski, & Muller, 1997; Wolanski & Duke, 2002; Wolanski, Spagnol, & Ayukai, 1998).

Mud deposited on the reef flat is trapped in the algal mat. It is occasionally locally resuspended in patches, with SSC peaking at  $60 \text{ mg l}^{-1}$ , by small, locally generated, wind waves. This increases turbidity and smothers corals when settling again, further stressing the reef system.

Airai Bay is protected from oceanic swell. Typhoons are exceedingly rare in Palau. Thus, storm-driven resuspension, and the flushing of sediment out of Airai Bay, is probably exceedingly rare. No such events were observed during our study. The fate of terrigenous fine sediment in Airai Bay is thus markedly different from that observed in coral-fringed bays of Guam, another oceanic island North of Palau; these bays are not protected from typhoon-driven waves that flush out the terrigenous mud once or twice a year (Wolanski, Richmond, Davis, & Bonito, 2003). In Airai Bay, the sediment may continue to accumulate, and the resulting phase shift from coral-dominated to algae-dominated may be permanent.

Freshwater runoff probably has limited impact on corals in Airai Bay because it floats above the coral except during periods of extreme low tides. Terrigenous

sediment appears to strongly impact corals in Airai Bay. The data show that about 30% of the terrigenous mud was trapped and settled in the mangroves, 69% in the bay itself, and only 1% may be exported, allowing for continuous accumulation to occur.

## 5. Conclusion

Terrigenous mud, and not freshwater, is responsible for the death of corals in Airai Bay and the phase shift from coral to algal dominance. Burial of corals was observed prior to and during the study. The implication is that coral reef conservation and related fisheries management efforts may not be possible without simultaneously preventing soil erosion in the surrounding catchment.

The mangroves are presently being cleared, adding to the overall impact of poor land-use practices within Ngerikiil watershed. Protection of the surrounding mangroves is a critical issue because they help protect Airai Bay by trapping 15–30% of the riverine fine sediment load. An immediate moratorium on mangrove clearing coupled with erosion control measures are specific actions that can be undertaken to support recovery of the corals and related marine resources of Airai Bay. These recommendations are more likely to be implemented if the community of stakeholders actively pursues and participates in the process of building political will.

The results of this study have broad applications to numerous coastal coral reef ecosystems around the world. Sedimentation associated with poor land-use practices has been identified as a dominant problem by the U.S. Coral Reef Task Force. While the receiving water characteristics of flow, volume and wave exposure may vary among coral reef sites, the underlying principles do not: the accumulation of sediment is one of the worst outcomes possible. In addition to the initial effect of causing outright mortality and drastic changes in community composition, sediment can prevent recruitment of coral larvae as well as recovery of adult colonies that are stressed and or killed as a result of resuspension events.

Mangroves and seagrass beds serve as primary buffers between land-based activities and coral reefs, slowing water flow and allowing sediment particles to settle. Protection of these ecosystems is an essential element of any coastal coral reef conservation effort. In areas flushed by higher levels of wave energy, natural cleansing of coastal bays can occur if the amount of sediment running off land is reduced through erosion control measures. In areas of restricted water circulation, like Airai Bay, recovery may be a much longer process following initiation of land-based watershed management practices.



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## References

- Asaeda, T., & Wolanski, E. (2002). Sinking of muddy marine snow. *Wetlands Ecology and Management* 10, 283–287.
- Ayukai, T., & Wolanski, E. (1997). Importance of biologically mediated removal of fine sediments from the Fly River plume, Papua New Guinea. *Estuarine, Coastal and Shelf Science* 44, 629–639.
- Brunskill, G. J., Zagorskis, I., & Pfitzner, J. (2002). Carbon burial rates in sediments and a carbon mass balance for the Herbert River Region of the Great Barrier Reef continental shelf, North Queensland, Australia. *Estuarine, Coastal and Shelf Science* 54, 677–700.
- Duke, N. C., & Wolanski, E. (2001). Muddy coastal waters and depleted mangrove coastlines-depleted seagrass and coral reefs. In E. Wolanski (Ed.), *Oceanographic processes of coral reefs: Physical and biological links in the Great Barrier Reef* (pp. 77–91). Boca Raton, FL: CRC Press (356 pp.).
- Fabricius, K. E., Wild, C., Wolanski, E., & Abele, D. (2003). Effects of transparent exopolymer particles (TEP) and muddy terrigenous sediments on the survival of hard coral recruits. *Estuarine, Coastal and Shelf Science* (in press). (doi: 10.1016/S0272-7714(02)00400-6).
- Fabricius, K. E., & Wolanski, E. (2000). Rapid smothering of coral reef organisms by muddy marine snow. *Estuarine, Coastal and Shelf Science* 50, 115–120.
- Fortes, M. (2001). The effects of siltation on tropical coastal ecosystems. In E. Wolanski (Ed.), *Oceanographic processes of coral reefs. Physical and biological links in the Great Barrier Reef* (pp. 93–111). Boca Raton, FL: CRC Press (356 pp.).
- Furukawa, K., Wolanski, E., & Muller, H. (1997). Currents and sediment transport in mangrove forests. *Estuarine, Coastal and Shelf Science* 44, 301–310.
- Gilmore, J. (1999). Experimental investigation into the effects of suspended sediments on fertilization, larval survival and settlement in a scleractinian coral. *Marine Biology* 135, 451–462.
- T. Healy, Y. Wang, J. A. Healy (Eds.), *Muddy coasts of the world: Processes, deposits and function* (542 pp.). Amsterdam: Elsevier.
- B. Kjerfve (Ed.), *Coastal lagoon processes* (577 pp.). Amsterdam: Elsevier.
- Lick, W., Lick, J., & Ziegler, C. K. (1992). Flocculation and its effect on the vertical transport of fine-grained sediments. *Hydrobiologia* 235/236, 1–16.
- Logan, B. E., Passow, U., Alldredge, A. L., Grossart, H., & Simon, M. (1995). Rapid formation and sedimentation of large aggregates is predictable from coagulation rates (half-lives) or transparent exopolymer particles (TEP). *Deep Sea Research* 42, 203–214.
- McCook, L. J., Wolanski, E., & Spagnol, S. (2001). Modelling and visualizing interactions between natural disturbances and eutrophication as causes of coral reef degradation. In E. Wolanski (Ed.), *Oceanographic processes of coral reefs. Physical and biological links in the Great Barrier Reef* (pp. 113–125). Boca Raton, FL: CRC Press (356 pp.).
- McManus, J. W., Meñez, L. A. B., Reyes, K. N. K., Vergara, S. G., & Ablan, M. C. (2000). Coral reef fishing and coral–algal phase shifts: implications for global reef status. *ICES Journal of Marine Science* 57(3), 572–578.
- Meade, R. H. (1996). River-sediment inputs to major deltas. In J. D. Milliman, & B. U. Haq (Eds.), *Sea level rise and coastal subsidence* (pp. 63–85). Dordrecht: Kluwer Academic Publishers.
- Peters, E. C., Gassman, N. J., Firman, J. C., Richmond, R. H., & Power, A. (1997). Ecotoxicology of tropical marine ecosystems. *Journal of Environmental Toxicology and Chemistry* 16, 12–40.
- Richmond, R. H. (1993). Coral reefs: present problems and future concerns resulting from anthropogenic disturbance. *American Zoologist* 33, 524–536.
- Richmond, R. H. (1994a). Coral reefs: pollution impacts. *Forum for Applied Research and Public Policy* 9(1), 54–57.
- Richmond, R. H. (1994b). Effects of coastal runoff on coral reproduction. In R. N. Ginsburg (Ed.), *Proceedings of the colloquium on global aspects of coral reefs: health, hazards and history* (pp. 360–364). Rosenstiel School of Marine and Atmospheric Science, University of Miami.
- Richmond, R. H. (1995). Reproduction and recruitment in corals: critical links in the persistence of reefs. In C. Birkeland (Ed.), *Life and death of coral reefs* (pp. 175–197). New York: Chapman and Hall.
- Rogers, C. (1990). Responses of coral reefs and reef organisms to sedimentation. *Marine Ecology Progress Series* 62, 185–202.
- Sato, M. (1985). Mortality and growth of juvenile coral *Pocillopora damicornis* (Linnaeus). *Coral Reefs* 4, 27–33.
- USDI (United States Department of the Interior). (1997). *Environmental impact statement for construction of the Palau compact road, Babeldaob Island, Republic of Palau, Vol. II*. Project No. 296-001, Washington, DC.
- Wolanski, E., & Duke, N. (2002). Mud threat to the Great Barrier Reef of Australia. In T. Healy, Y. Wang, & J.-A. Healy (Eds.), *Muddy coasts of the world: Processes, deposits and function* (pp. 533–542). Amsterdam: Elsevier (542 pp.).
- Wolanski, E., Mazda, Y., Furukawa, K., Ridd, P., Kitheka, J., Spagnol, S., & Stieglitz, T. (2001). Water circulation through mangroves and its implications for biodiversity. In E. Wolanski (Ed.), *Oceanographic processes of coral reefs: Physical and biological links in the Great Barrier Reef* (pp. 53–76). Boca Raton, FL: CRC Press (356 pp.).
- Wolanski, E., Richmond, R. H., Davis, G., & Bonito, V. (2003). Water and fine sediment dynamics in transient river plumes in a small, reef-fringed bay, Guam. *Estuarine, Coastal and Shelf Science* 56, 1029–1040.
- Wolanski, E., & Spagnol, S. (2000). Environmental degradation by mud in tropical estuaries. *Regional Environmental Change* 1(3–4), 152–162.
- Wolanski, E., Spagnol, S., & Ayukai, T. (1998). Field and model studies of the fate of particulate carbon in mangrove-fringed Hinchinbrook Channel, Australia. *Mangroves and Salt Marshes* 2, 205–221.