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Water and fine sediment dynamics in transient river plumes in a small, reef-fringed bay, Guam

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Abstract

Fouha Bay is a 400-m-long funnel-shaped, 10-m-deep, coral-fringed embayment on the southwest coast of Guam. It drains a small catchment area (5 km^2) of steeply sloping, highly erodible lateritic soils. River floods are short-lived and the sediment load is very large, with suspended sediment concentration (SSC) exceeding 1000 $mg\,l^{-1}$. The resulting river plume is about 1 m thick and is pulsing in a series of 1–2 h-long events, with outflow velocity peaking at 0.05 $m\,s^{-1}$. Turbulent entrainment results in an oceanic inflow at depth into the bay. As soon as river flow stops, the plume floats passively and takes 5 days to be flushed out of Fouha Bay. The suspended fine sediment flocculates in 5 min and aggregates on ambient transparent exopolymer particles to form muddy marine snow flocs. In calm weather, about 75% of the riverine mud settles out of the river plume into the underlying oceanic water where it forms a transient nepheloid layer. This mud ultimately settles and is trapped in Fouha Bay. Under typhoon-driven, swell waves, the surface plume is at least 7 m thick and bottom entrainment of mud results in SSC exceeding 1000 $mg\,l^{-1}$ for several days. It is suggested that successful management of fringing coral reefs adjacent to volcanic islands may not be possible without proper land use management in the surrounding catchment.

Keywords: river plume; fine sediment; flocculation; sedimentation; muddy marine snow; coral; Guam

1. Introduction

The impact of sediment-laden river runoff on fringing coral reefs has been the subject of intensive research (see reviews in Fortes, 2001; McCook, Wolanski, & Spagnol, 2001; McManus, Menez, Reyes, Vergara, & Ablan, 2000), yet knowledge of the effects remains qualitative. This is because much of the research to date has focused on studying the changes in coral and algae cover on impacted reefs while little quantitative data have been collected on the quantity and quality of suspended sediments impacting the fringing coral reefs. Quantity is important because sediment can literally bury coral; sedimentation is a major cause of mortality in the initial life stages of hard corals (Cnidaria: Scleractinia). It can locally reduce recruitment rates (Gilmour, 1999; Sato, 1985) and at higher concentrations affects a range of life history parameters in juvenile and adult corals (Richmond, 1994; Rogers, 1990). Quality is also important because the sediment can contain substances harmful to corals such as pesticides and nutrients (Peters, Gassman, Firman, Richmond, & Power, 1997; Richmond, 1993). Additionally, the level of effect also depends on whether or not the suspended sediment is aggregated into marine snow (Fabricius & Wolanski, 2000). Because of increasing levels of reef degradation in coastal waters worldwide, a predictive, quantitative model for this impact is needed to facilitate appropriate coastal zone management.

To develop such a model, a detailed study of the dynamics of fine sediments in a fringing coral reef environment was carried out at Fouha Bay, Guam (143°39′E, 13°17′N; Fig. 1). Fouha Bay is reef-fringed, funnel-shaped, about 400 m wide at the mouth, and 10 m deep on average with a depth varying between

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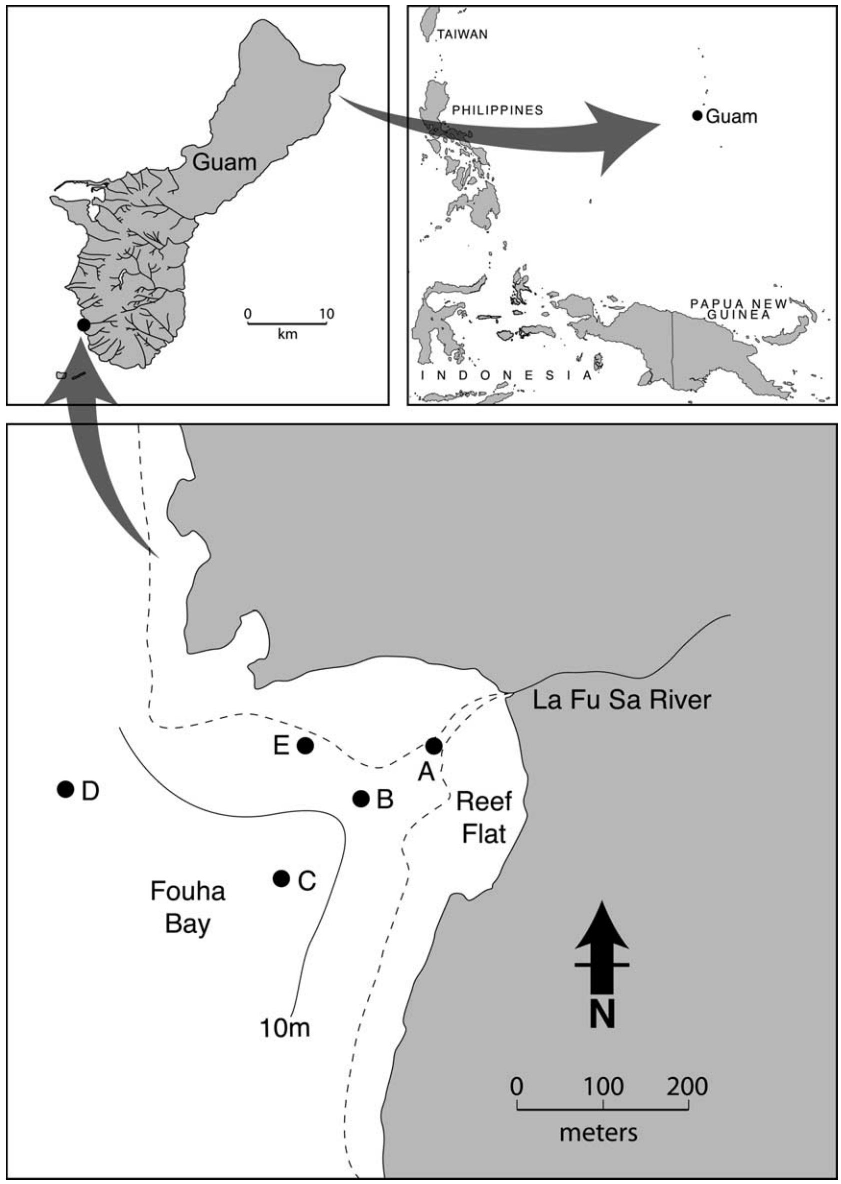


Fig. 1. Map of Fouha Bay in Guam showing the mooring sites and general location maps.

8 m at the base of the reef flat to about 11 m at the mouth of the bay. The adjoining La Sa Fua River catchment area is 5 km^2 and much of it is composed of volcanic, steeply sloping, highly erodible lateritic soils. Annual rainfall is about 2.5 m. The dry season extends from December to June, while the wet season usually lasts from July through November with August to October as the wettest months having a mean rainfall of 35 cm month^{-1}. Much of this rainfall occurs in a few days from local storms or the passage of a typhoon. This causes short, transient river floods, because the La Sa Fua River catchment is small. Minimum and maximum river discharges measured over a 5-year period were, respectively, 0.008 and 29.7 m^3 s^{-1} (Randall & Birkeland, 1978). The La Sa Fua River discharges into Fouha Bay through a small canyon cut through the reef flat. This canyon is about 20–30 m wide with depth varying between 0.5 m at the shore and about 7 m at the reef edge. The canyon is studded with coral outcrops, the tops of which are emergent at low tide. Several other coral outcrops are scattered around Fouha Bay. The coral reef over the reef flat and the coral outcrops were still healthy in 1978 (Birkeland, Tsuda, Lassuy, & Hedlund, 1978; Randall & Birkeland, 1978). Much of the coral died after being buried by sediment in between 1988 and 1990 as a result of sediment-laden runoff following land clearing and road construction (Richmond, 1993). Algal overgrowth followed soon after.

Eleven years later, in 2001, we found that the reef was still heavily overgrown with an algae mat. These algae trapped a large amount of fine sediment that was readily released as a muddy plume when the algal mat was manually shaken. In 2001, hard coral cover in the bay on the outcrops and reef areas along the canyon edge was only 30% with the greatest coral cover found in the inner half of the bay. Total species richness for the bay included 102 hard corals, with the greatest species richness found in the outer half of the bay. Coral cover on the surrounding fringe reef outside the bay was 5%. Species richness on the surrounding fringe reef included 77 hard corals. Substrate in the bay and on the surrounding fringe reef that was not living coral was predominantly covered with turf algae, however, seasonal blooms of *Padina* sp. and cyanobacteria can overgrow the turf algae and dominate the benthos. In 2001, the bottom of Fouha Bay between the opposing reef flats was muddy.

This article reports on a study of the hydrodynamics and fine sediment dynamics in Fouha Bay, during the wet season of July to September 2001. The fresh water/sediment plume has an active and a passive stage. In the active stage, river water forms a jet about 1 m thick and with a velocity of about $0.05\,m\,s^{-1}$. This jet lasts only as long as the river floods, typically a few hours. As soon as significant river runoff stops, the plume floats passively over the underlying oceanic water. The plume thickness is typically 1 m in calm weather and up to 7 m under typhoon-driven swell. In both weather conditions, salinity values seldom are less than 30 in the plume. The riverine suspended sediment concentration (SSC) varies between 1000 and $5000\,mg\,l^{-1}$.

2. Methods

Two field experiments were carried out in Fouha Bay. In the first experiment, five oceanographic moorings were deployed at sites A–E (see location map in Fig. 1) for 2 weeks in July–August 2001. Sites A–D formed an along-bay transect while sites D and E measured the across-bay variability. Salinity, temperature and SSC were measured using self-logging Analite nephelometers, DataFlow salinometers and a YSI self-logging CTD-cum nephelometer. 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 1.5 and 2 m, respectively. At site C, the vertical profiles of horizontal currents were measured using a bottom-mounted Workhorse ADCP. Sites A and B were coral outcrops and the instruments were attached onto star pickets (rebar) driven into the carbonate substratum. At the other sites, the instruments were attached onto mooring lines kept taut by a subsurface buoy. In addition, the vertical profile of salinity, temperature and SSC was measured at intervals of 2–5 days from a ship-born YSI CTD profiler-cum nephelometer.

In the second experiment, the self-logging YSI CTD-cum nephelometer was deployed at site A at 3 m depth. Also at site A, a Dataflow salinometer was deployed at 7 m depth, which was 1 m above the bottom. The vertical profile of salinity, temperature and SSC was measured at deployment.

The nephelometers were calibrated in situ using water samples brought to the laboratory and filtered on $0.45\,\mu m$ filters. These were dried and weighed. The SSC in riverine water during flood periods was also occasionally measured by this method.

Samples for microscopic observations of suspended matter were obtained using the modified technique of Ayukai and Wolanski (1997). Briefly, water samples were collected using a 2.5-cm diameter tube moored at the sampling sites for 10 min. The tube was then capped and the suspended matter settled onto a microscope slide with a 3-mm-deep well. A cover glass was then pushed over the microscope slide. The seal between the slide and cover glass was made water tight, so that settling particles intercepted into the well were recovered without being physically disturbed. The sample was immediately examined under an Olympus inverted microscope with a Sony CCD video camera. The images were captured on an IBM-compatible PC with an interface video card. Riverine water collected during a flood was also examined using this method.

The microscope and image capture facility was also used in a laboratory experiment to determine the speed of flocculation. Turbid freshwater sampled during a local flood of the La Sa Fua River was diluted with unfiltered reef seawater to reach a salinity of 17 and the size of the suspended matter was monitored at 5 min intervals over 1 h.

La Sa Fua River hourly discharge and SSC data were provided by the United States Geological Survey. Discharge was measured at a gaging station located approximately 1 km upstream from the bay and gages just over 50% of the watershed. Reliable river SSC data were obtained from only one flood event.

3. Results

3.1. Calm weather—ship born observations

River runoff was minimal ($\approx 0.1\,m^3\,s^{-1}$) on July 27, 2001, when calm weather prevailed. Fouha Bay waters were vertically fairly well mixed in salinity and SSC (Fig. 2a); the surface river plume was only 0.5 m thick

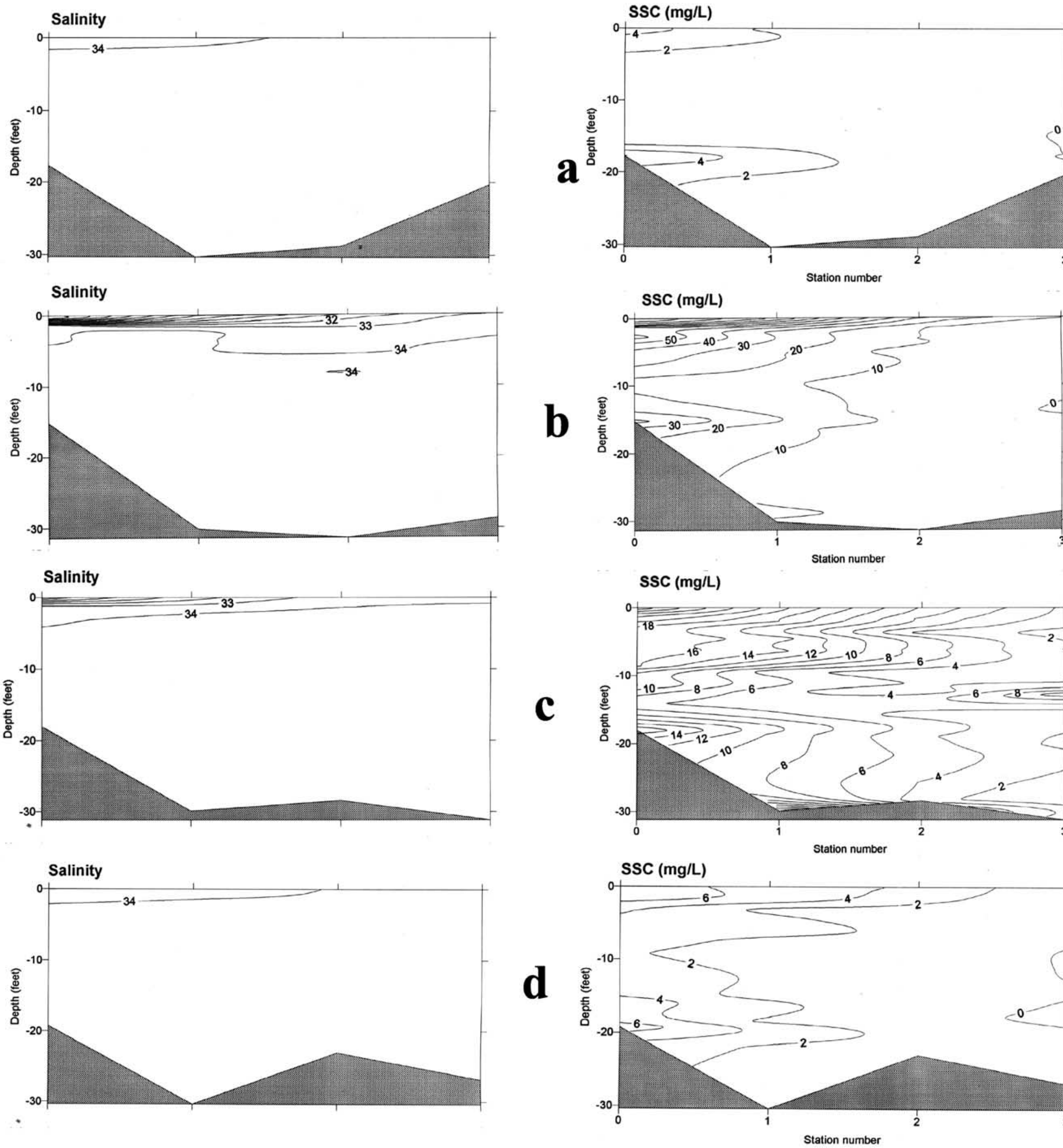


Fig. 2. Along-bay transect of (left) salinity and (right) SSC on (a) 27 July 2001, (b) 30 July 2001, (c) 1 August 2001 and (d) 3 August 2001. Stations 0–3 are labelled A, B, C and D in Fig. 1.

and the minimum salinity about 34. SSC values peaked at $4\,mg\,l^{-1}$ in the river plume near the surface and near the bottom while the mid-waters SSC were less than $2\,mg\,l^{-1}$.

Intense rainfall on July 28, 2001, generated a rapid, short-lived, rise of the discharge of the La Sa Fua River, peaking at $2\,m^3\,s^{-1}$ (Fig. 3). On July 30, 2001, a flood plume was present in Fouha Bay (Fig. 2b). This flood plume was about 1.5 m thick with a minimum surface salinity of 22 at site A and 33 at site D, indicating vertical mixing as river water moved offshore. The isohalines were practically horizontal, indicating that the vertical mixing between fresh and salt water was compensated by radial spreading of the plume made possible by the funnel-shape of Fouha Bay. No major temperature plume was observed. At the same time, the SSC distribution (Fig. 2b) showed no measurable increase of SSC offshore (site D), indicating that much of the riverine sediment remained trapped in Fouha Bay. Within the Fouha Bay there was a 2-m-thick,

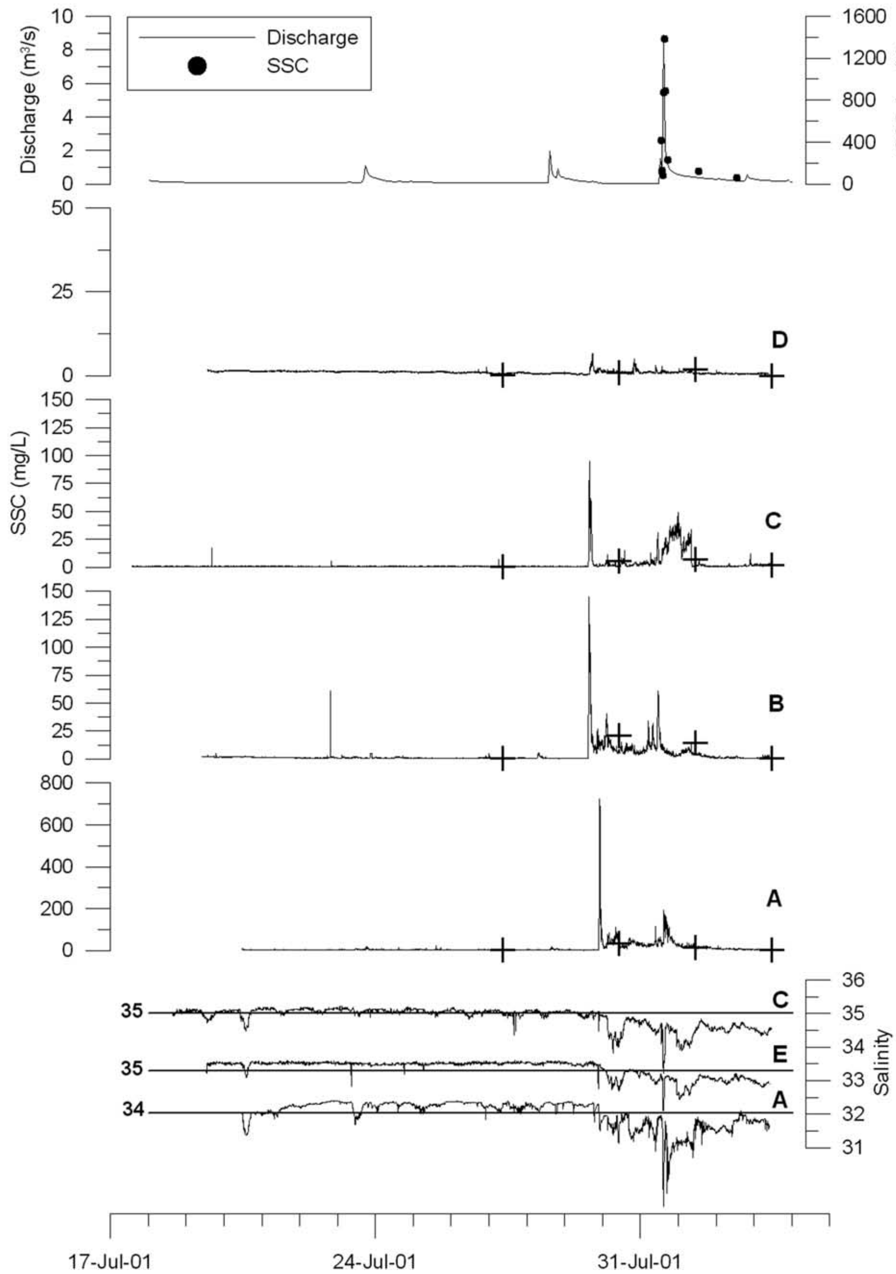


Fig. 3. Time series plot of the discharge ($m^3 s^{-1}$) and SSC of the La Sa Fua River, and the SSC ($mg\,l^{-1}$) and salinity at the mooring sites A–D in July 18–August 3, when calm weather prevailed. Depth is shown in feet (1 ft = 0.3048 m). The crosses indicate independent SSC measurements made using the ship-born YSI nephelometer.

turbidity plume, with SSC peaking at $100\,mg\,l^{-1}$ at site A and $20\,mg\,l^{-1}$ at site C. Contrary to the isohalines, which were nearly horizontal, the SSC contour lines sloped upward with increasing distance offshore, indicating that the suspended matter was settling out of the river plume. The settling, riverine sediment was found throughout the water column below the river plume, with SSC values in the range $10–50\,mg\,l^{-1}$ and decreasing with increasing depth. The settling sediment formed a nepheloid layer with SSC values of about $30\,mg\,l^{-1}$ at 5 m depth between sites A and B.

As shown in Fig. 3, the La Sa Fua River flooded with a peak discharge of about $8\,m^3\,s^{-1}$ on July 31, 2001; this flood was very short-lived. Indeed, the river discharge was ten times smaller 3 h later. River SSC values peaked at $1382\,mg\,l^{-1}$ for this flood with a mean SSC of $528\,mg\,l^{-1}$ during the event. On August 1, 2001 (Fig. 2c), the salinity plume was 1 m thick, with a minimum salinity of 29 at site A and 34 at site D (Fig. 2c). The SSC values were maximum near the surface, peaking at $28\,mg\,l^{-1}$ at site A and $6\,mg\,l^{-1}$ at site C. A second maximum in SSC occurred in the near-bottom nepheloid layer, which covered the sea floor over the whole bay with a peak SSC of 20 mg l^{-1}.

Another 2 days later, on August 3, 2001 (Fig. 2d), the bulk of the salinity plume was flushed out of Fouha Bay and the minimum salinity was about 34. Much of the suspended sediment had been removed based on the maximum values of SSC that peaked at 6 mg l^{-1}. These maximum SSC values occurred both near the surface and near the bottom at site A.

3.2. Calm weather—mooring observations

Semi-diurnal tides prevailed with an amplitude usually less than 0.6 m (see Fig. 5 discussed later).

Three small river floods were experienced peaking at about 1, 2 and 8 $m^3 s^{-1}$ on, respectively, July 23, July 28, and July 31, 2001 (Fig. 3). All these floods were short-lived; the river discharge increased to peak values in 2 h and decreased to baseflow values about 10 h later. There was no significant decrease in salinity at the mooring sites until July 29, after which time the salinity fluctuated widely (see Fig. 3). The fluctuations were highly coherent at all sites in Fouha Bay, indicating that the plume affected the whole bay more or less simultaneously. Minimum salinity was about 31 at the instrument depth (1.5 m) and this agreed closely with that from the ship-born CTD.

The SSC time series at the mooring sites shows a very different pattern than that of the salinity (Fig. 3). The river flood caused no measurable SSC increase at site D (offshore), the maximum SSC increase was about 5 mg l^{-1}, and this was short-lived and occurred immediately following a river flood. Large and rapid SSC fluctuations occurred throughout Fouha Bay following river floods. The largest SSC fluctuations occurred on July 29, 2001 (day 210) immediately following the river flood, peak SSC was about 700 mg l^{-1} at site A (inshore), 150 mg l^{-1} at site B (mid-bay) and 100 mg l^{-1} at site C (mouth of Fouha Bay). This peak presumably corresponds to the initial river plume forming and spreading throughout Fouha Bay, the initial pulse of freshwater containing most of the eroded soil. The salinity time series shows little freshening of the water at the time of peak SSC, implying that this peak was due to sediment that had settled out of the surface plume into the underlying oceanic water. For the next 2 days, SSC fluctuated widely with peak values of 200 mg l^{-1} at site A and about 50 mg l^{-1} at both sites B and C. These peaks occurred during a period of decreased salinity in Fouha Bay, however, there was no apparent correlation between SSC and salinity fluctuations. This observation suggests that riverine sediment reached the instruments both directly with the river plume and by settling from the overlying river plume.

Before the river flood, the currents peaked at 0.02 $m s^{-1}$, fluctuated with the tides, and were fairly uniform with depth (Fig. 4a). In Fig. 4 the data appear noisy, this is because these small velocities are only slightly above the resolution ($\approx$0.01 $m s^{-1}$) of the ADCP.

During the river flood starting in the early hours of day 210, the currents fluctuated rapidly (Fig. 4b). From day 210 to 210.5, the mid-water and surface currents were small (<0.02 $m s^{-1}$) and uniform with depth. Near the surface the currents were different during most of the day, as there were several events (marked O, P, Q, R and S), each lasting 1–2 h, of outflow of water from Fouha Bay with velocities peaking at 0.05 $m s^{-1}$. This outflow is due to the buoyant jet formed by the river discharge exiting Fouha Bay. During the periods of surface outflow, there was also an inflow into Fouha Bay in the bottom half of the water column (Fig. 4b). This flow is interpreted as a return flow of oceanic water entrained into the surface buoyant jet. Hence, there was an outflow of freshwater at the surface and an inflow of saline water underneath the plume. There were also occasional events of inflow in Fouha Bay at the surface (e.g. between events R and S in Fig. 4b), suggesting that internal waves were generated on the pycnocline.

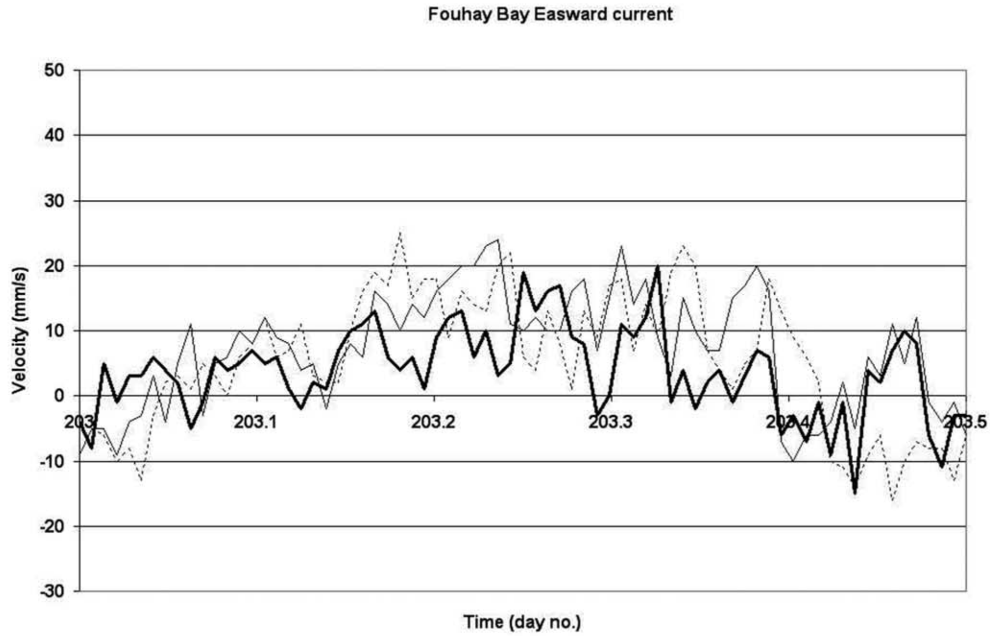
On day 211, the currents were once more fairly uniform with depth, suggesting that the river discharge was small again and the freshwater plume seen in our CTD casts (Fig. 3c) had become passive.

3.3. Typhoon swell—mooring observations

The La Sa Fua River flooded several times between August 11 and 17, 2001, and once on August 21, 2001 (Fig. 5).

The time series of the depth, as measured by the YSI instrument, shows tidal fluctuations with a normal range less than 0.6 m (Fig. 5). From August 13 to 20, 2001, the depth sensor also recorded wide fluctuations, up to 4 m peak to trough, due to swell waves driven by the passage of a typhoon. There was a second, smaller, typhoon between August 26 and 29, 2001.

There were small differences in temperature (up to 0.4 °C; the top waters being warmer) between top and bottom waters before the typhoon passed nearby, and no differences during and after the typhoon (Fig. 5). There were small differences in salinity (up to 0.7; the top waters being fresher) between top and bottom waters before the typhoon, and no differences during the typhoon. This indicates that the swell waves were able to vertically mix the river plume to at least 7 m depth. During the typhoon, which was accompanied by several river floods, minimum salinity was 30 for about 3 h on August 13, 2001. A second, major low salinity event occurred on August 21, when the minimum salinity was about 24 and this lasted about an hour. The salinity data (Fig. 5) show that freshwater was



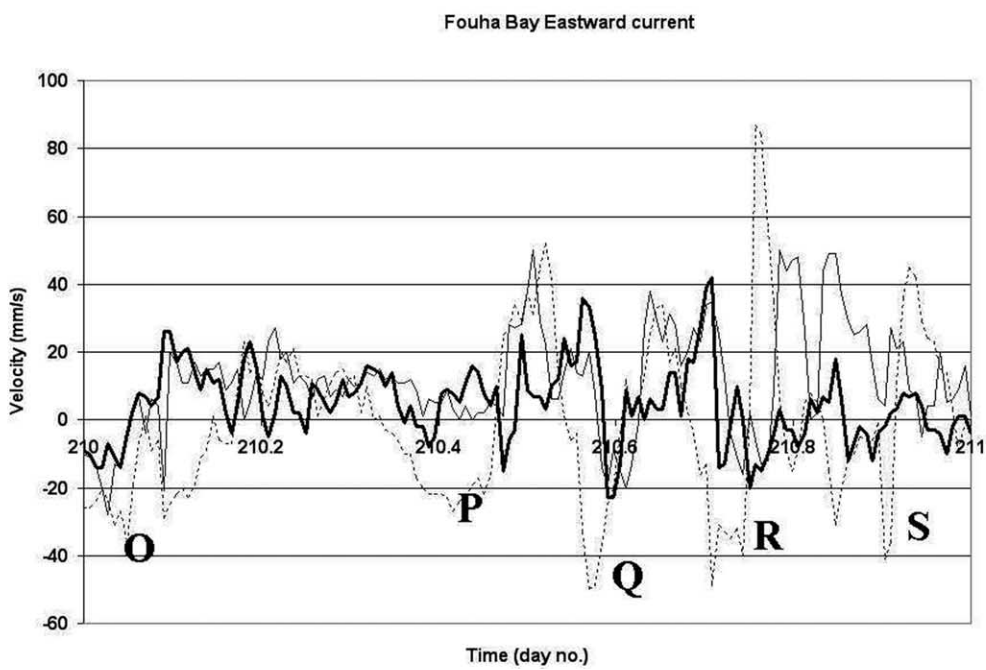


Fig. 4. (a) Time series plot of the along-axis (positive for eastward, i.e. shoreward) current at site C at (thick line) 1 m off the bottom, (thin line) mid-depth and (dotted line) 1 m off the surface during day 203 when calm weather prevailed and river runoff was negligible. (b) Same as (a) for day 210 when calm weather prevailed and the La Sa Fua River was in flood. The symbols O, P, Q, R and S indicate pulses of freshwater outflow (see text).

flushed out in 2 days from Fouha Bay under the typhoon-generated swell.

During the typhoon, SSC values at 3 m depth peaked at 2000 mg l^{-1} (Fig. 5) and this peak occurred at the same time as the minimum salinity, suggesting this sediment pulse was a river-driven event. From August 15 to 19, SSC values at 3 m depth frequently exceeded 1000 mg l^{-1}, with a maximum value of 2000 mg l^{-1}. These high SSC values were due both to mud resuspension from the bottom and runoff (the latter mainly on August 15 and 16).

There was a second period of high SSC during the period 27–28 August 2001, when no significant salinity decrease was observed (Fig. 5). This period also corresponds to high wave activity. This suggests that waves resuspended the bottom. There was also a small flood on the 27th but no SSC reported from the river.

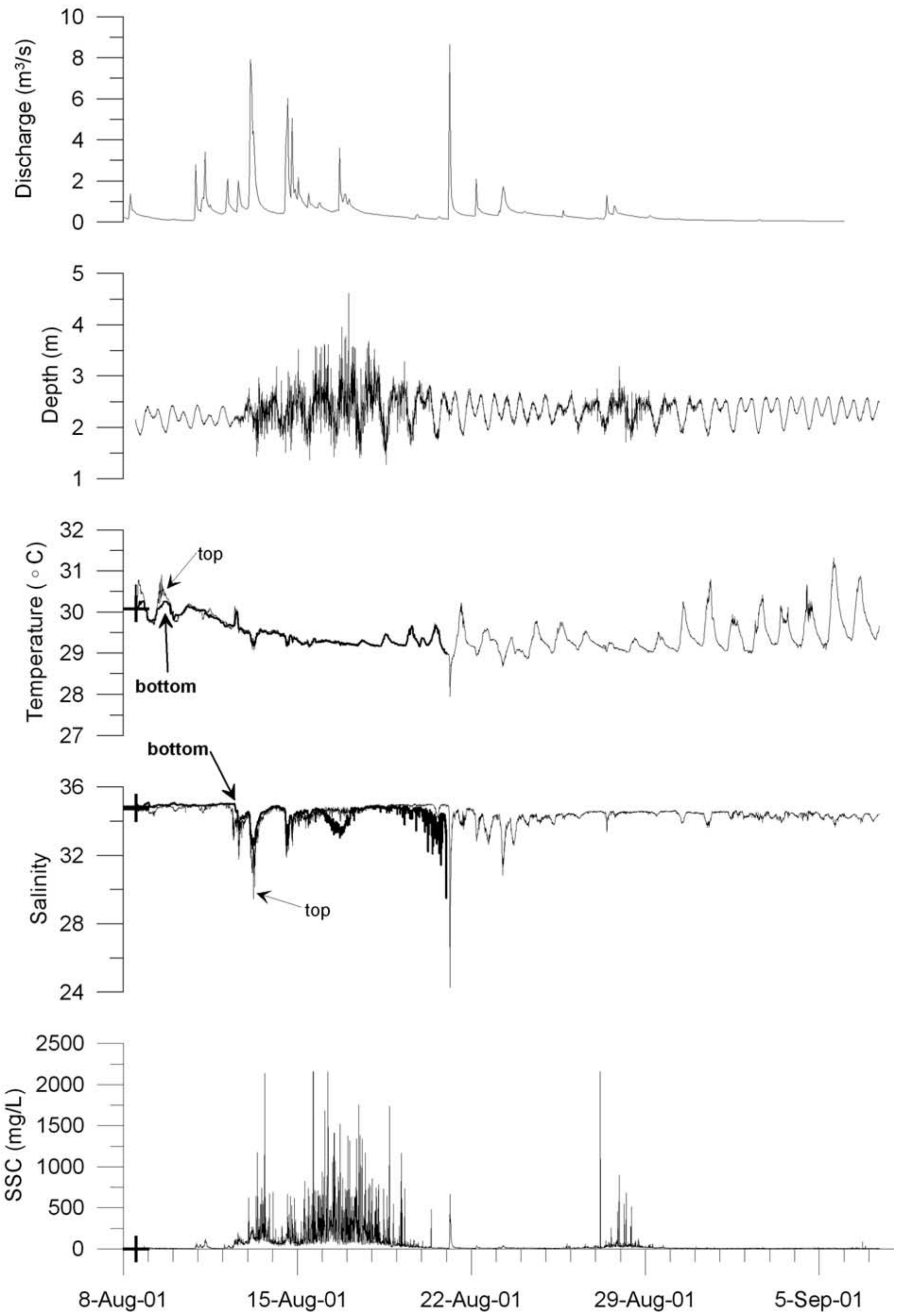


Fig. 5. Time series plot from August 8, 2001 to September 12, 2001, of the discharge of the La Sa Fua River ($m^3\,s^{-1}$) and the water depth (m), temperature (°C), salinity and SSC ($mg\,l^{-1}$) at mooring site A. Water depth and SSC were measured by the YSI CTD attached to a coral outcrop at a nominal depth of 2 m; salinity and temperature were measured both by (top) the YSI CTD at 2 m depth and by (bottom) a DataFlow salinometer attached to the same coral outcrop at 7 m depth which was 1 m off the bottom.

3.4. Flocculation

The suspended matter in Fouha Bay underneath the river plume was observed to be composed of muddy marine snow flocs (Fig. 6), that is, aggregates of mud and transparent exopolymer particles (TEP). These flocs were similar in size and appearance to those described by Ayukai and Wolanski (1997) and Wolanski, Spagnol, and Ayukai (1998). Water containing such flocs was sampled in tubes and allowed to settle in quiet conditions. The floc settling velocity was found to be typically 0.5–1 $mm\,s^{-1}$, according to the size and shape of the floc and the mud content. Typical floc size was 200–700 μm before the river flood (Fig. 6). In the river flood plume, the floc size was similar and the settling velocity appeared higher, peaking at 3 $mm\,s^{-1}$. Visual

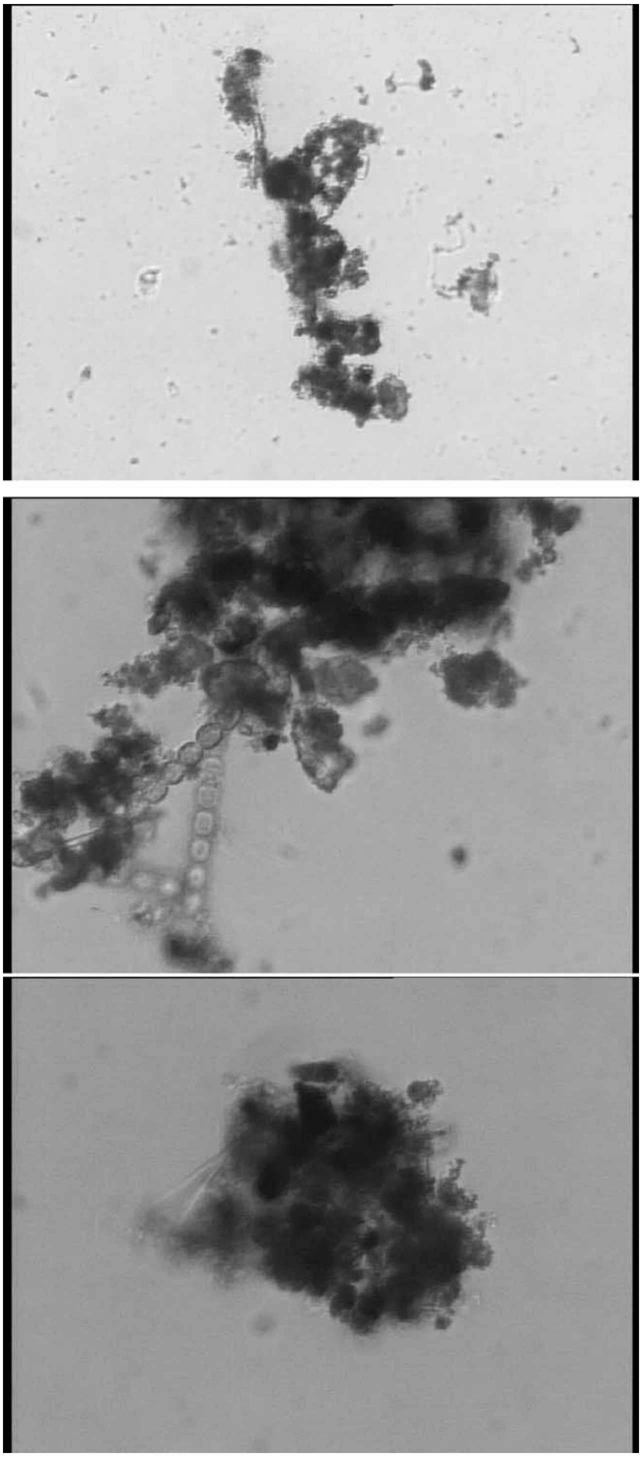


Fig. 6. Microphotographs of typical muddy marine snow in Fouha Bay (top and middle) below the river plume and (bottom) in the river plume. The width of the photograph is 1 mm.

observations using a microscope suggest that this higher settling velocity may be due to the higher mud concentration on the flocs, the mud behaving like a ballast for the marine snow. During river floods the flocs were observed to host numerous zooplankton that were feeding on organic matter, similarly as reported by Ayukai and Wolanski (1997).

The suspended sediment in the river was observed (not shown) to be largely unflocculated. No flocs greater than 50 μm were observed and flocs greater than 30 μm were rare. After this water was mixed in a ratio of 1 : 1 with clear, unfiltered reef seawater, the sediment was observed to flocculate rapidly, with flocs of 300 μm formed in 5 min. Floc size reached 1000 μm in 10 min and did not increase thereafter (not shown).

4. Discussion

River runoff is minimal in fall, winter and spring. In summer, the wet season, rainfall often results from local storms as well as from typhoons. Because of the small catchment, the river floods are short-lived, typically lasting less than 12 h. Several such events were sampled in July–September, 2001. Our study showed that the dynamics of river runoff and suspended sediment dynamics fluctuated at time scales of hours. These short time scales may invalidate the conclusions from previous studies of salinity and suspended sediment in Fouha Bay, since these were carried out at monthly intervals (Randall & Birkeland, 1978).

The field data highlight the key processes controlling the fate of river runoff for small rivers in coastal waters in poorly flushed embayments such as Fouha Bay; these are sketched in Fig. 7. When the river flood occurred in calm weather, i.e. when rainfall results from local, short-lived storms, the river plume was less than 1 m thick with a minimum salinity of about 30. The active stage of the river plume, i.e. the period when brackish water formed a surface jet, occurred in a series of events, each lasting about 1–2 h for a total of about 8 h. This pulsing of the jet outflow, at few hourly periods, may be due to non-linear dynamics of the buoyant jet (Garvine, 1995). After cessation of the river discharge, the plume floated passively at the surface. The maximum along-bay flow velocity in the plume peaked at $0.05\,\mathrm{m\,s^{-1}}$ during an outflow event; the mean velocity during an outflow event was about $0.025\,\mathrm{m\,s^{-1}}$. Outflow events were accompanied by a return flow of oceanic water, due to turbulent entrainment into the jet. After the flood, the surface freshwater plume was passive and negligible net currents resulted. Flushing was thus very slow; the salinity data revealed that it took 5 days for the plume to be flushed out from Fouha Bay after a river flood.

When the river flood occurred accompanied by a 4-m typhoon-driven swell, vertical mixing was enhanced and the plume reached 7 m in thickness, with minimum salinity of 25, but more commonly 30. The salinity data revealed that in such cases flushing is much more rapid, with time scales of 1–2 days.

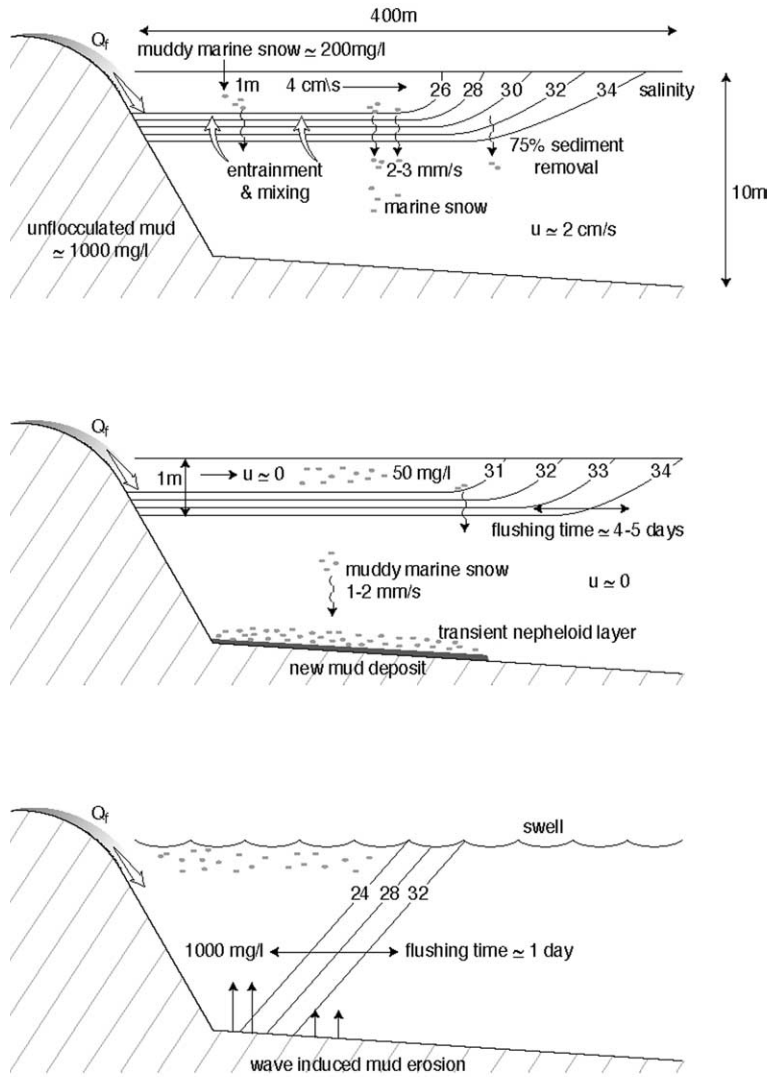


Fig. 7. Sketch of the dynamics of river and fine sediment in the transient river plume in Fouha Bay (top) during the river flood in calm weather, (middle) after the river flood in calm weather, and (bottom) during the river flood under a typhoon-driven swell.

The river inflow was extremely muddy, with SSC in the range of 1000–5000 $\mathrm{mg\,l^{-1}}$. In reaching Fouha Bay, the fine sediment in suspension coagulated on the existing marine snow and formed muddy marine snow. In calm weather, this material settled out of the plume to mix in the bulk of the coral-containing seawater underneath the plume (Fig. 7). It formed a transient, near-bottom nepheloid layer.

It is possible to estimate the riverine sediment budget in calm weather for the river flood of July 29, 2001. The ADCP data suggest that during the active stage of the plume, freshwater took about 8 h to exit Fouha Bay. With a typical settling velocity of 2 $\mathrm{mm\,s^{-1}}$, the bulk of the suspended sediment settled out of the river plume in 6 h into the oceanic waters of Fouha Bay which has negligible flushing in calm weather, as shown by the ADCP data. Thus, about 75% of the riverine sediment exited the plume and mixed in the underlying oceanic water of Fouha Bay in calm weather. Because these waters are little-flushed, and indeed are entrained shoreward during a surface outflow event, this sediment is effectively trapped in Fouha Bay.

SSC values were even higher under a typhoon-driven swell, reaching 2500 $\mathrm{mg\,l^{-1}}$ in hours-long events that were frequently repeated during a week. Such high SSC values were probably caused by bottom sediment re-suspension by the 4-m typhoon-driven swell. At such high SSC the corals in the bay lived in complete darkness for a week.

On September 16, 2001 a flood occurred in Fouha Bay from which river SSC data were obtained (not shown). River SSC peaked at 3759 $\mathrm{mg\,l^{-1}}$ with a mean value of 1497 $\mathrm{mg\,l^{-1}}$ for the event. Based on two flood events recorded by the USGS, a mean river SSC value of 1000 $\mathrm{mg\,l^{-1}}$ during flood events is a reasonable assumption.

The La Sa Fua River has a mean discharge of $0.125\,m^3\,s^{-1}$, 70% occurring in the wet season. During the wet season, the bulk of the flow is made up of about 10 river floods, each lasting 10 h, with a peak discharge of about $8\,m^3\,s^{-1}$. These floods bring eroded, fine sediment in Fouha Bay at a mean concentration of about $1000\,mg\,l^{-1}$. If the bay has a sediment trapping efficiency of 75%, the annual sedimentation rate in Fouha Bay is about $1.8 \times 10^6\,kg\,year^{-1}$. With a surface area of about $4 \times 10^4\,m^2$, Fouha Bay sedimentation rate is about $2.2\,cm\,year^{-1}$. Some of this sediment may be removed by wave action associated with passing typhoons. The typhoon of August 2001, kept $4 \times 10^5\,kg$ of fine sediment in suspension during 7 days. During those 7 days there were four periods when the SSC values decreased to values less than $50\,mg\,l^{-1}$ while the rest of the time SSC values were larger than $500\,mg\,l^{-1}$. This suggests that the bay was cleared of suspended sediment four times, i.e. a total of $1.6 \times 10^6\,kg$ of mud either settled or was exported out of Fouha Bay during this typhoon. Settling appears unlikely because swell was experienced throughout. Thus, the data suggest that 7 days of typhoon-driven swell may flush out the annual riverine sediment inflow.

Observations by divers suggest that the central part of Fouha Bay is covered by 0.5 m of mud, corresponding to a deposit of $7 \times 10^6\,kg$ of mud. The mean residence time of riverine fine sediment in Fouha Bay is thus 4.3 years. In the absence of any additional riverine sediment inflow, this sediment could be exported after 30 days of typhoon-driven waves, for a similar typhoon strength as the one in August 2001. Such flushing of a bay was observed at a nearby site, Facpi Point, following a relatively dry typhoon in 1992 (Richmond, 1993).

In calm weather, freshwater runoff probably had no major impact on coral because it floated on the ocean surface. Only during typhoons could brackish water impact the corals below 1 m depth. Riverine sediment may, however, strongly impact coral in Fouha Bay. The data show that much of the terrigenous mud was trapped and settled in Fouha Bay. A key reason for that was the formation of muddy marine snow. The unconsolidated clay particles in riverine water have a settling velocity of about $0.001\,mm\,s^{-1}$ (Gibbs, 1985), thus they are readily carried by the turbulent river flow to the coast. There they coagulated within 5 min—as our laboratory experiments showed—into ambient TEP (or marine snow; Alldredge, Passow, & Logan, 1993; Passow & Alldredge, 1994), forming muddy marine snow. This muddy marine snow had a settling velocity of typically $0.05–3\,mm\,s^{-1}$. Such high settling velocities have been observed in other muddy, organic-rich coastal environments (e.g. Eisma, 1986). The origin of TEP may be due to microbes, diatoms and metazoans such as appendicularians, that exude dissolved mucopolysaccharides that may become particulate through the formation of cation bridges (Alldredge, Cole, & Caron, 1986; Hansen, Kiørboe, & Alldredge, 1996; Logan, Passow, Alldredge, Grossart, & Simon, 1995). They also serve as substrate for microbes (Alldredge et al., 1986) and as particulate food for grazing plankton (our observations).

In Fouha Bay, the formation of muddy marine snow may be the key process leading to reef degradation for a number of reasons. Firstly, it leads to rapid settling of the suspended mud out of the river plume, thereby preventing the export of this material out of Fouha Bay. About 75% of the riverine sediment inflow may be trapped in the bay. This sedimentation occurs during the wet season, which is also when juvenile corals of many, but not all, species have just settled on the substrate, and these juveniles are particularly susceptible to sedimentation even if they are spared freshwater impacts if the river plume floats on top of them. Secondly, since Fouha Bay is a fine sediment trap, mud has presumably accumulated in quantity since the adjoining land was cleared. This mud resuspends under typhoon-driven swell. This may occur few times a year. In each such event, high SSCs ($\approx 1000\,mg\,l^{-1}$) essentially shuts off all light at a few meter depth for several days. When the weather calms down after the typhoon leaves, this sediment settles on both adult and juvenile corals. Thirdly, high turbidity may lead, in the nepheloid layer, to oxygen consumption exceeding production (Richmond, 1987); if this lasts several days in calm weather, significant dissolved oxygen may result that will further stress the juvenile corals.

5. Conclusions

It appears thus that terrigenous mud, and not freshwater, may be responsible for the failure of coral to recover in Fouha Bay. The implication is that coral conservation and management may not be possible in fringing reefs facing volcanic islands without simultaneously preventing soil erosion in the surrounding catchment.

The data suggest that Fouha Bay is flushed annually by waves generated from typhoons passing to the south of Guam. If sediment input can be substantially reduced through improved land-use practices, water and substratum quality should improve and provide the conditions for reef regeneration to occur.

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