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Research Article

Effects of Land-Use Change on Characteristics and Dynamics of Watershed Discharges in Babeldaob, Palau, Micronesia

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This study assessed the impacts of differing levels of land development in four watersheds in Palau on river sediment yield and on sedimentation and turbidity. Area corrected sediment yield was strongly related to land development ($r^2 = 0.96$, $P = 0.02$), varying from 9.7 to 216 tons km^{-2} yr^{-1} between the least and most developed watershed. Mean sedimentation rates on reefs ranged from 0.7 to 46 mg cm^{-2} d^{-1}, and mean turbidity ranged from 9 to 139 mg l^{-1}. The higher values exceeded those known to harm corals. Because Palau's watersheds and estuaries are small, river floods were short-lived (typically lasting less than a day) and the estuaries adjusted just as quickly to a number of different estuarine circulation patterns that, in turn, generated a large variability in the export of riverine fine sediment to the reefs. The ultimate fate of the fine sediment deposited on the reefs depended on wind resuspension, local currents, and geomorphology (whether the bay was open or semi-enclosed). Palau's small estuaries were generally not as effective as bigger estuaries in trapping sediments and thus at sheltering the reefs. Therefore, greater efforts are needed to control and mitigate land activities that contribute to the increase in sediment yield.

1. Introduction

Coral reef ecosystems include some of the most diverse biological communities on earth, and like other ecosystems, are being lost due to anthropogenic disturbance. Approximately 20% of the world's coral reefs are already severely degraded, with another 24% under imminent risk and 26% expected to be lost within the next several decades [1]. Documented losses include taxonomic diversity, genetic diversity, elements of ecosystem structure and function, resilience to disturbance and ecosystem services. The major human-induced stressors affecting coral reefs include exploitation of resources (including overharvesting of herbivorous fishes that control algal populations), global climate change responsible for mass-bleaching events and ocean acidification, and land-based sources of pollution tied to increased levels of erosion and sedimentation from the modification of adjacent watersheds.

Sedimentation of coastal environments is a major issue worldwide, with most of the increase attributed to land clearing for agriculture and other activities that disturb the land surface [2]. A worldwide analysis of high sediment areas shows that coral reefs are less likely to be found near areas with naturally high terrestrial runoff [3]. For those areas that do have coral reefs, 22% of them face medium to high threats from increased sedimentation [4].

Numerous studies have documented the effects of sedimentation on local coral reefs at the community level [5, 6]. Declining coral cover [7–12], low coral density [11], low biodiversity [7–9, 12, 13], and reduced coral recruitment [11, 14–16] have been found on reefs exposed to sediment stress. Sedimentation combined with overfishing can hinder the

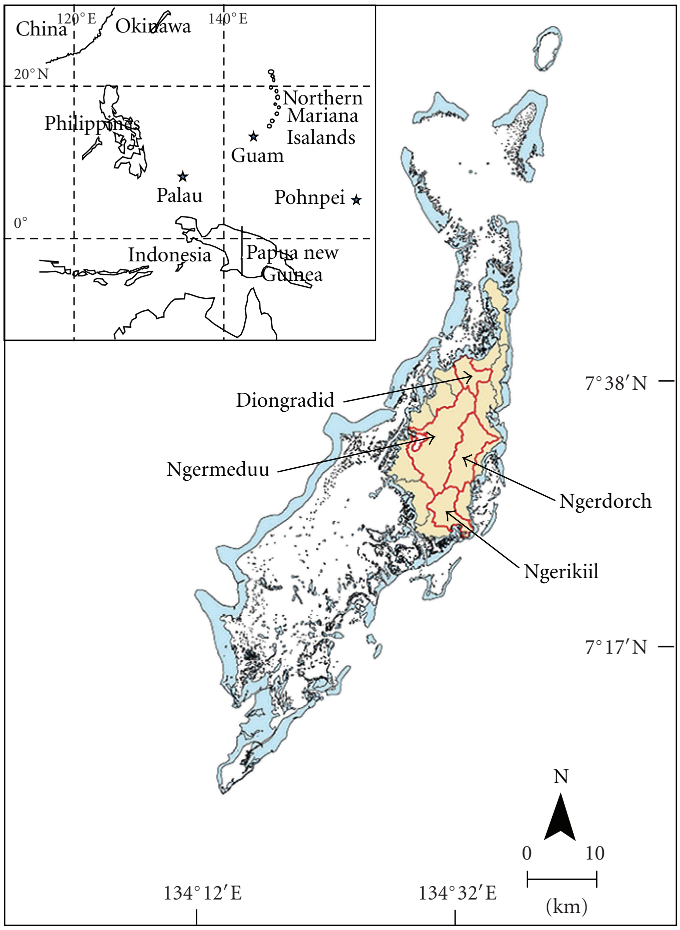


Figure 1: Map of region and Palau showing the four watersheds studied. Beige color indicate Babeldaob land area, blue indicates the reef area and the red lines mark the boundaries of the four watersheds studied.

recovery of coral reefs damaged by bleaching [17]. Fabricius et al. [18] documented species-specific mortality of coral reef organisms exposed to high sedimentation, and predicted that repeated sedimentation will lead to lower cover and diversity on reefs.

Recent studies have demonstrated that increases in sediment discharges from watersheds associated with poor land-use practices can impact reefs over 100 km from shore, and that ecosystem-based management efforts that integrate sustainable activities on land with maintaining the quality of coastal waters and benthic habitat conditions are critically needed if coral reefs are to persist [19]. Land-sea connections are well recognized within Pacific Island communities, and several of these cultures reflect this understanding through land ownership practices that incorporate the “ridge to reef” concept and the integration of sustainable activities and responsibilities. Many Pacific Island cultures maintain reef tenure systems, where village ownership extends from “ridge to reef”, with a clear understanding that upstream activities will impact downstream ecosystems including mangroves, seagrasses and coral reefs. These cultures demonstrate recognition of key elements of ecosystem-based management and even marine spatial planning that segregates incompatible activities through traditional restrictions on certain practices, the prohibition of harvesting particular species, and keeping certain areas closed or accessible only during limited periods to avoid harvesting during spawning events.

Micronesia is a region in the western Pacific made up of many small islands and island states, including Palau (Figure 1). While coral reefs in Micronesia are generally healthy and in good condition [20], most face threats from increasing sedimentation due to their close proximity to land, and the increasing activities and development within adjacent watersheds. Several studies in Micronesia have shown that an increase in sedimentation had severe consequences for the adjacent coral reefs [13, 19, 21–24]. These studies focused on single watersheds on Micronesian islands that have been degraded by human activities. What is lacking is the analysis and quantification of how varying levels of development in the different watersheds with similar soil types and rainfall affect adjacent coral reefs, and in turn, how these findings may be used to promote ecologically sustainable development in island states that have few other natural resources on which to rely.

Our study area is the island of Babeldaob in the Palau archipelago. Babeldaob has experienced major landscape

Table 1: Summary of physical parameters and sediment rates at the four watershed study sites.

Watershed	Size (km^2)	*Non forested area (km^2)	# of earthmoving permits (2000–2007)	Mean rainfall (mm month^{-1})	River Flow Q (m^3 s^{-1})	Sediment Flux (kg s^{-1})	Sediment Yield (tons km^{-2} yr^{-1})	**Sedimentation rate (mg cm^{-2} d^{-1})	Mean SSC on reef (mg l^{-1})	Peak SSC on reef (mg l^{-1})
Diongradid	20.6	1.3	20	231	5.7	0.03	49.2	1.1	9	636
Ngermeduu	86.3	9.1	55	292	18.4	0.59 (0.19)***	215.7	4.6	139	1,123
Ngerdorch	47.4	7.8	15	235	3.8	0.01	9.7	1.8	2	24
Ngerikiil	28.5	2.8	168	312	7.2	0.42	462.4	4.1	38	943

*Mike Aurelio, David Idip, Jr. and Tarita Holm provided the data on nonforested area. The data were digitized from Quick Bird satellite image of Babeldaob. It was digitized as a shapefile using Arc view. Later the data was converted into arcinfo coverage.

**Data are from the first reef station with the highest sedimentation rate closest to the river mouth.

***Number in parenthesis indicates the sediment flux of one river. This number was multiplied by 3 to get total sediment flux for this watershed. This was done because only one of the three rivers that drain into Ngermeduu Bay was gauged and we assumed that all three rivers have about the same sediment flux, since their catchment areas and degree of development were similar.

modifications over time, including extensive terracing and population growth, resulting in development and the overharvesting of resources [25]. The reefs in our study sites were not in pristine condition at the start of our study in the year 2006 because they had suffered from numerous anthropogenic and natural disturbances including an extensive bleaching event in 1998 [26, 27]. There is concern that today's rapid rate of development and extensive land clearing may lead to further degradation and eventual demise of reefs adjacent to Babeldaob.

To support and inform local land management initiatives, the aim of this study was to assess the impact of differing levels of development in the watersheds on sedimentation and health of adjacent coral reefs. In particular, this study provides answers to the following questions: (1) how can differences in land use and land development be quantified? (2) what is the explicit relationship between land development in the four watersheds and their river sediment fluxes? (3) what is the relationship between the river sediment fluxes in the four watersheds and the rates of sedimentation on coral reefs, based on local sediment dynamics? This paper also explains how the data from this and previous studies are being used by communities to guide development through activities that bridge science to management and policy in a culturally appropriate manner.

2. Materials and Methods

2.1. Study Sites. The volcanic Babeldaob Island in Palau (Figures 1 and 2) was our study area. It is the largest island in the Palau archipelago, with a total land area of 409 km^2. It is dominated by highly weathered and highly erodible tropical soils, some of which occur on steep slopes. The island is drained by numerous streams and rivers that flow either directly onto the fringing reefs surrounding the island or into the bays before flowing to the reefs. The most developed watersheds are on the southern part of the island, while farther north, the watersheds are less affected by human activities. Between the fringing reef and the barrier reef, patch reefs occur at varying distances from the mouths of the rivers. Four watersheds were selected for this study. Two of the watersheds (Ngerdorch and Ngerikiil) are located on the east coast, and the other two watersheds (Diongradid and Ngermeduu) are on the west coast. The soils in our study sites are volcanic in origin [28]. The degree of development varies among the different watersheds. Earth moving permits in the period from 2000 to 2007 were used to indicate the level of development in each of the four watersheds, as summarized in Table 1. The Ngerikiil watershed was the most developed watershed followed by Ngermeduu and Diongradid. Ngerdorch was the least developed, having the least amount of earth moving permits issued for activities in this watershed.

2.1.1. Diongradid Watershed and Bay. The Diongradid watershed, with an area of 20.6 km^2, is the smallest of the four watersheds in this study. Unpaved roads are an issue here as well as in the other three watersheds. There are also abandoned bauxite mining sites from the 1900s that still have little vegetation cover. Ninety-four percent of the area is forested while 6% is impacted by human development (Table 1). The Diongradid watershed drains into Diongradid Bay (Figure 2).

2.1.2. Ngermeduu Watershed and Bay. The Ngermeduu watershed is the biggest watershed in Babeldaob with an area of 86.3 km^2, containing several big farms and many unpaved roads. Eighty-nine percent of the Ngermeduu watershed is forested, while 11% of the area is nonforested (Table 1). Our study focused on the Ngermeskang River, one of the three rivers of the Ngermeduu watershed. These rivers drain into Ngermeduu Bay, which is an area of high marine biodiversity, with well-developed reefs near its mouth (Figure 2).

2.1.3. Ngerdorch Watershed and Bay. The Ngerdorch watershed has an area of 47.4 km^2(Figure 2). While Ngerdorch does not have the large-scale development found in Ngerikiil, there are unpaved roads and minor housing projects in the watershed. The watershed area is 84% forested, while 16% is not covered by forest (Table 1).

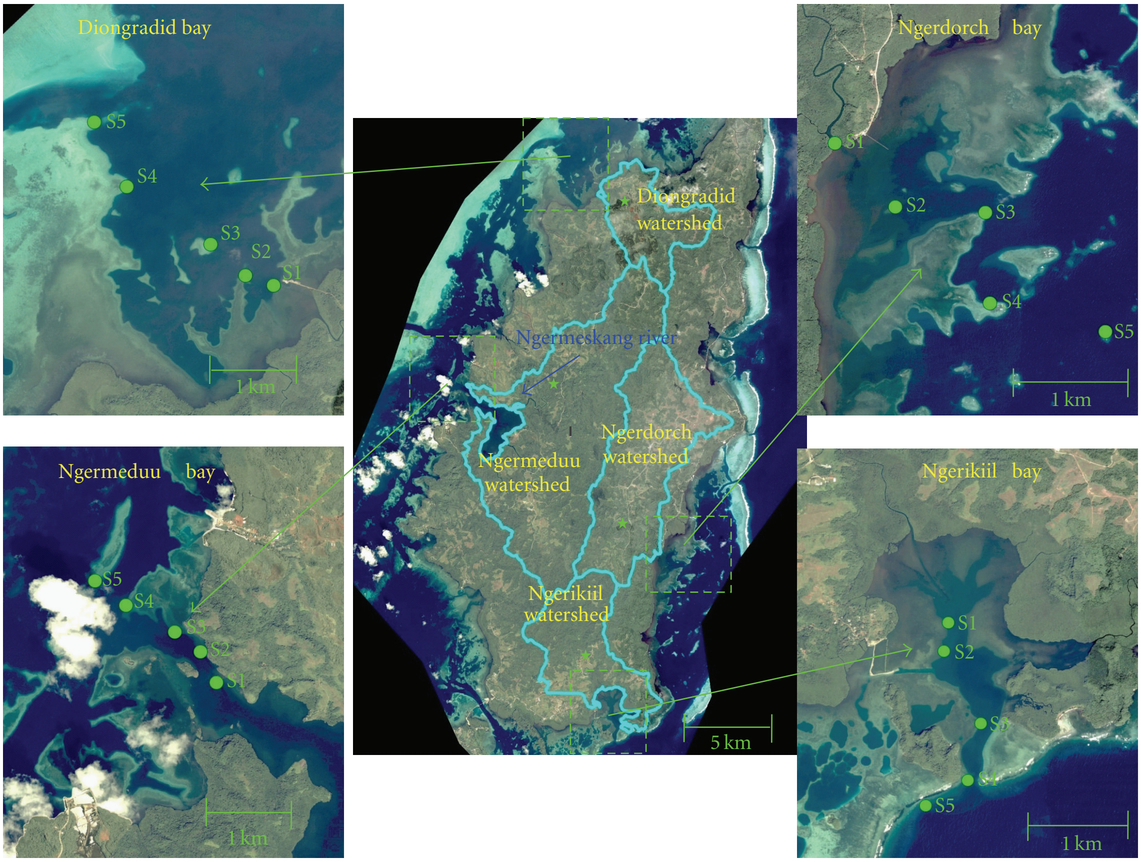


FIGURE 2: Aerial photograph of Babeldaob showing the four watersheds and a close-up of their adjacent bays with stations (S) marked. Stars indicate locations of level loggers along the river in each watershed.

2.1.4. Ngerikiil Watershed and Bay. The Ngerikiil watershed has an area of 28.5 km^2. It is the closest watershed to Koror, the main city in Palau, and is thus subject to the largest development pressure (Figure 2). Ninety percent of the area is vegetated, while 10% is heavily impacted by human development including many unpaved roads, urbanization, commercial and artisanal farms, and various land clearing activities (Table 1). The watershed is located in Airai State, bordered by Koror State, the commercial center for Palau.

The watershed delineations were provided by Palau Automated Land and Resource Information System. The data was digitized from USGS topographic maps. It was digitized as a shapefile following the contours of the USGS Topo map, using ArcView, and converted into coverage data using Arcinfo. The original line definition for the watershed shapes were created by the USDA Natural Resource Conservation Service along with official watershed identification numbers (codes). The Natural Resource Conservation Service delineates watershed boundaries based on United States federal guidelines [29]. The topography of Babeldaob, with little flatlands, allow for easy delineation of the watershed boundaries. Each watershed drains into a single bay, and any flows from adjacent watersheds would be very minor compared to those coming directly from the rivers in the watershed studied.

2.2. Rainfall. Daily rainfall data were collected using HOBO (Onset Computer Corporation, Massachusetts, USA) Weather Station Rain Gauges at the four watershed sites from April 2005 to August 2007.

2.3. River Sediment Flux. Water level loggers (Solinst Levelogger model 3001, Solinist Canada Ltd., Ontario, Canada) were placed in the rivers draining the four watersheds from December 2005 to February 2007 (Ngermeduu data are only available up to May 2006). The water level loggers recorded the water level every 10 minutes. For each of these four rivers, we measured water currents over the entire depth of the river cross-sectional area. Measurement were conducted at ten stages of discharge that ranged from very low flow to flood conditions. We thus obtained a rating curve to convert water level data into river discharge data. Similarly, a sediment-rating curve was obtained by measuring the suspended sediment discharge and relating it to flow and water level. Using both generated rating curves, we calculated the water flow and sediment discharge in each river at 10 minutes intervals throughout the study period.

2.4. Oceanographic Moorings. Oceanographic moorings were deployed at the four bays draining the watershed study sites (Figure 2). Within each of the bay, five reef stations were established along a perceived discharge gradient from the mouth of the rivers to offshore. YSI (YSI incorporated, Yellow Springs, Ohio) self-logging CTD-cum nephelometers were used to measure coastal turbidity (quantified as suspended solid concentration, SSC), temperature, and salinity. The YSI loggers were placed about 0.3 m above the bottom of the reef at a depth of 3 m. The YSI instruments had wipers that cleaned the sensors every 10 minutes and the data were logged every 10 minutes. A bottom-mounted Sontek (YSI Environmental Company, San Diego, California) ADP logger was used to measure currents every second and these readings were averaged over one minute at 10 minutes intervals. Data from the current meter could be rotated to show currents moving in different directions.

Data were collected over consecutive time periods from each of the four watersheds. At Diongradid Bay (Figure 2), SSC was measured at stations 1, 2, 4 and 5, salinity at stations 1 and 2, and currents at station 2, from June-July 2005. At Ngermeduu Bay, the SSC loggers were deployed at stations 1–4, salinity loggers at stations 1–3, and currents were measured at station 1, from December 2005 to January 2006. At Ngerdorch, the SSC and salinity loggers were deployed at stations 1–3, salinity only was recorded at station 4, and currents at station 1, from December 2006 to January 2007. For Ngerikiil Bay, SSC and salinity were measured at stations 1, 2, 3 and 4 and currents at station 4, while only salinity was recorded at station 5, from January through February 2007. The data were recorded at 10 minutes intervals.

2.5. CTD Casts. Vertical profiles of salinity, temperature and SSC were taken at each of the four sites. During flood events, and for 6–8 days afterwards, casts were made along transects moving from inshore to offshore at stations 1 through 5. The number of days during which vertical profiles were taken was based on how long it took the freshwater plume to clear the area. A YSI (YSI incorporated, Yellow Springs, Ohio) multiparameter probe attached to a YSI 650 Multiparameter Display System with a long field cable was used from a small boat to profile the sites at different depths to record salinity, temperature and SSC.

2.6. Sediment Traps. At each of the five reef stations, duplicate bottom-mounted sediment traps with 5.1 cm diameter openings were deployed. The traps were collected and replaced every month for one year. Sediment samples collected from the traps were dried, weighed to the nearest 0.1 mg using an A&D (A&D Company Limited, Tokyo, Japan) analytical semimicro balance (GR-120) to obtain total sedimentation rates (mg DW $\text{cm}^{-2}\,\text{d}^{-1}$), reweighed after treatment with 10% hydrochloric acid to remove carbonate to obtain the carbonate fraction, and then burned at 600°C for 2 hours to remove organic matter, to obtain the organic matter fraction. The remaining weight was used to estimate terrestrial (inorganic noncarbonate) sediments. The volcanic soils of the watersheds in Babeldaob contain insignificant amount of calcium carbonate [28].

2.7. Statistical Analyses. Because rainfall data did not meet the assumptions of normality, a Kruskal-Wallis analysis was used to test the differences in rainfall among the four watershed sites. A Kolmogorov-Smirnov Test was used to test the differences between sedimentation rates in watershed sites in Palau and Pohnpei. Linear regression models were used to determine the relationships between sediment yield and earth moving permits, and between the ranked locations of the stations and reef sedimentation rates. Statistical analyses were conducted with the statistical software, Statistica (StatSoft, Oklahoma, USA).

3. Results

3.1. Rainfall. There were no significant differences in rainfall among the four watersheds ($P = 0.69$, Kruskal-Wallis). The daily mean rainfall averaged 10 mm $\text{day}^{-1} \pm 0.8$ (SE) and the daily maximum was 148 mm day^{-1}. The monthly mean for the study period was 272 mm $\text{month}^{-1} \pm 27$ and the monthly maximum was 531 mm month^{-1}.

3.2. River Sediment Flux. All rivers showed episodic high flows (i.e., short-lived floods). The Diongradid River averaged sediment flux was 32.2 $\text{g}\,\text{s}^{-1} \pm 0.05$ (1014 tons yr^{-1}; Table 1). The Ngermeskang River had an average sediment flux of 196.8 $\text{g}\,\text{s}^{-1} \pm 2.5$ (6205 tons yr^{-1}). The Ngermeskang River is one of the three rivers that drain into Ngermeduu Bay; if all three rivers have about the same sediment flux (their catchment areas and degree of development are similar), the combined sediment flux from the Ngermeduu watershed would be about 590.3 $\text{g}\,\text{s}^{-1}$ (18615 tons yr^{-1}). The Ngerdorch River had the lowest average sediment flux among the gauged rivers at 14.6 $\text{g}\,\text{s}^{-1} \pm 0.02$ (460 tons yr^{-1}), while the Ngerikiil River had the highest average sediment flux at 417.9 $\text{g}\,\text{s}^{-1} \pm 0.59$ (13178 tons yr^{-1}). In terms of area-corrected sediment yield (sediment flux divided by watershed size), Ngerikiil had the highest and Ngerdorch had the lowest among the four watersheds (462.4 versus 9.7 tons $\text{km}^{-2}\,\text{yr}^{-1}$; Table 1). There was a strong positive relationship between the number of earth moving permits across the four watersheds and area-corrected sediment yield ($R^2 = 0.96$, $P = 0.02$). There were no significant relationships between the number of earth moving permits and sediment flux in the river ($r^2 = 0.007$, $P = 0.9$), coastal turbidity ($r^2 = 0.03$, $P = 0.8$), and sedimentation rate at the stations ($r^2 = 0.6$, $P = 0.2$).

Ngerikiil watershed is the most developed and had the highest average river sediment flux, while it had lower SSC than Ngermeduu and Ngerdorch and lower sedimentation rates than Ngedorch (Table 1). Ngermeduu watershed has the biggest nonforested area and had the highest coastal turbidity, while its sediment flux in the river was lower than in Ngerikiil, and its reef sedimentation rate was lower than Ngerdorch and Ngerikiil. Diongradid was the least developed and had the smallest nonforested area. It also had the lowest sediment flux in the river, the lowest coastal turbidity and the lowest reef sedimentation rate compared to the rest of the watersheds. The results show that the measure "nonforested area" (which includes areas with substantial vegetation cover that produce less sediment than areas under construction) is insufficient to predict coastal turbidity and reef sedimentation rates.

3.3. Tides and Currents. The tides were similar at the four sites, and were semidiurnal with a conspicuous diurnal inequality. The tidal range was about 2 m during spring tides and 1 m during neap tides at the four reef sites.

The currents at Diongradid (station 3) did not show strong spring-neap fluctuations and were variable, similar to those at Ngerdorch. Both the currents moving in the southeasterly-northwesterly directions from land toward the ocean, and a longshore current in the southwesterly-northeastly direction fluctuated around 0.06 $\mathrm{m\,s^{-1}}$.

The currents at Ngermeduu Bay (station 1) were strongly tidal, semidiurnal with a strong spring-neap tidal fluctuation. There are two entrances to Ngermeduu Bay (Figures 1 and 2); the narrower but deeper northwest entrance and the shallower but wider southwest entrance. Flood tidal currents through the northwest channel peaked at 0.17 $\mathrm{m\,s^{-1}}$ during spring tides and 0.08 $\mathrm{m\,s^{-1}}$ during neap tides. Flood tidal currents through the southwest channel were larger, peaking at 0.30 $\mathrm{m\,s^{-1}}$ during spring tides and 0.13 $\mathrm{m\,s^{-1}}$ during neap tides. The outflowing current was similar for both channels, peaking at 0.2 $\mathrm{m\,s^{-1}}$.

The currents at Ngerdorch Bay (station 1) flowed predominately toward the east and south, and were not strictly tidal, nor did they show strong spring-neap tide fluctuations. The freshwater plumes coming out of the estuary as well as the predominant winds from the northeast had strong influences on the tides, especially near the ocean surface. The maximum near-surface currents moving out of the estuary toward the east reached 0.1 $\mathrm{m\,s^{-1}}$, while the incoming current peaked at 0.07 $\mathrm{m\,s^{-1}}$. There was also a north-south current near the surface with the current going north peaking at 0.08 $\mathrm{m\,s^{-1}}$, while the southern current peaked at 0.06 $\mathrm{m\,s^{-1}}$.

The currents at Ngerikiil Bay (station 4) were mainly semidiurnal tidal, with strong spring-neap tide fluctuations. The outflowing current peaked at 0.5 $\mathrm{m\,s^{-1}}$ while the inflowing current reached 0.7 $\mathrm{m\,s^{-1}}$. Station 4 was the narrow channel leading into the bay so the currents were faster there than inside the bay. There was a pronounced vertical shear in currents moving in and out of the channel with larger currents near the surface than the bottom of the channel due to friction slowing the water closest to the bottom. Inshore from station 4, during river floods, the freshwater plumes flowed over the bay as a near surface outflow. This effect extended to site 4 only during large river floods. Closer to the mouth of the bay, the freshwater inflow was more apparent at neap tides than at spring tides when strong currents favored vertical mixing. During flood events around neap tides, the surface currents took longer than the bottom currents to turn from an outgoing tide to incoming tide, therefore, the surface and bottom currents were out of phase. This difference between phases of the surface and bottom currents was not observed during spring tides.

3.4. Suspended Solid Concentration (SSC) as a Measure of Coastal Turbidity. At Diongradid, SSC at station 1 peaked at 636 $\mathrm{mg\,l^{-1}}$ and averaged 9 $\mathrm{mg\,l^{-1}}$ ± 0.4 (Figure 3(a)). At stations 2 and 5, the SSC maximum only reached 34 $\mathrm{mg\,l^{-1}}$ and 15 $\mathrm{mg\,l^{-1}}$, respectively. Station 5 was exposed to strong winds and waves, hence many of the SSC spikes were due to sediment resuspension rather than floods.

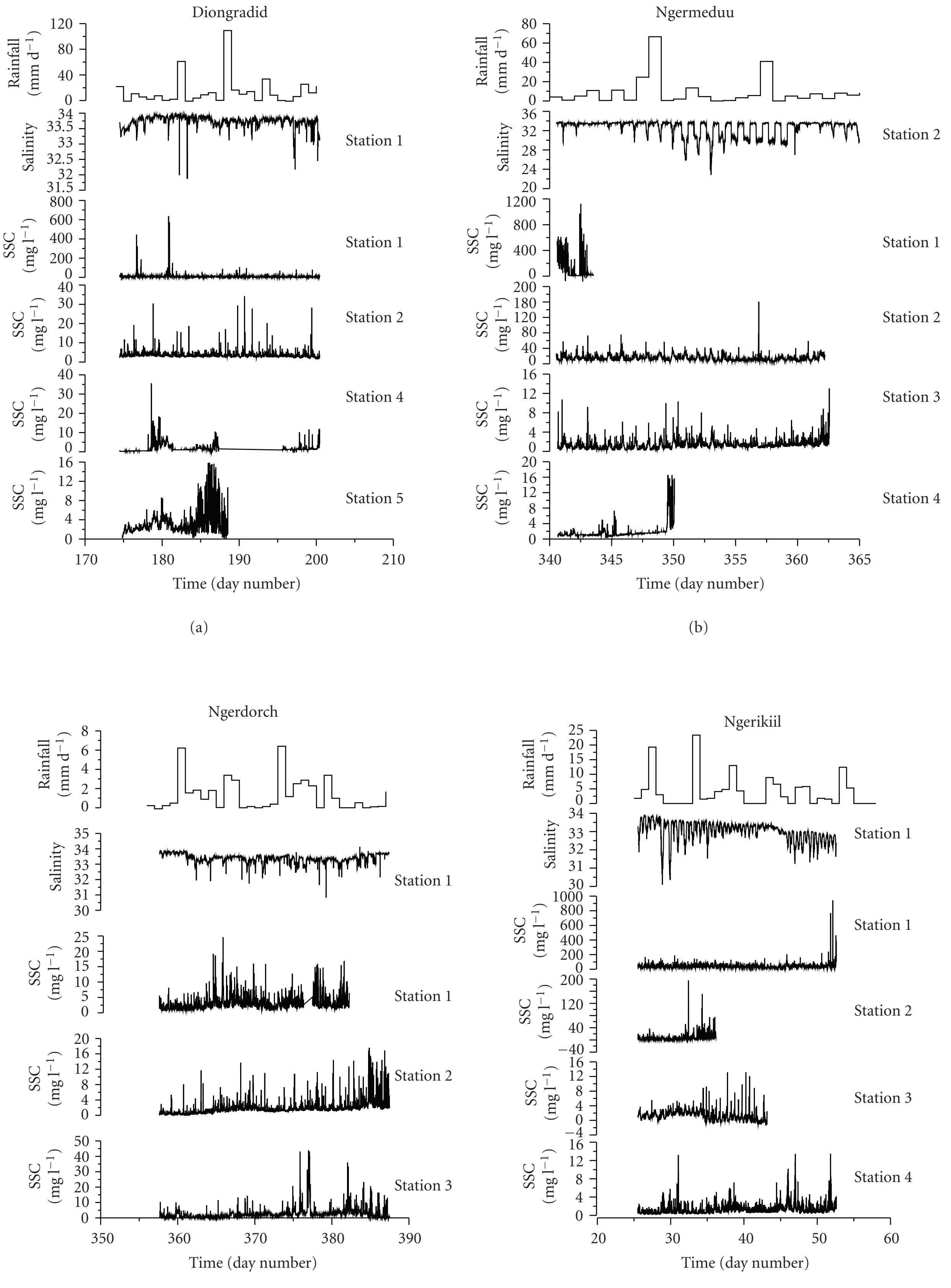
At Ngermeduu, station 1 had the highest SSC of all the sites, with maximum values exceeding 1000 $\mathrm{mg\,l^{-1}}$, and high turbidity also outside of flood events at 20–40 $\mathrm{mg\,l^{-1}}$ (Figure 3(b)). At station 2, maximum SSC reached 160 $\mathrm{mg\,l^{-1}}$ with the average SSC at 14 $\mathrm{mg\,l^{-1}}$ ± 0.1. Station 3 and 4 had maximum SSC values at 13 and 16 $\mathrm{mg\,l^{-1}}$ respectively, and both stations had SSCs of less than 3 $\mathrm{mg\,l^{-1}}$ outside of flood events.

At Ngerdorch, SSC was highest at station 1, exceeding 1,000 $\mathrm{mg\,l^{-1}}$ (Figure 3(c)). Outside of flood events, station 1 also had high turbidity ranging from 40–60 $\mathrm{mg\,l^{-1}}$. At station 2, turbidity was much lower, with a maximum of 24 $\mathrm{mg\,l^{-1}}$ during flood events and 0–3 $\mathrm{mg\,l^{-1}}$ outside of flood events. At station 3, the maximum SSC was 43 $\mathrm{mg\,l^{-1}}$, with spikes both from flood events and resuspension due to strong winds in these open waters.

At Ngerikiil, SSC was highly variable depending on the sites and tidal cycle. At station 1, SSC averaged 38 $\mathrm{mg\,l^{-1}}$ ± 0.5 while the maximum exceeded 900 $\mathrm{mg\,l^{-1}}$ (Figure 3(d)). SSC decreased from station 2 to station 4 (means: 6.4 versus 1.1 $\mathrm{mg\,l^{-1}}$, maxima 195 versus 13.4 $\mathrm{mg\,l^{-1}}$). During a falling tide, the SSC was higher than during a rising tide, with spikes in SSC occurring during low tides. The high SSC spikes resulted from river runoff, as evidenced by the drop in salinity during the rise in SSC.

3.5. CTD Casts. At Diongradid, there was inflow of turbid water with high SSC at station 1 on 3 July 2006 (Figure 4). On the next day, the plume, as indicated by lower salinity, was still present but the suspended sediments had disappeared. Unlike observations made at the other sites, the sediments at Diongradid rapidly settled to the bottom and were not resuspended. On 5-6 July, the plume decreased in size. On 7 July, there was a smaller flood than the one on the 3 July. The flood brought in new sediments that dropped out of suspension as the plume moved seaward.

At Ngermeduu, a river plume was evidenced by the upward slope of the temperature and salinity contour lines on 15 December 2005 (Figure 5). The plume upstream was touching the bottom; and on reaching deeper water it lifted off the bottom (lift-off point). The SSC contours followed the same pattern. SSC values were small (10 $\mathrm{mg\,l^{-1}}$) underneath the plume in offshore waters. A turbidity maximum existed at the plume lift-off point. The next day, temperature showed minimal stratification, suggesting strong tidal mixing. Salinity had increased but the plume was still active since the isohalines were sloping upward offshore. The SSC contour lines also sloped upward offshore. The SSC values were smaller than those of the previous day; therefore the peak of the sediment flux had passed. On 17 December, the 3rd day of the river plume, cold oceanic water was moving in under the plume. The isohalines were horizontal, indicating that the lift-off point had moved landward into the bay. The sediments were dropping out of the plume but they



(a)

(b)

(c)

(d)

Figure 3: Time-series plot of rainfall, salinity and SSC at (a) Diongradid bay, (b) Ngermeduu bay, (c) Ngerdorch bay, (d) Ngerikiil bay.

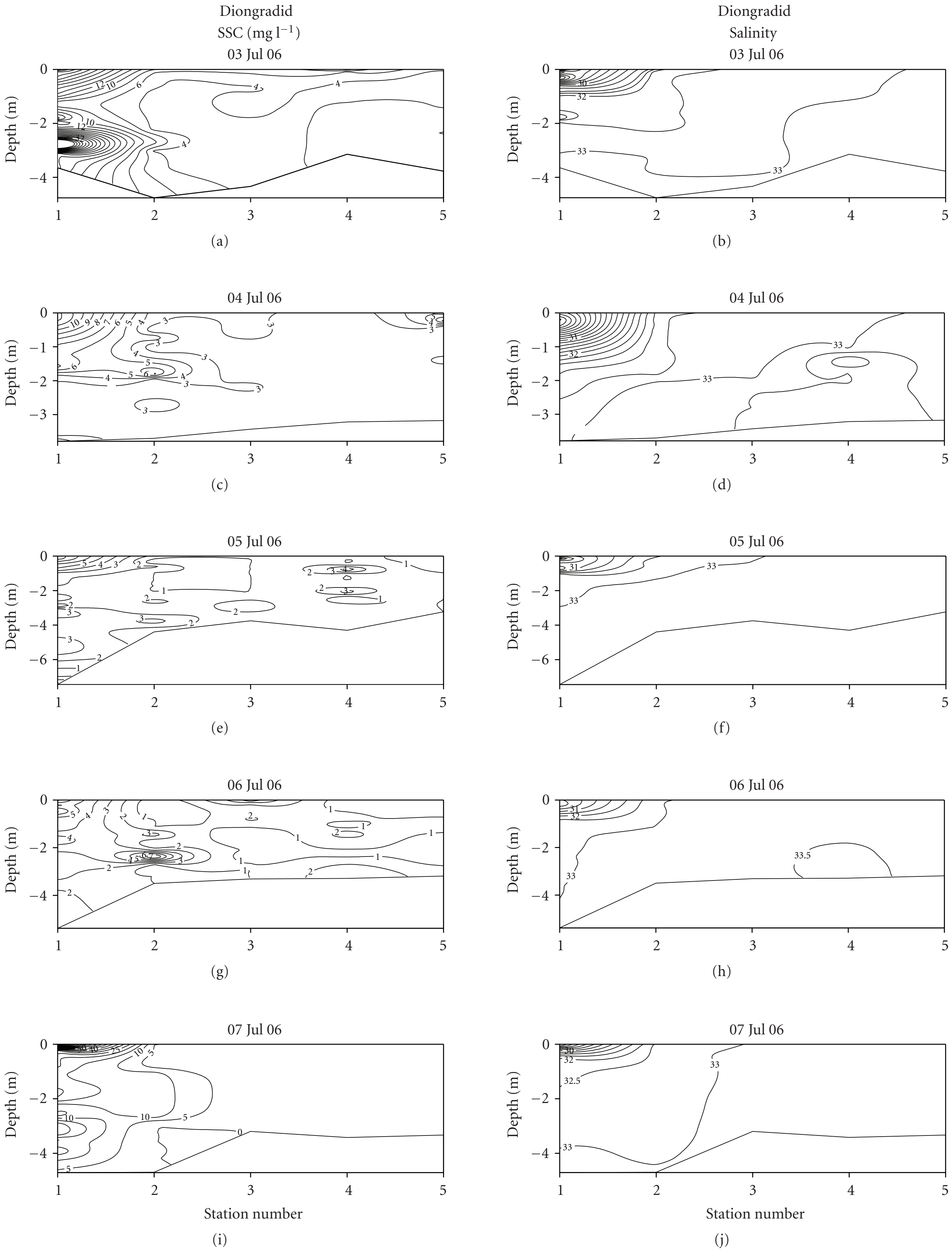


Figure 4: Snapshots at daily intervals of the two-dimensional distribution along the channel of salinity and SSC at Diongradid from CTD casts. The bottom line indicates the sea floor.

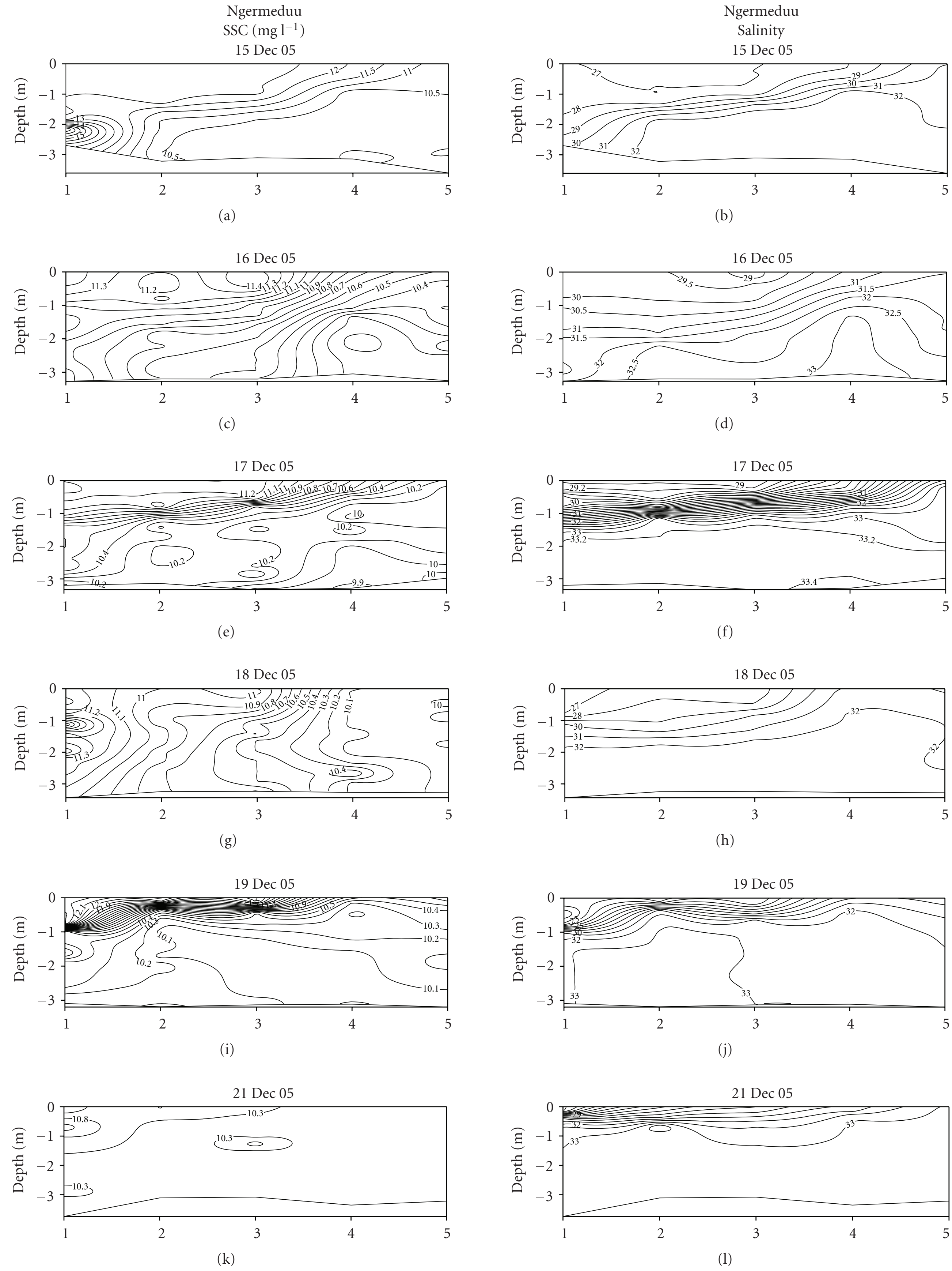
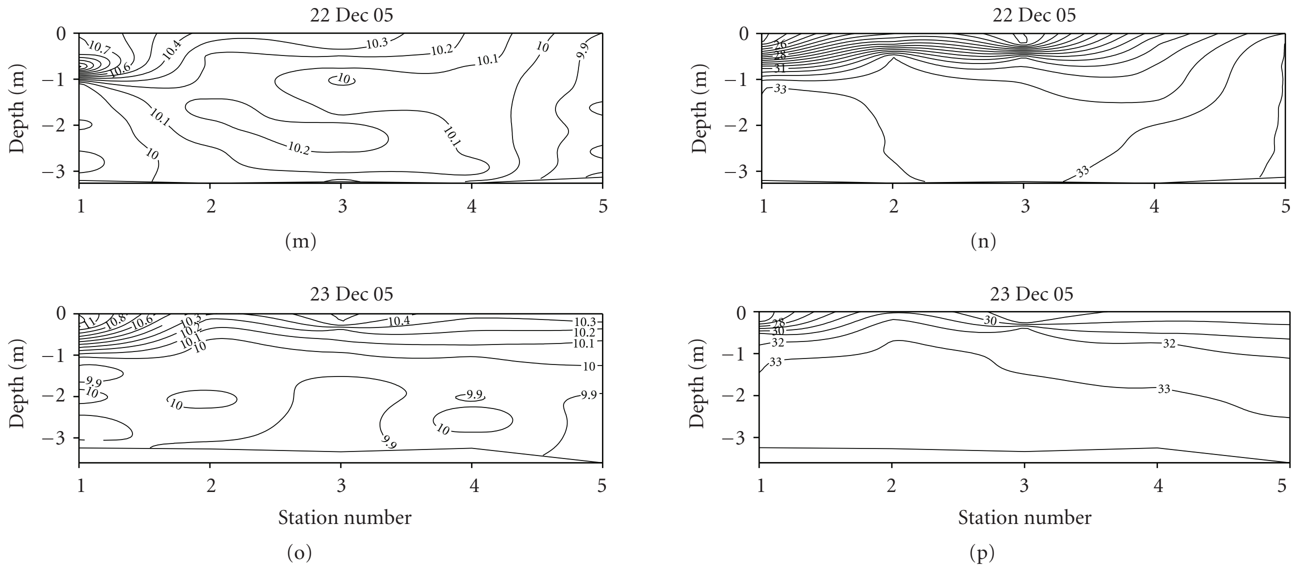


Figure 5: Continued.



(m)

(n)

(o)

(p)

Figure 5: Snapshots at daily intervals of the two-dimensional distribution along the channel of salinity and SSC at Ngermeduu from CTD casts. The bottom line indicates the sea floor.

were being advected back toward the river mouth by the bottom intrusion of seawater, as indicated by the SSC profile (Figure 5). On the 4th day, the system had recovered. On 19 December, the river flooded again but the flood was smaller since the plume lift-off point was located upstream from station 1. From 20–23 December, the surface plume remained but the sediments had largely dropped out.

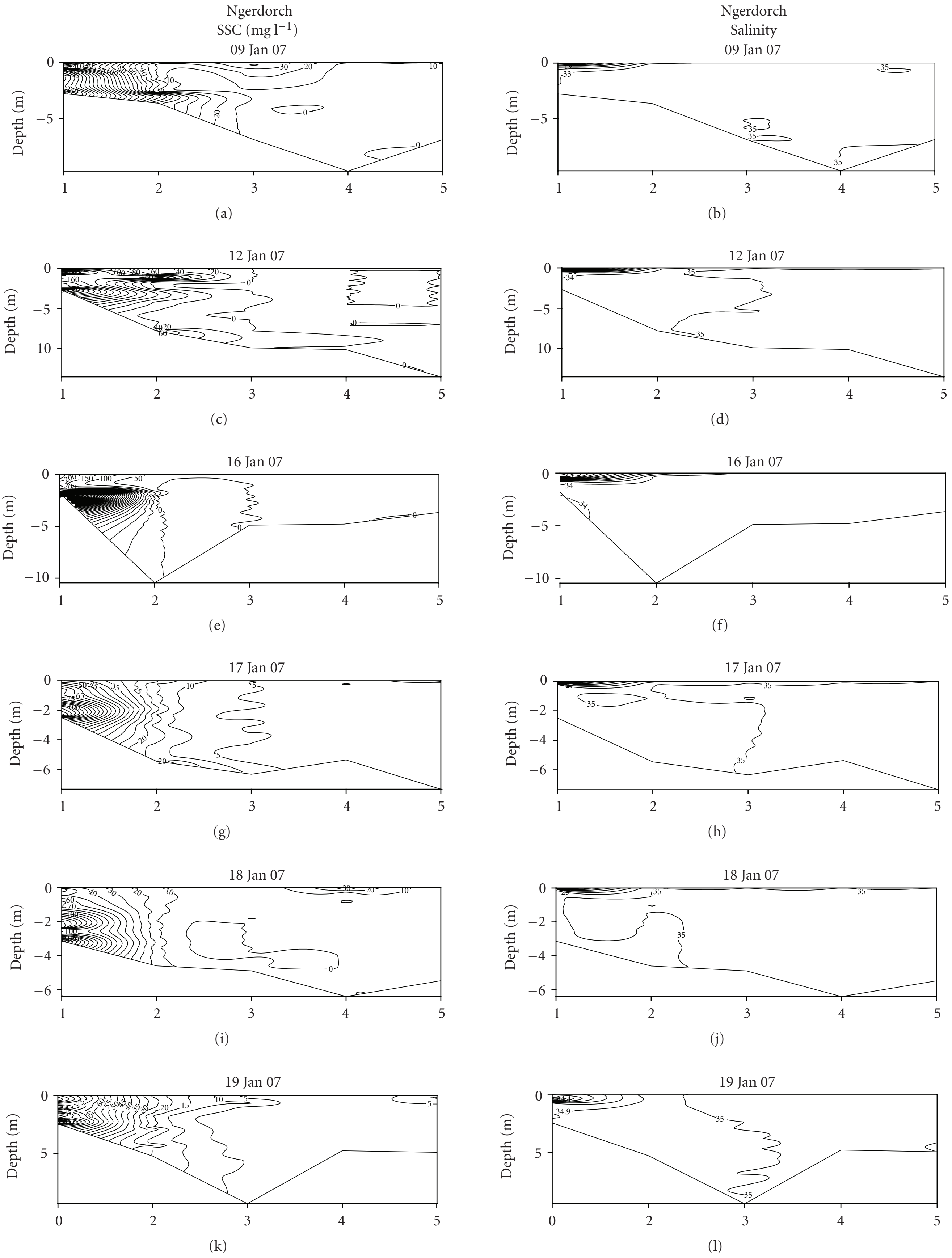
At Ngerdorch, there was an inflow of cooler, turbid river water at station 1, which was situated right next to the mangroves, on 9 January 2007 (Figure 6). The highest SSC values (280 mg/l) were recorded at this site. The freshwater plume barely reached site 2 since the fine sediments had already settled out of the plume. The system recovered slowly at station 1, as evidenced by the increase in salinity while the SSC remained high until 18 January. Farther offshore, seawater moved in while SSC decreased. On 19 January, river inflow increased slightly and a new river plume formed. From 21–23 January, there was another flood and a new plume formed. The plume remained on the surface while sediments dropped out.

At Ngerikiil, after a flood event, there was an abnormal temperature stratification due to the intrusion of cooler water as a river plume on 29 January 2007 (Figure 7). The SSC was largest ($182\,\mathrm{mg\,l^{-1}}$) at the plume lift-off point during the river flood. One day later, after the peak of the flood had subsided, the abnormal temperature stratification remained and the freshwater plume was still present, but was less sharply delineated. Sediments were dropping out of suspension as the plume was moving out of the bay so by the time the plume passed station 3, most of the sediments had dropped out. By the third day, the temperature stratification was negligible, the salinity plume was passively floating on top of ambient water, as evidenced by the nearly horizontal salinity contours, indicating negligible river inflow. Sediments were settling out throughout the bay. On the fourth day, water temperature was well mixed throughout, the plume was passive, and SSC was low throughout the bay. Sediment was accumulating at the bottom near the plume lift-off point, forming a nepheloid layer. By the 5th day, the temperature anomaly no longer existed. The SSC was more uniform with depth, indicating that tidal mixing and turbulence predominated. By the 7th day, the plume had disappeared and SSC was low throughout the bay; thus at that stage the system had recovered from the flood. For Ngerikiil Bay, the recovery stage for SSC depended on the tidal range. Spring tides resuspended the mud causing the SSC lines to become more vertical, while neap tides did not resuspend the mud as much causing the SSC lines to become horizontal.

3.6. Sedimentation. Terrestrial sedimentation rate was highest at station 1 in all bays except for Ngermeduu, where rates were highest at station 2 (Table 2). There was a general gradient of decreasing terrestrial sedimentation from station 1 to station 5 in all bays. Terrestrial sedimentation rate was related to the ranked locations of the stations, decreasing by $0.9\,\mathrm{mg\,cm^{-2}\,day^{-1}}$, ($-0.9 \pm 0.1$ SE, $r^2 = 0.1$, $P < 0.001$) from one station to the next moving offshore.

4. Discussion

In Palau, construction activities that involve movement of soil require an Earth Moving Permit. These permits were used to quantify development in each watershed. Among the three measures, river sediment yield, reef sedimentation rate, and reef turbidity, the river sediment yield increased strongly with increasing numbers of earth moving permits ($R^2 = 0.96$, Table 1). These sediments are directly discharged onto the reefs where they undergo deposition (measured as sedimentation rates) or (re) suspension (measured as turbidity). Our study quantified how sedimentation and coastal turbidity depended in complex fashions not only



Ngerdorch
SSC (mg l^{-1})
09 Jan 07

Ngerdorch
Salinity
09 Jan 07

(a) (b)

12 Jan 07

(c) (d)

16 Jan 07

(e) (f)

17 Jan 07

(g) (h)

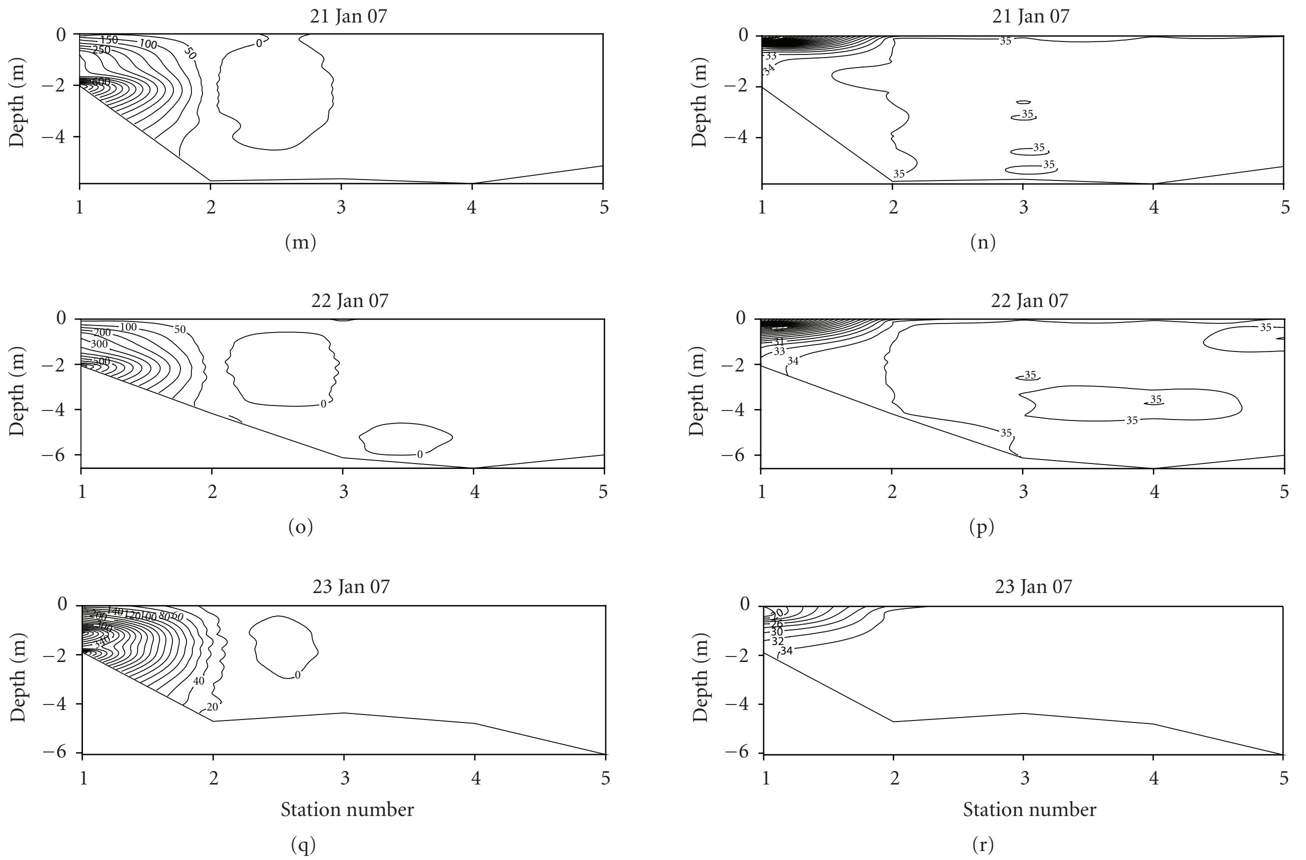
18 Jan 07

(i) (j)

19 Jan 07

(k) (l)

FIGURE 6: Continued.

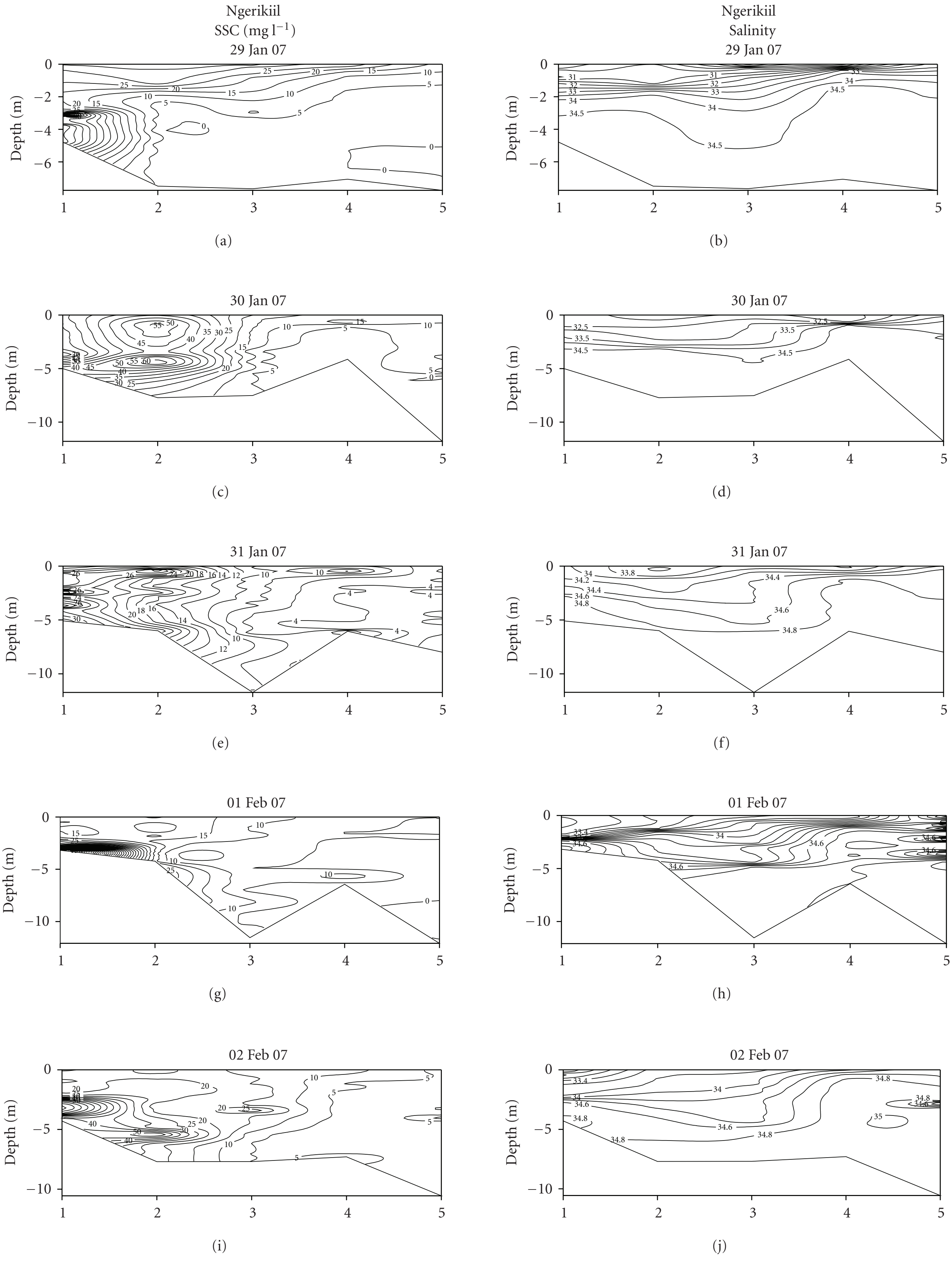


(m) (n) (o) (p) (q) (r)

FIGURE 6: Snapshots at daily intervals of the two-dimensional distribution along the channel of salinity and SSC at Ngerdorch from CTD casts. The bottom line indicates the sea floor.

TABLE 2: Terrestrial, organic, and carbonate sediments recorded in sediment traps at the different stations at the four reef sites. Numbers shown are mean sedimentation rates in mg cm^{-2} d^{-1} ± SE.

Bay site	Station	Sample size (n)	Terrestrial sediments	Organic sediments	Carbonate sediments	Total sediments
Diongradid	1	22	1.05 ± 0.24	0.47 ± 0.11	0.66 ± 0.10	2.18 ± 0.42
Diongradid	2	22	0.12 ± 0.01	0.09 ± 0.01	0.57 ± 0.13	0.77 ± 0.51
Diongradid	3	22	0.15 ± 0.05	0.09 ± 0.02	0.87 ± 0.14	1.11 ± 0.14
Diongradid	4	22	0.12 ± 0.04	0.07 ± 0.01	0.62 ± 0.06	0.82 ± 0.07
Diongradid	5	22	0.25 ± 0.10	0.18 ± 0.07	1.92 ± 0.24	2.35 ± 0.35
Ngermeduu	1	18	3.21 ± 0.47	1.20 ± 0.12	1.36 ± 0.36	5.77 ± 0.91
Ngermeduu	2	18	4.62 ± 0.66	2.65 ± 0.45	3.13 ± 0.92	10.09 ± 1.53
Ngermeduu	3	18	2.14 ± 0.15	1.12 ± 0.11	2.57 ± 0.38	6.84 ± 1.12
Ngermeduu	4	18	0.48 ± 0.08	0.29 ± 0.04	1.31 ± 0.13	2.07 ± 0.24
Ngermeduu	5	18	0.41 ± 0.06	0.18 ± 0.02	1.78 ± 0.19	2.36 ± 0.26
Ngerdorch	1	14	29.95 ± 1.26	9.49 ± 0.47	6.32 ± 0.36	45.76 ± 2.10
Ngerdorch	2	14	1.76 ± 0.39	0.57 ± 0.12	1.27 ± 0.15	3.47 ± 0.57
Ngerdorch	3	14	0.54 ± 0.10	0.21 ± 0.04	2.00 ± 0.36	2.70 ± 0.45
Ngerdorch	4	14	0.65 ± 0.09	0.20 ± 0.03	3.40 ± 0.47	4.17 ± 0.57
Ngerdorch	5	14	0.40 ± 0.07	0.20 ± 0.03	4.77 ± 0.71	5.32 ± 0.80
Ngerikiil	1	14	4.08 ± 0.37	1.51 ± 0.13	1.75 ± 0.16	7.24 ± 0.55
Ngerikiil	2	14	0.85 ± 0.11	0.31 ± 0.04	0.98 ± 0.44	2.05 ± 0.44
Ngerikiil	3	14	1.08 ± 0.09	0.81 ± 0.14	5.73 ± 1.37	7.59 ± 1.53
Ngerikiil	4	14	0.88 ± 0.16	0.47 ± 0.07	6.80 ± 1.14	8.11 ± 1.31
Ngerikiil	5	14	0.30 ± 0.06	0.39 ± 0.08	10.68 ± 3.01	11.7 ± 3.7



(a) (b)

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Figure 7: Continued.

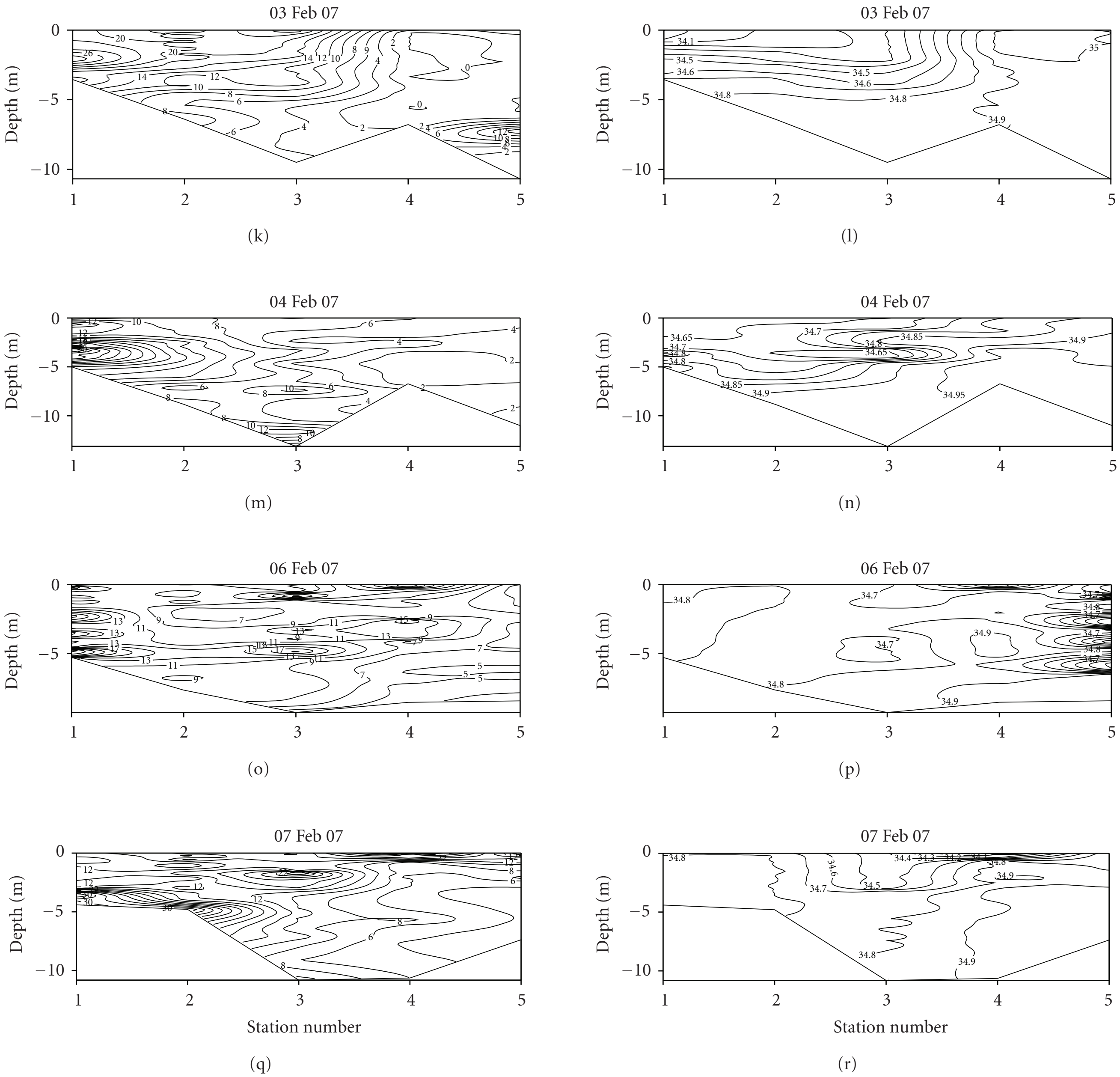
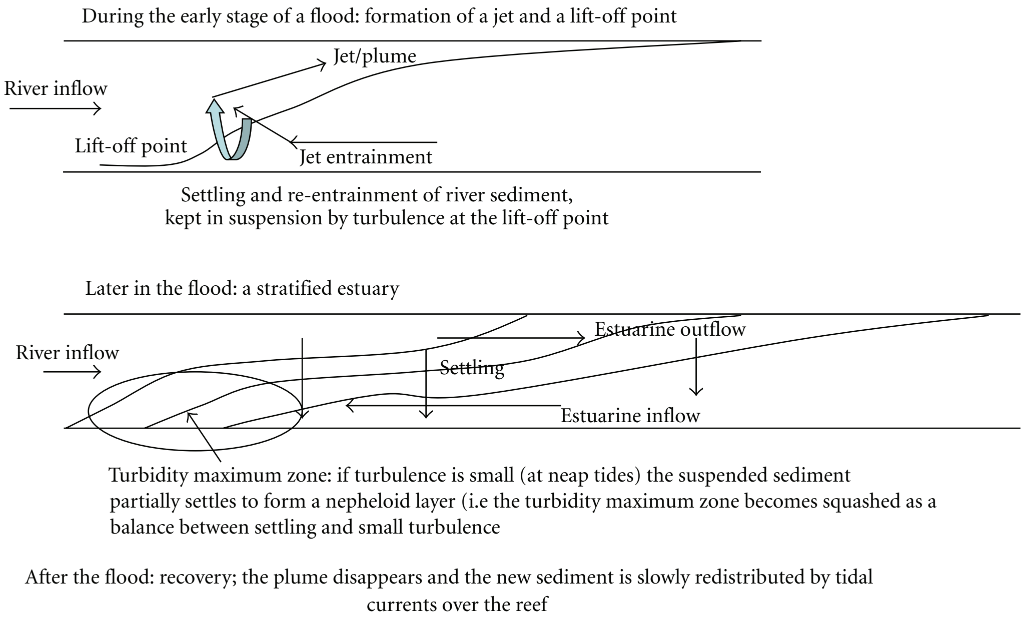


Figure 7: Snapshots at daily intervals of the two-dimensional distribution along the channel of salinity and SSC at Ngerikiil from CTD casts. The bottom line indicates the sea floor.

on river sediment yields but also on factors that control the ultimate flushing or retention of this mud on the reefs, namely winds, currents and the geomorphology (i.e., whether the areas constituted open or semi-enclosed bays). For example, at Diongradid Bay, the sedimentation rate and water turbidity exceeded levels considered harmful to corals [5, 30] because sediments were constantly being resuspended by the winds and currents, and were not exported away. Generally, total rates of sedimentation were similar to rates of terrestrial sediment patterns (Table 2). Differences were only found at stations with strong winds and waves that caused resuspension. For example, in Ngerikiil, Ngerdorch and Diongradid, station 5 had higher total but smaller terrestrial sediment loads than the inner stations.

Sediment dynamics varied for each reef station based on currents and tidal turbulence. In Ngerikiil, Ngerdorch and Ngermeduu, the river plume formed a jet and a jet lift-off point during the early stage of a flood (Figure 8). At that point, the plume lifts off the bottom as it moves seaward, while oceanic waters move in landward under the plume. As sediment particles dropped out of the plume into intruding oceanic waters, they were advected towards the plume lift-off point, where they were mixed upward by the intense turbulence at the plume lift-off point [30]. Spring tides



During the early stage of a flood: formation of a jet and a lift-off point

Settling and re-entrainment of river sediment, kept in suspension by turbulence at the lift-off point

Later in the flood: a stratified estuary

Turbidity maximum zone: if turbulence is small (at neap tides) the suspended sediment partially settles to form a nepheloid layer (i.e the turbidity maximum zone becomes squashed as a balance between settling and small turbulence

After the flood: recovery; the plume disappears and the new sediment is slowly redistributed by tidal currents over the reef

Figure 8: Diagram showing the jet formation and lift-off during the early and later stages of a flood.

also resuspended the sediment (Figure 8). During neap tides when the turbulence was smallest, the suspended sediment partially settled to form a nepheloid layer (Figure 8). In Ngerdorch and Ngermeduu, the turbulence was high so sediment was readily resuspended into the water column, while in Ngerikiil, it was only suspended to mid-depth because of the smaller tidal turbulence. During the later stages of the floods, the systems recovered, the plume disappeared and new sediments were slowly redistributed by tidal currents. In contrast to the other three sites, sediments were not resuspended at Diongradid, and once sediments dropped out of the plume, they settled to the bottom where they remained.

The data show a large variability in Palau's small estuaries in the dynamics and fate of the riverine fine sediment. All the classical types of estuarine water circulation were encountered in Palau, including well mixed, partially stratified, and salt-wedge [31]. The small estuaries of Palau switched from one type to another in a day or a few days at most, as a result of the rapid changes in freshwater discharge from the small catchments. As a result, Palau's small estuaries in general are not effectively shielding the reef from riverine sediment. The results are different from well-studied, large estuaries, where the time scales are longer (weeks to months) and much of the riverine sediment is trapped in the estuaries [32]. The important lesson learned in Palau is that small estuaries are much less effective in trapping sediment than larger estuaries.

Sedimentation had previously been recorded at Ngerdorch in 2003, when the mean total sedimentation rate at station 2 was 8.8 ± 3.6 mg cm^{-2} day^{-1} [22] compared with 3.4 ± 0.8 mg cm^{-2} days^{-1} in this study in 2006. The mean sedimentation rate had decreased by 52%, probably due to decreased erosion after completion and paving of the road around Babeldaob in 2004.

Pohnpei is another wet, high island in Micronesia. The sedimentation rates on coral reefs adjacent to the four Palau watersheds in this study (Table 2) were smaller than those reported for the Enipein watershed in Pohnpei, Federated States of Micronesia [23]. In Enipein, the mean sedimentation rate over the reef was 37.7 ± 1.1 (SE) mg cm^{-2} day^{-1} [23], 10–20 times higher than values from this study (Table 1). The sedimentation rates at each of the four sites in Palau were significantly lower than those from Enipein (Kolmogorov-Smirnov Tests, $P < 0.005$). The sedimentation rates in impacted reefal areas off the Enipein River are lethal to corals and other reef organisms, while those in Palau may be sublethal for some species [5, 29] but lethal to the more sensitive taxa [18].

Guam is yet another wet, high island in Micronesia. Data for shallow reefal waters off the La Sa Fua watershed show the sedimentation rate peak at 30 mg cm^{-2} day^{-1} [24]. Such high sedimentation rates are harmful to most corals [6, 25]. The Guam receiving waters and reef are frequently flushed of fine sediment by typhoon-driven swell waves, so that there might be some potential for coral cover to regenerate somewhat on clean substrate after a typhoon, at least until the next flood deposits riverine sediment again. Nevertheless, as a result of the very high sedimentation rate immediately following river floods, coral cover is minimal [33]. In Palau however, the sediment remains largely trapped in the bay and the degradation within the bay is longer-term or permanent, with no chance for the coral to recover, unless the sediment is removed through active remediation measures.

5. Conclusion

The results of this study show that land-based development activities have a direct impact on the amount of sediment that goes into rivers and eventually ends up on coral reefs. The amount of sediments being released into the rivers and reefs on Babeldaob Island, Palau, depended on the degree of development within adjacent watersheds. While different reef areas had different geomorphology and hydrodynamic regimes that affected the flow of sediments on the reef, the biggest factor contributing to sedimentation on the reef was from development on land. Once sediments reached the reef, geomorphology and hydrodynamic properties determined the fate of sediments. Previous studies have demonstrated the numerous negative impacts of sediments on coral reef resources [6]. Thus, the fate of reefs around Babeldaob ultimately will depend on the type and number of development activities within the watersheds.

The clear and quantifiable relationships between land-use activities and coral reef ecosystem structure and function are being used to support ecosystem-based management activities. Interestingly, scientifically documented problems associated with the overharvest of key fish guilds were addressed in Palau by re-implementation of traditional "bul" or closures made possible by passing the Marine Protection Act of 1994. Since then, similar efforts guided by the use of our data and traditional Pacific Island practices are being applied to land-use activities to address negative impacts of sedimentation on coral reefs. Following a study in the Ngerikill Watershed, the Ngerikiil community placed a moratorium on clearing coastal mangroves [19]. Having learned the lessons of severe coral reef degradation in Ngerikiil Bay through the lack of land-use management and realizing that this degradation may be permanent in the absence of practical remediation measures, the Ngerikiil Bay community leaders are actively developing a master plan that includes zoning and land-use management. In addition, EBM partners in Palau, including the Babeldaob Watershed Alliance, are communicating these lessons through public meetings with communities in the other less-affected watersheds. These efforts with communities affected by the watersheds in this study are leading to better planning activities including state and national legislation requiring watershed management plans, the use of best management practices, and the restriction of unsustainable activities in specific sites. While ecosystem-based management, Marine Protected Areas and marine spatial planning are often presented as relatively new, western concepts, Palau and other Pacific Islands have been using these for generations, and it was largely due to outside influences, that sustainable practices were either lost or ignored. The inclusion of indigenous researchers has facilitated the bridging of the science to policy development and implementation to better management of human activities responsible for the decline of ecosystems of cultural, economic and ecological value.

Coral reefs are important to the people of Palau economically, culturally and ecologically; they provide food resources, materials for construction, areas for recreation and support a world renowned diving industry. Tourism is a very important industry in Palau with 80% of visitors who come to Palau doing so because of Palau's coral reefs [34]. For the people of Palau to continue to enjoy the benefits of productive and healthy coral reefs, efforts must focus on controlling land activities that increase sediments going into the rivers and onto the reefs.

Acknowledgments

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