Journal of Marine Research, 75, 1–17, 2017

Rainfall effect on sediment and nutrient fluxes in a small mangrove river, Okinawa, Japan

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ABSTRACT

To understand the effect of rainfall on sediment and nutrient fluxes in a mangrove river ecosystem, field observations were conducted in the Fukido River, Okinawa, Japan. Water currents and water quality parameters (salinity and turbidity) were measured at the river mouth and upstream, and surface water samples were analyzed for nutrient concentrations (NO_3-N, NH_4-N, PO_4-P, SiO_2-Si, suspended solids [SS], total nitrogen [TN], and total phosphorus [TP]). Observations were conducted on both clear and rainy days, which revealed the effect of weather. SS flux at the river mouth (outflux to sea) and upstream (influx from land) showed that sediment deposition occurred in the mangrove swamp, and the amount of sediment deposition on a rainy day (324 kg d^{-1}) was approximately 14 times greater than that on a clear day (24 kg d^{-1}). The higher influx from upstream on the rainy day caused levels of TN and TP deposition in the mangrove swamp that were 9.1 and 3.4 times higher, respectively, than levels on a clear day. Our findings highlight the importance of considering local weather conditions in the estimation and management of nutrient budgets, especially in a small mangrove river.

Keywords: Nutrient flux, sediment deposition, dissolved nutrients, precipitation, land use, field observation, chemical analysis, coastal ecosystem, mangrove creek, flow velocity

1. Introduction

Mangrove swamps along tropical and subtropical coastlines play a crucial role in the exchange of sediments and nutrients between terrestrial and oceanic environments, and the sustainability of coastal ecosystems, such as seagrass meadows and coral reefs. The outflow of dissolved and particulate nutrients such as ammonium, phosphate, and suspended solids (SS) can strongly influence biogeochemical processes in coastal areas (Dittmar and Lara 2001). To elucidate carbon and nutrient exchanges from mangrove forest to the coastal ocean, observational and computational studies of nutrient dynamics have been undertaken

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in various mangrove-dominated estuaries (Ayukai et al. 1998; Mfilinge, Atta, and Tsuchiya 2002; Tappin 2002; Sánchez-Carrillo et al. 2009; Zhou et al. 2010). Adame and Lovelock (2011) reported that mangrove forests have a tendency to export carbon to the coastal ocean in the form of litter and particulate organic carbon and indicated the effect of precipitation on the amount of carbon exported (especially litter export). However, dissolved and particulate nitrogen and phosphorus show variable patterns; they are exported to the coastal zone by some mangrove forests (e.g., Celestún, Mexico: Young et al. 2005; Bahia de Lobos, Mexico: Sánchez-Carrillo et al. 2009), and imported by others (e.g., Queensland, Australia: Adame et al. 2010; Rio Coco Solo, Panama: Lin and Dushoff 2004). Whether dissolved and particulate nitrogen and phosphorus are retained in mangrove swamps or carried to coastal areas remains under debate.

Local environmental factors such as weather conditions, microtopography, hydrology, tidal range, geography, soil chemistry, and mangrove community structure may affect material budgets. Berre do, Costa, and Progene (2008) indicated the impacts of physical and biological parameters, such as mangrove litter fall, tidal regimes, and weather conditions on nutrient fluxes. Sánchez-Carrillo et al. (2009) also studied the impact of variables such as tidal range, river discharge, and rainfall on mangrove nutrient dynamics and suggested these local characteristics have site-specific impacts on nutrient budgets. To gain an understanding of the nutrient exchange between a mangrove forest and the surrounding coastal area, further detailed study of nutrient flux, especially focusing on the impacts of the local environment, is required.

Rainfall is one key parameter that could affect nutrient exchange in mangrove swamps. Rainfall leads to an increase in river discharge and thus an increase in the outflow of nutrient and sediment load to the adjacent ocean. The magnitude of the effect (i.e., how much a given amount of precipitation will affect river discharge and nutrient fluxes) depends on geomorphological factors such as river length and width, mangrove classification, and the catchment area. Previous studies on nutrient exchange have been conducted in many types of mangrove forest. The area of mangrove forest investigated has also varied widely—for example, the Caeté Coast in Brazil, with 10,000 km^2 of mangroves (Dittmar et al. 2006); the Southern Everglades in the United States, with 460 km^2 (Sutula et al. 2003); Red River in Vietnam, with 84 km^2 (Wösten et al. 2003); Bahia de Lobos in Mexico, with 5 km^2 (Sánchez-Carrillo et al. 2009); and Mngazana estuary in South Africa, with 1 km^2 (Rajkaran and Adams 2007). We hypothesized that the nutrient budget of rivers with a smaller mangrove area would be more strongly affected by hydrological parameters, geomorphological features, and even small changes in weather conditions. The aim of this study was to quantify sediment and nutrient budgets in a small mangrove river and determine the effects of weather conditions. Here, we present the results of field observations conducted in Fukido River on Ishigaki Island in western Japan (Fig. 1). The Fukido River is about 20 km from the nearest urban area and has a small mangrove area (0.12 km^2).

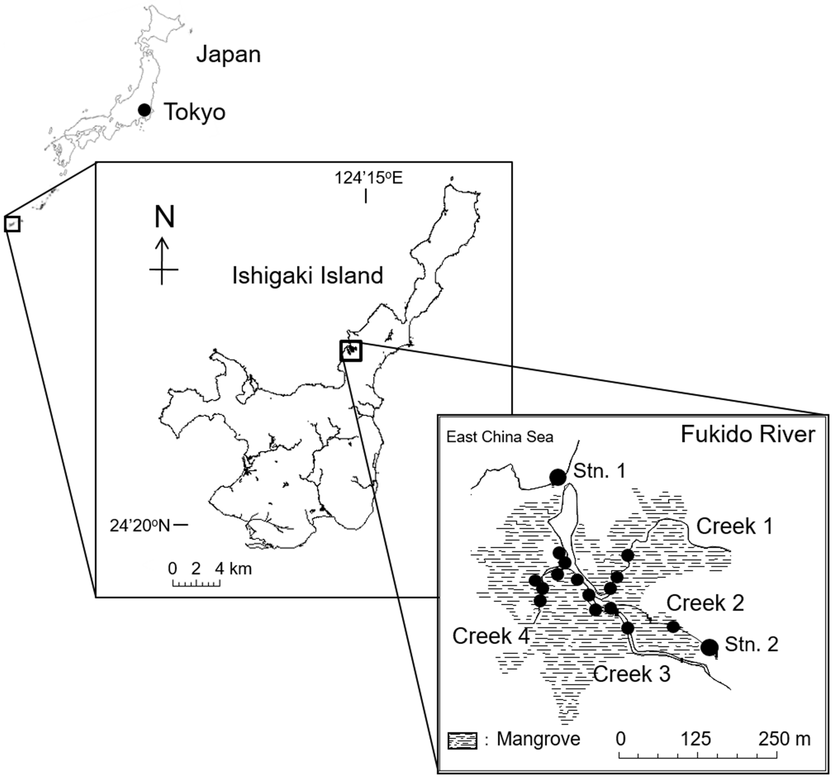

Figure 1. Location of the study site in the Fukido River on Ishigaki Island, Okinawa Prefecture, Japan. Water quality loggers were installed at Station (Stn.) 1 and Stn. 2. Water sampling and vertical water quality profiles were taken at all sampling sites.

2. Materials and methods

a. Study area

The Fukido River has a length of 2.2 km. The width and depth of the river mouth change with tidal dynamics but the river mouth never runs dry. The average width and depth at the river mouth were 14.1 and 0.74 m, respectively, during the observation period. The Fukido River is connected to an adjacent estuary with seagrass beds and coral reefs. The estuary is subject to semidiurnal tides, and the spring and neap tides in January 2007 were around 1.8 and 0.8 m, respectively.

The Fukido River has one major creek (Creek 2) that accepts inflow from three other small creeks (Creeks 1, 3, and 4). The area of the watershed is 2.8 km^2, of which 0.12 km^2 is covered with mangrove swamp with dominant mangrove species *Rhizophora stylosa* and *Bruguiera gymnorhiza* (Nihei et al. 2002; Kinjo et al. 2005). Analyzing land use

Table 1. Annual average number of rainy days from 1978 to 2012 classified by daily precipitation level.

	Daily precipitation (mm d^{-1})					
	10–29	30–49	50–69	70–99	≥100	Total
Average number of rainy days (d y^{-1})	34	11	4	3	3	55

imagery data with ArcGIS software, the watershed area and the land use of each creek were determined. Land use was categorized as sugarcane fields, livestock, or broadleaf forest.

The climate is classified as subtropical with average seasonal temperatures of 28.2°C in summer and 18.8°C in winter, with an average annual rainfall (averaged over 10 years from 2003 to 2012) of 2,106 mm. Data on rainfall days for the years 1978 to 2012 were obtained from the Japan Meteorological Agency (2014), and rainfall days were reported in 20 mm intervals (Table 1). The annual average number of clear days was 310, meaning that rainy days occurred at intervals of about 7 days.

b. Study design

Observations were made at spring tide from 17 to 22 January 2007. The total daily precipitation during the observation period was greatest on 19 January at 26 mm d^{-1} and least on 20 January at 2 mm d^{-1} (Fig. 2). The precipitation amount on 20 January was obtained by integrating periods of very low rainfall ($\leq$0.5 mm h^{-1}). Thus, we defined 19 January as a rainy day and 20 January as a clear day.

Water depth, salinity, and turbidity were measured at Station (Stn.) 1 (the mouth of the Fukido River; GPS coordinates: 24.487020°N, 124.230561°E) and Stn. 2 (a nonmangrove area about 150 m upstream from the boundary of the mangrove swamp; GPS coordinates: 24.483759°N, 124.233780°E) using water data loggers (U20-001-04-Ti, Onset Computer Corporation; COMPACT-CTCW, COMPACT-CKU, JFE Advantech Co. Ltd.). These loggers were placed on the river bottom at Stns. 1 and 2, and measurements were taken at 10 min intervals throughout the observation period. Flow velocity was measured for cross sections at Stns. 1 and 2 with a handheld acoustic Doppler velocimeter (FlowTracker, Sontek/YSI Inc.). In order to determine tidal effects on current, current measurements were repeated 10 times during both high and low tide at approximately 1 h intervals at both stations. At the same time, the width of the river mouth was measured, and water depth was measured at 2 m intervals across the river mouth. These data were used to calculate the water area and determine the water flow rate at each station. Fluxes were obtained by multiplying water flow data by nitrogen and phosphorus concentrations.

Surface water sampling was performed at Stns. 1 and 2 and at 16 other fixed stations (Fig. 1). In order to examine the change in water quality because of tides, water sampling was conducted 14 times at Stn. 1 (4 times at flood tide, 6 times at ebb tide, and 5 times at low tide) throughout the observation period. Water samples were collected 4 times at Stn. 2 (once at flood tide, once at ebb tide, and twice at low tide). One sample was collected

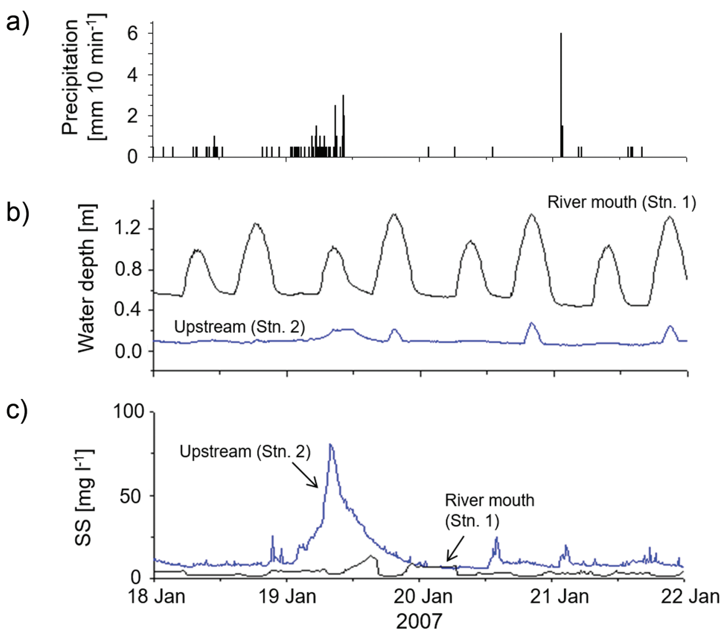

Figure 2. Precipitation (a), water depth measured from the riverbed (b), suspended solids (SS) at the river mouth (Station [Stn.] 1) and upstream (Stn. 2) (c).

from each of the other 16 stations without replication in order to evaluate water quality among the reaches of the creeks during ebb and low tides. The depth at each station varied from about 0.3 to 1.0 m, and the width of the creek was almost 2 m. Of the 16 stations, 7 were 50 to 150 m apart along Creeks 2 and 3, 4 were at about 80 m intervals (including at the upper reaches) along Creek 1, and 5 were at about 30 m intervals along Creek 4. All water samples were immediately filtered through Millipore 0.45 μm pore diameter polytetrafluoroethylene filters and stored in polypropylene bottles. The water samples were kept frozen until chemical analysis.

Vertical salinity and turbidity profiles were taken at the time of water sampling at these 18 fixed stations using a portable multiparameter water quality meter (AAQ 1183, JFE Advantech Co. Ltd.). Nutrient fluxes were estimated both at the river mouth (Stn. 1) and upstream (Stn. 2) in the Fukido River. Material flux was integrated over 24 h from 0:00 h to 0:00 h and taken as the daily flux.

c. Chemical analyses

Dissolved inorganic nutrients (SiO_2-Si, NO_3-N, NH_4-N, and PO_4-P), total nitrogen (TN), and total phosphorus (TP) were determined spectrophotometrically using a continuous flow analyzing system (AACS III system, Bran+Luebbe) based on the Japanese Standards Association JIS-K0170 (Japanese Standards Association 2011). The following methods were used: for PO_4-P and TP, acidic molybdate with ascorbic acid reduction (phosphomolybdenum blue); for NH_4-N, alkaline phenate method with hypochlorite and sodium nitroprusside (indophenol blue); and for NO_3-N and TN, cadmium coil reduction followed by sulfanilamide reaction in the presence of *N*-(1-naphthylethylenediamine) dihydrochloride. TN and TP samples were digested using the potassium peroxodisulphate method and heated at 120°C for 40 min in an autoclave (Grasshoff, Erhardt, and Kremling 1983). SS were measured by the photometric method described in Krawczyk and Gonglewski (1959), using a portable spectrophotometer (DR 2800, Hach Company).

3. Results

a. Environmental variables

The water depth at the river mouth (Stn. 1) in Figure 2 is tidal dominated, whereas the water depth upstream (Stn. 2) remained largely unaffected by tides, except for an increase at the highest tide of the spring tide. The water depth at the upstream station showed an approximately 0.1 m increase starting before noon on 19 January. The increase appears to have been triggered by steady rainfall, as a brief rainfall event of 6 mm per 10 min at 1:30 a.m. on 21 January did not have an effect on the water depth and SS at the upstream station.

SS quickly increased at the upstream station on 19 January, reaching a peak of 80.5 mg L^{-1}, which is more than 9 times the average concentration of 8.7 mg L^{-1} observed on 18 January. In contrast, SS at the river mouth started to increase about 6 h after the rain stopped.

The average number of days per year with low rainfall (10–29 mm d^{-1}) is 34 in the Fukido River area (Table 1). Small rainfall events occur as frequently as once every 10 days, on average. SS at the upstream area has the potential to increase significantly (in this study, 9.2 times the baseline concentration) at the same frequency.

The flow velocity at the river mouth and upstream was converted into volume by multiplying by water cross-sectional area. Water exchange at the river mouth was approximately 40,000 m^3 d^{-1}, which is about 7 times the water inflow from upstream (about 6,000 m^3 d^{-1} on the rainy day). Tidal flow in the Fukido River during this period regulated the water balance at the mouth of the river.

b. Distribution of dissolved nutrients

The relationship between salinity, dissolved nutrients, and sampling location and date over the period of 17–21 January 2007 is shown in Figure 3. SiO_2-Si shows a negative correlation with salinity, indicating that SiO_2-Si was diluted with seawater, showing conservative behavior during estuarine mixing. Samples with lower SiO_2-Si were taken on the rainy day, and the concentration in these samples was 50% lower than on clear days, suggesting that rainfall also diluted the upstream SiO_2-Si concentration.

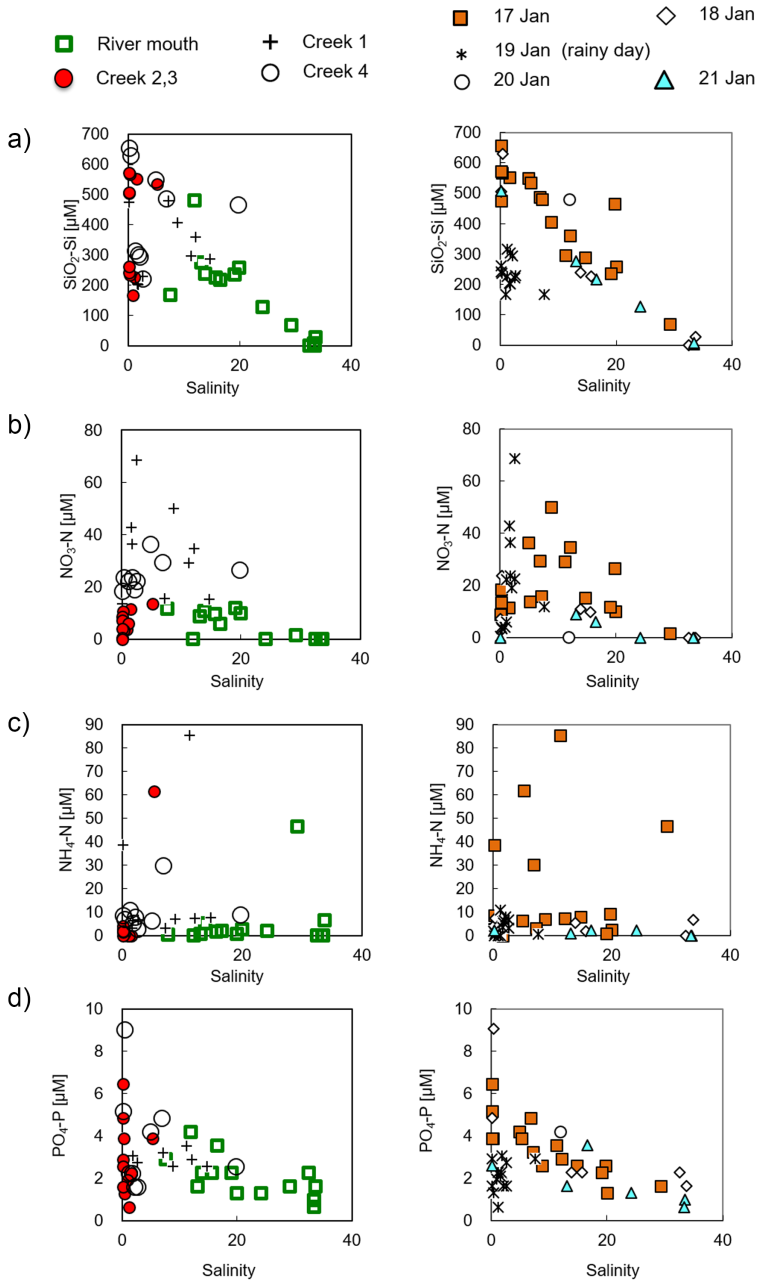

Figure 3. Surface water nutrient concentrations plotted against salinity by sampling location (left) and date (right) for SiO_2-Si (a), NO_3-N (b), NH_4-N (c), and PO_4-P (d).

Table 2. Watershed area of the Fukido River by creek and land use calculated using ArcGIS software.

Land use	Watershed area[a] (km^2) Creek 1	Creeks 2, 3	Creek 4	Total
Sugarcane field	0.07	0.04	0.11	0.22
Livestock production	0.06	0	0	0.06
Broadleaf forest	0.78	0.96	0.6	2.33
Other	0.07	0.06	0.06	0.19
Total	0.97	1.06	0.77	2.8

Note: [a]Values reported in this table are rounded.

NO_3-N at the river mouth showed comparatively lower values (<12 μM) than those in Creeks 1 and 4 and was widely distributed over salinity values ranging from 7 to 34. NO_3-N at other stations also varied and decreased in the order of Creek 1 > Creek 4 > Creeks 2 and 3. This indicates that nitrate concentrations in the inflow water were different in the various creeks and that the highest concentration was in Creek 1. As shown in Table 2, land use in the watershed of each creek differs; there is livestock production in the watershed of Creek 1, but not Creeks 2, 3, and 4, whereas there are more sugarcane fields and fruit orchards in the watershed of Creek 4. Livestock waste and storage facilities could be a source of NO_3-N contamination. Differences in land use could explain the differences in upstream nitrate loading.

NH_4-N was less than 12 μM, except in five very concentrated samples (>30 μM). In the Fukido River basin, there was a period of no precipitation for 12 days preceding 17 January. All five samples greater than 30 μM were taken on 17 January, prior to the start of precipitation (11:30 a.m.), indicating a temporarily high nitrogen input from local dissolved inorganic nitrogen pools in the mangrove swamp that remained undisturbed during clear days. Eight sediment samples were taken along Creeks 1, 2, and 4. NH_4-N adsorbed on the surface of sediments was extracted using 1 M KCl with the Harper method (Harper 1924), and the concentration of NH_4-N was determined spectrophotometrically. The concentration of NH_4-N adsorbed on the sediment surface varied from 0.6 to 2.0 mg L^{-1}. The sample with the highest concentration was taken in the center of the mangrove swamp. This indicates that ammonium-nitrogen accumulates in the sediments of mangrove creeks and can elute to water.

PO_4-P also showed a decrease with increasing salinity, indicating conservative behavior. PO_4-P at Creeks 2 and 3 decreased on the rainy day in a manner similar to, but less pronounced than, that of SiO_2-Si. This indicates that upstream phosphorus inputs were diluted by rainfall.

c. *Sediment and nutrient fluxes*

Sediment and nutrient fluxes were calculated by multiplying average concentrations and flow rate (Table 3). Influx refers to the nutrient flux entering the mangrove swamp from

Table 3. Precipitation and nutrient influx from upstream and net outflux at the mouth of the Fukido River during 18–21 January 2007.

Sampling date (2007)	Precipitation (mm)	Daily flux (kg d^{-1})					
		SS		TN		TP	
		Influx	Outflux	Influx	Outflux	Influx	Outflux
18 Jan	10	108.6	20.0	4.90	0.54	0.53	0.04
19 Jan	26	335.3	11.1	9.29	0.21	0.88	0.03
20 Jan	2	35.0	11.4	1.85	0.86	0.31	0.07
21 Jan	10	64.3	12.1	3.62	−2.00	0.35	0.00

Note: SS, suspended solids; TN, total nitrogen; TP, total phosphorus.

Stn. 2, and net outflux is the tidal exchange at Stn. 1 (direction from the mangrove creek to the coastal area is negative). SS fluxes on a clear day at the river mouth were 103 kg d^{-1} at ebb tide and 92 kg d^{-1} at flood tide. Both fluxes were larger than the input flux upstream (35 kg d^{-1}). Tidal dynamics had a major influence on the SS budget.

However, on a rainy day, the SS influx from upstream was 335 kg d^{-1}, twice as big as the fluxes at the river mouth (169 kg d^{-1} at ebb tide and 158 kg d^{-1} at flood tide) and 9.6 times greater than the influx on the clear day (Fig. 4). The net outflux at the river mouth did not vary between clear and rainy days (11.1 and 11.4 kg d^{-1}, respectively). This resulted in abundant deposition of SS in the mangrove swamp on the rainy day, amounting to 324 kg d^{-1} or 13.5 times higher than on a clear day.

Spatial distribution of salinity and turbidity along the main creek (Creek 2) on a rainy day showed high salinity (>10) and turbidity ($>1{,}000$ ppm) at the bottom of the main creek (Fig. 5). Sediment resuspension occurs in the bottom of creeks, and in ebb tide sediments including resuspended sediments flowing into the river mouth, a water body with high salinity. An increase in salinity is likely to decrease the ionic charge of the sediment and promote adherence of particles and deposition.

TN and TP influxes from upstream differed between rainy and clear days. TN influx on the rainy day was 9.3 kg d^{-1}, 4.9 times that on the clear day (Fig. 6). TP influx increased on the rainy day and was 2.8 times that on the clear day (Fig. 7). Outfluxes of TN and TP showed little difference between rainy and clear days. The amounts of TN and TP deposition in the mangrove swamp on the rainy day were 9.1 and 3.4 times those of the clear day, respectively.

Net fluxes of SS, TN, and TP at the river mouth on the rainy day were not much different from those on the clear day, although influxes of SS, TN, and TP increased significantly on the rainy day, resulting in large depositions of SS, TN, and TP in mangrove swamps on rainy days. Correlations between TN versus SS and TP versus SS were positive ($r = 0.84$, 0.92, respectively; Fig. 8), indicating that SS carried much nitrogen and phosphorus during its transport. SS could be the major source of nutrients likely to be deposited in the bottom sediment because of settlement of SS.

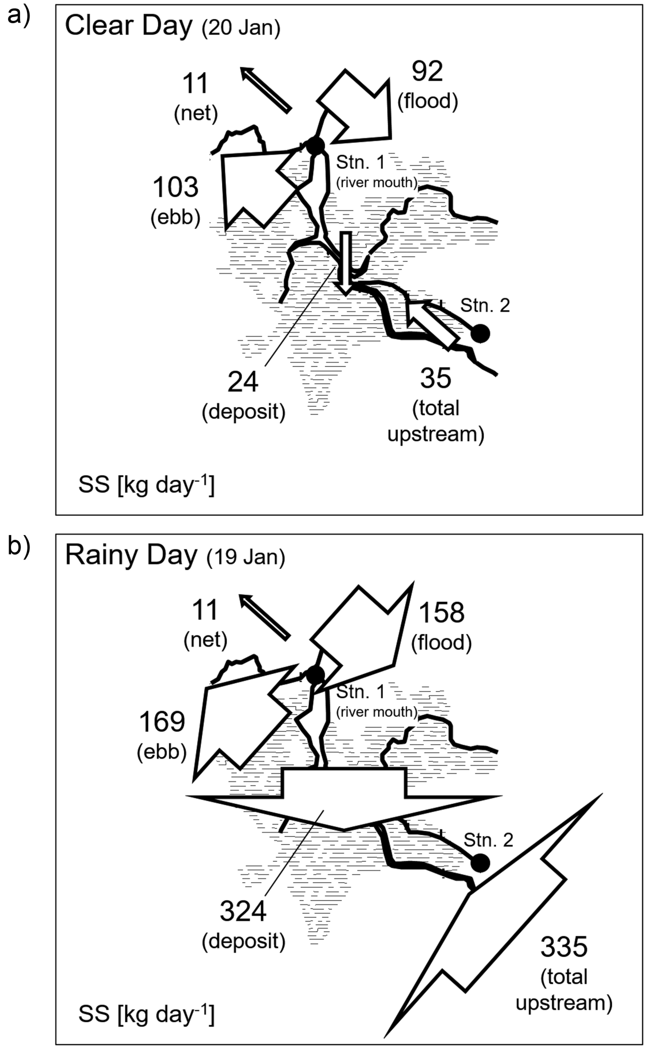

Figure 4. Suspended solids (SS) flux in the Fukido River on a clear day (20 January) (a) and a rainy day (19 January) (b). Amount of tidal exchanges (during ebb, flood, and net one tide) and influx from upstream (the sum of four creeks) are shown in each panel. The center arrow shows the net outflux (i.e., the total amount of SS deposited in the mangrove swamp). Stn., Station.

4. Discussion

Our results show that deposition of SS, TN, and TP in the mangrove swamp was particularly high on the rainy day. Although rainfall of 26 mm d^{-1} was not considered heavy, it had an effect on water quality in the upstream reaches. Among the average of 55 rainy days per year from 1978 to 2012, the most common precipitation level (n = 34 days) was

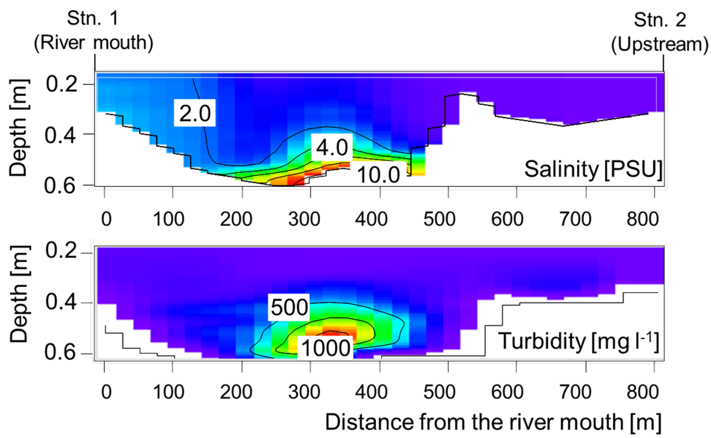

Figure 5. Cross-sectional distribution of salinity and turbidity in Creek 2 on a rainy day (19 January). Creek topography is represented by white shading. PSU, practical salinity units; Stn., Station.

within the range of 10 to 29 mm d^{-1}, which includes the precipitation level on the rainy day in our study. There is an average of 21 days per year with precipitation greater than 30 mm d^{-1}. Landfalls of typhoons on the island resulting in precipitation of more than 100 mm d^{-1} may produce a completely different phenomenon. Under such conditions, the input flux from upstream will significantly increase. However, the tidal exchange of material flux at the river mouth could also change markedly because of passing typhoons, and the flow rate in creeks could be affected. As a result, SS, TN, and TP deposited in creeks on dry days may be flushed out to the ocean in significant amounts, and the material deposited in mangrove swamps may be swept away. The results of this study, thus, demonstrate the critical importance of measuring nutrient fluxes on rainy days and of considering the total balance of nutrients. The effects of rainfall are expected to be variable, and more data collected under various weather conditions are necessary to characterize nutrient fluxes.

Investigations of nutrient fluxes in a semiarid mangrove in the Gulf of California (a shallow-water area of approximately 160 km^2) revealed that neither tides nor rainfall showed a significant correlation with nutrient concentrations (Sánchez-Carrillo et al. 2009), as carbon, nitrogen, and phosphorus loads during flood and ebb tides were not significantly different. Senthilkumar, Purvaja, and Ramesh (2008) reported that the tsunami in the Indian Ocean in December 2004 produced no significant changes in dissolved nutrient export in the Pichavaram mangrove forest (area of 13 km^2). Nutrient fluxes in the Fukido River (mangrove swamp area, 0.12 km^2) in our study were affected by differences in weather conditions particularly relating to rainfall. This indicates that the effect of weather conditions, particularly rainfall, on nutrient fluxes may vary with mangrove estuary size and is likely to appear in a small mangrove area.

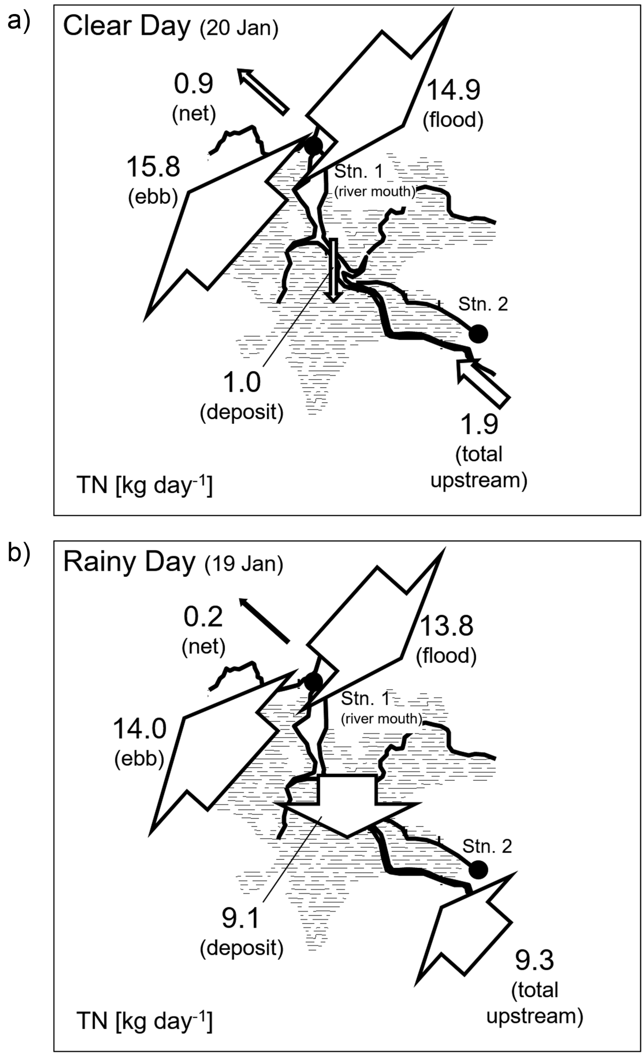

Figure 6. Total nitrogen (TN) flux in the Fukido River on a clear day (20 January) (a) and a rainy day (19 January) (b). Amount of tidal exchanges (during ebb, flood, and net one tide) and influx from upstream (the sum of four creeks) are shown in each panel. The center arrow shows the net outflux (i.e., the total amount of TN deposited in the mangrove swamp). Stn., Station.

Nutrient concentrations were relatively high compared with other mangrove estuaries. The watershed of the Fukido River includes sugarcane fields and livestock production. Runoff from agriculture and human activities is a major source of nitrogen and phosphorus to neighboring rivers (Carpenter et al. 1998). Massive amounts of nutrients derived from human activities could flow into the Fukido River via surface water and groundwater and may

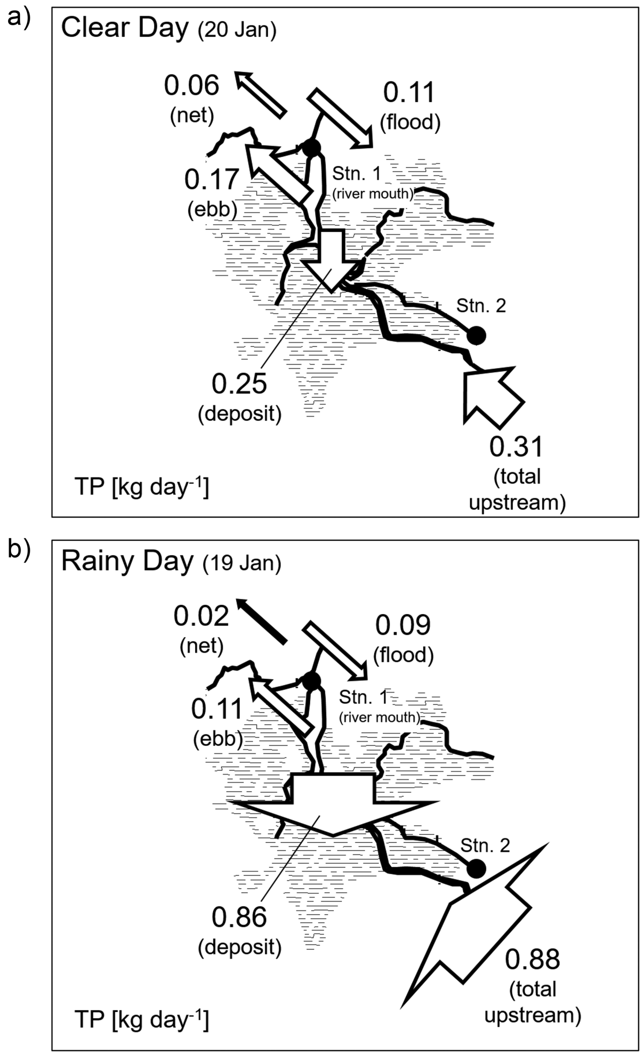

Figure 7. Total phosphorus (TP) flux in the Fukido River on a clear day (20 January) (a) and a rainy day (19 January) (b). Amount of tidal exchanges (during ebb, flood, and net one tide) and influx from upstream (the sum of four creeks) are shown in each panel. The center arrow shows the net outflux (i.e., the total amount of TP deposited in the mangrove swamp). Stn., Station.

influence nutrient concentrations; this effect may exceed the impact of weather conditions on dissolved nutrients.

The effect of salinity on sediment flocculation remains a controversial subject. Eisma et al. (1991) and van Leussen (1999) found a positive correlation between floc size and salinity. Burt (1986) measured floc sizes under different salinity conditions but found no

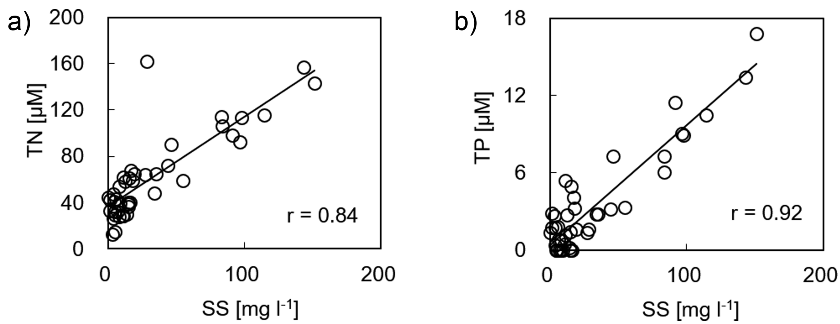

Figure 8. Relationship between total nitrogen (TN) and suspended solids (SS) (a) and total phosphorus (TP) and SS (b).

correlations among them. Sediment flocculation could be influenced by salinity, shear stress, sediment concentration, and organic matter content (Mietta et al. 2009); thus, it is difficult to identify a single parameter that controls sediment flocculation. In our case, higher salinity and turbidity were detected near the bottom of the mangrove creek, suggesting that salinity contributed to sediment flocculation and that this enhanced the high turbidity and sediment deposition in the mangrove swamp.

Kurosawa et al. (2003) proposed a model to investigate the export of nitrogen at the mouth of the Fukido River. They reported that fluxes of NH_4^+ and total organic nitrogen (TON; -0.31 and -0.85 kg d^{-1}, respectively) were exported to the coastal zone from the mangrove creek and that there is a net influx of NO_3^- + NO_2^- (0.87 kg d^{-1}). This indicates that the creeks of the Fukido River supplied NH_4^+ and TON to the coastal ecosystems and served as sinks for NO_3^- + NO_2^-. These fluxes are in the same range of results as in our study.

We focused on changes in nutrient fluxes only in creek water. In order to estimate nutrient exchange accurately in the mangrove estuary, we need to consider other important factors associated with nutrient dynamics, such as groundwater exchange, evapotranspiration, primary production, denitrification, and phytoplankton. Furthermore, dissolved and particulate organic matter attributable to litter leaching is exported from the dense mangrove area to the coastal zone during ebb tides; hence, the actual nutrient outflux is expected to be higher than the estimates presented in this article. Recently, studies on mangrove tree plantations have been conducted in Thailand (Moriizumi, Matsui, and Hondo 2010), Malaysia (Alongi 2005), China (Luo, Sun, and Xu 2010), the Philippines (Salmo and Duke 2010), and Kenya (Kairo, Wanjiru, and Ochiewo 2009). Data on material fluxes in these mangrove areas, particularly in small areas such as our study field, can contribute to the management of new plantations and estimation of the effects of weather conditions.

The relationships between nitrogen loading that originates from upland and fringing coastal wetlands or seagrass meadows have been studied (Valiela and Cole 2002). These studies reveal that fringe wetlands between land and ocean are sufficient to reduce anthropogenic nitrogen loads and to protect coastal seagrass beds. In addition, Unsworth et al. (2008) found that mangroves likely enhance fish assemblages in nearby seagrass beds by increasing the availability of shelter and food. On Ishigaki Island, coral reefs have been disappearing, and one possible cause is red soil runoff. Our research suggests that the mangrove swamps in the Fukido River trap sediments from the uplands and serve as a store of the material outflux of sediment and nutrients that occurs on rainy days. This means that the mangrove swamps of the Fukido River mitigate material loading from upstream areas into adjacent coastal areas and contribute to sustaining coastal habitats.

5. Conclusions

Nutrient fluxes in a small mangrove river on Ishigaki Island, Okinawa, Japan, were influenced by rainfall events. The magnitude of influxes from upstream increased on the rainy day, and the deposition of SS, TN, and TP in the mangrove swamp also increased significantly. Such fluctuations because of weather conditions have not been demonstrated in previous studies conducted in large mangrove estuaries, such as those in Australia and Southeast Asia. This study suggests the importance of considering the influence of weather conditions on nutrient cycling as a function of mangrove drainage area, especially for a small mangrove estuary.

Acknowledgments. This study was supported by the Japanese Society for the Promotion of Science KAKENHI (grant numbers JP25820229 and JP22246065) and a grant from the Toda Scholarship Foundation. We thank Mr. Kenji Kanemura of Megaropa for supporting our fieldwork and Editage (http://www.editage.jp) for English-language editing.

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Received: *2 March 2016*; revised: *21 March 2017.*