Thesis

An analysis of the nitrogen cycling in mangrove ecosystem: A case study in Fukido mangrove estuary, Ishigaki Island, South-west Japan

マングローブ生態系における窒素循環解析：西南日本　石垣島吹通川河口域のマングローブ林における事例研究

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平成16年２月

ABSTRACT

This study aims to quantify the nitrogen cycle in mangrove ecosystem, especially I focused the net fluxes of inorganic and organic nitrogen between mangrove ecosystem and adjacent coastal water. Fukido River Estuary and the adjacent lagoon (Ishigaki Island, Japan) were investigated four times as an example of mangrove ecosystem during 1999-2002. In this study, the mangrove ecosystem was defined as a system which was comprised creeks (Fukido River and its tributaries) and swamps, and the coastal water was defined as the lagoonal water. Concentrations of inorganic and organic nitrogen oscillated with the tidal change, and concentrations of those in ebb tide were higher than those in flood tide in creek water. In the lagoon, concentration of NO_3^- (NO_3^-+NO_2^-) and organic nitrogen (TON or PON and DON) were increased near the mouth of the creek. These mean that the mangrove ecosystem supplies nitrogen compounds to the adjacent coastal water. To quantify the fluxes of inorganic and organic nitrogen per day between the mangrove ecosystem and the adjacent coastal water, the fluxes of those were estimated by subtract the freshwater fluxes of those from the total fluxes of those across the mouth of the creek. The oceanic fluxes of inorganic and organic nitrogen and the fluxes of those originated from the mangrove ecosystem were estimated too. The contribution of the freshwater fluxes of inorganic and organic nitrogen to the total fluxes of those were up to

35 %. This shows that the freshwater fluxes of inorganic and organic nitrogen were considerable to the total fluxes of those across the mouth of the creek. The evaluated fluxes were distinguished steady-state fluxes from the magnitude of fluxes of inorganic and organic nitrogen by using multivariate cluster analysis. In steady-state, the magnitude of the steady-state fluxes of inorganic and organic nitrogen were -0.10 ~ -0.23 mmol m^{-2} day^{-1}, and this means that all nitrogen compounds were supplied from the mangrove ecosystem to the adjacent coastal water. In non steady-state, the magnitude of fluxes of DON (dissolved organic nitrogen) and NH_4^+ were 7.0 ~ 29 mmol m^{-2} day^{-1}, and they were ten or hundred times higher than any other fluxes of inorganic and organic nitrogen. This may show that they returned to the mangrove ecosystem since their fluxes were dominated by the fluxes of those originated from the mangrove ecosystem. Further research would be required to analyze how to originate those fluxes at mangrove ecosystem in non steady-state. The net fluxes of inorganic and organic nitrogen in steady-state at Fukido River Estuary were compared with those reported by previous studies. Net fluxes of inorganic and organic nitrogen were -1.4 ~ -0.22 mmol m^{-2} day^{-1} (PON: particulate organic nitrogen), -0.74 ~ 0.25 mmol m^{-2} day^{-1} (DON), -0.29 ~ 0.00 mmol m^{-2} day^{-1} (NO_3^-+NO_2^-), -0.23 ~ 0.03 mmol m^{-2} day^{-1} (NH_4^+) and -0.04 ~ -2.3 mmol m^{-2} day^{-1} (TN: total nitrogen), respectively. These mean that PON and NO_3^-+NO_2^- were commonly supplied to adjacent coastal water from mangrove ecosystem, and mangrove ecosystem might be an important supplier of nitrogen on food web in coastal water. The annual net fluxes of inorganic and

organic nitrogen were calculated by the high tide and the average concentrations of those in steady-state at the mouth of Fukido River. It reached 0.8 t N yr^{-1} and suggested that inorganic and organic nitrogen were exported from the mangrove ecosystem to the adjacent coastal water. The annual net N_2 exchange rate and the normalized net nitrogen fluxes per year are same order to the nitrogen requirement in the mangrove ecosystem. We must focus detail character of net N_2 exchange between mangrove sediment and the atmospheric N_2 in mangrove ecosystem because it would be the beginning of nitrogen cycle in mangrove ecosystem.

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CHAPTER I: GENERAL INTRODUCTION

There are much concerns lately on the possible changes in global climate which may result "global warming." Global warming means an increase of average global temperature caused by increased concentrations of greenhouse gasses emitted by human activity (Carlson 2003, Lee and Li 2003, Rosenberg *et al.* 2003, Oh *et al.* 2003, Baranzini *et al.* 2003, Orkin *et al.* 2003, Limåo-Vieir *et al.* 2003, MacKenzie 2003, Centi *et al.* 2003 and Engvild 2003). There are various greenhouse gasses, but carbon dioxide (CO_2), methane (CH_4) and dinitrogen monoxide (N_2O) are estimated to dominant the greenhouse effect. Carbon dioxide contributes 1.56 W m^{-2}, more than 50% of the total direct radiative forcing from greenhouse effect gasses (2.45 W m^{-2}) (IPCC 1995: translated by Japan Meteorological Agency).

Fig. 1 shows annual carbon fluxes and pools in the global carbon cycle (Suzuki 1997). Since the Industrial Revolution, humans have emitted great amounts of CO_2 via activities including burning of fossil fuels, cement production, and land-use changes. These fluxes are smaller than other natural fluxes. However, if anthropogenic CO_2 emission continues at present rate, the concentration of atmospheric CO_2 will reach about 500 ppm in 2030 (IPCC 1995: translated by Japan Meteorological Agency).

Much experimental projects for abating global warming are carried out by scientists and engineers. Some scientists and engineers try to fix atmospheric carbon dioxide into natural ecosystems utilizing their primary production (KEPCO 2001). Mangrove forests have great potential because of their high productivity (Tateda *et al.* 1999 and Tateda 2002).

Mangrove forests are main ecosystems occupying about 60 - 75 % of the tropical coastline where annual average temperature is about 30 degrees (Dittmar and Lara 2001a and Clough 1998). Mangrove forests cover an area of 160,000 km^2 (Spalding *et al.* 1999) on the earth. Fig. 2 shows the distribution of number of species of mangrove vegetation by longitude. Southeast Asia area has the greatest species of mangrove vegetation in the world. People living in coastal regions of Southeast Asia have utilized these resources as a shelter, wood for fuel and a variety of natural products (Alongi 1998).

On the other hand, some scientists insist that mangrove forests could hardly contribute to global fixation of carbon dioxide, because their whole area is small compared with that of terrestrial forest globally (Suzuki 1997). The mangrove forests account for less than 1 % of the total forest area on Earth (Ayukai 1998 and Leith 1975). Furthermore, since 1950, mangrove forests were exploited extensively for shrimp pond, or deforested for export of timber. As a result of such industrial and economical deforestation, the whole area of mangrove forests has declined by 47,839 km^2 in the world (about 35% of the whole area of global mangrove forest: Cebrian 2002). Cebrian (2002) estimated that 3.8×10^8 t C stored as biomass of mangrove vegetation biomass has been lost over the last

20 years by human activities. Mangrove forest moderate the impacts floods, storm surges and coastal erosion in coastal area of tropical region (Alongi 1998). This deforestation has resulted in increased damages from sediment discharge and flooding by storm or typhoon for people living in coastal regions.

However, mangrove forests could still be important local sinks for atmospheric CO_2 along tropical coastlines (Clough 1998). If we want to utilize ecosystems for the enhancement of CO_2 sequestration, we should focus on their ability to produce and store organic carbon (Ayukai *et al.* 1998). Fig. 3 shows gross primary production and total respiration per unit area in various aquatic ecosystems, including streams and rivers (Alongi 1998). Most ecosystems are slightly autotrophic or slightly heterotrophic, and mangrove forests are the most productive ecosystem per unit area among the aquatic ecosystems. Furthermore, the mangrove forests have ability to accumulate much refractory organic matter as detritus in their sediments. Cebrian (2002) analyzed statistically 180 publications reporting data of carbon fluxes in marine communities, and showed that mangrove community has the largest accumulation of carbon per area among marine communities. Mangrove forests are the most useful ecosystem to trap and store atmospheric carbon dioxide.

However, nutrients (especially inorganic nitrogen) generally limit the growth of autotrophs in marine communities (Nishimura *et al.* 1994). Some scientists reported that inorganic nitrogen generally limits the growth of autotroph (mainly vegetation of mangroves) in mangrove forests too (Onuf *et al.* 1977, Boto and Wellington 1983 and

Boto and Wellington 1984). Boto *et al.* (1985) and Naidoo (1987) reported that authors fertilized inorganic nitrogen to *Avicennia marina*, and that growth rate correlated positively with amounts of fertilization. Nitrogen was also considered a limiting factor for microorganism activity in the mangrove swamp of the Indus Delta (Kristensen *et al.* 1992).

Though studies of the nitrogen cycle and balance in mangrove forests are important, the information available is confined to few regions in the world (Dittmar and Lara 2001a): Hinchinbrook Island (Australia) is the only mangrove area for which a quantitative long term export balance has been obtained (Boto and Bunt 1981, Boto and Wellington 1988, Alongi 1996, Alongi *et al.* 1998 and Ayukai *et al.* 1998). In Terminos Lagoon (Mexico), fluxes of dissolved inorganic and organic nitrogen, particulate nitrogen, and total suspended sediments between the swamps and the inundated sea water in the mangrove forest were evaluated by the flume technique (Rivera-Monroy *et al.* 1995). In Klong Ngao (Thailand), outwelling of dissolved nutrients from mangrove forests were evaluated (Wattayakorn *et al.* 1990). In Furo do Meio (Brazil), fluxes of dissolved nutrients and dissolved organic matter between the swamps and the creeks were determined (Dittmar and Lara 2001a).

This study aims to clarify the nitrogen balance and cycle in Fukido mangrove forest. I will focus on the following six subjects. (1) The spatial and temporal distribution of inorganic and organic nitrogen concentrations in Fukido River Estuary (Chapter II) (2) Evaluation of net fluxes of inorganic and organic nitrogen between the Fukido River

Estuary and the adjacent coastal sea via tidal exchange (Chapter III). (4) Comparison the net fluxes of inorganic and organic nitrogen between the mangrove ecosystem and the adjacent coastal water in Fukido River Estuary and those reported in any other mangrove ecosystem (Chapter III). (5) Evaluation of annual nitrogen fluxes via tidal exchange in the mangrove ecosystem along Fukido River (Chapter IV).

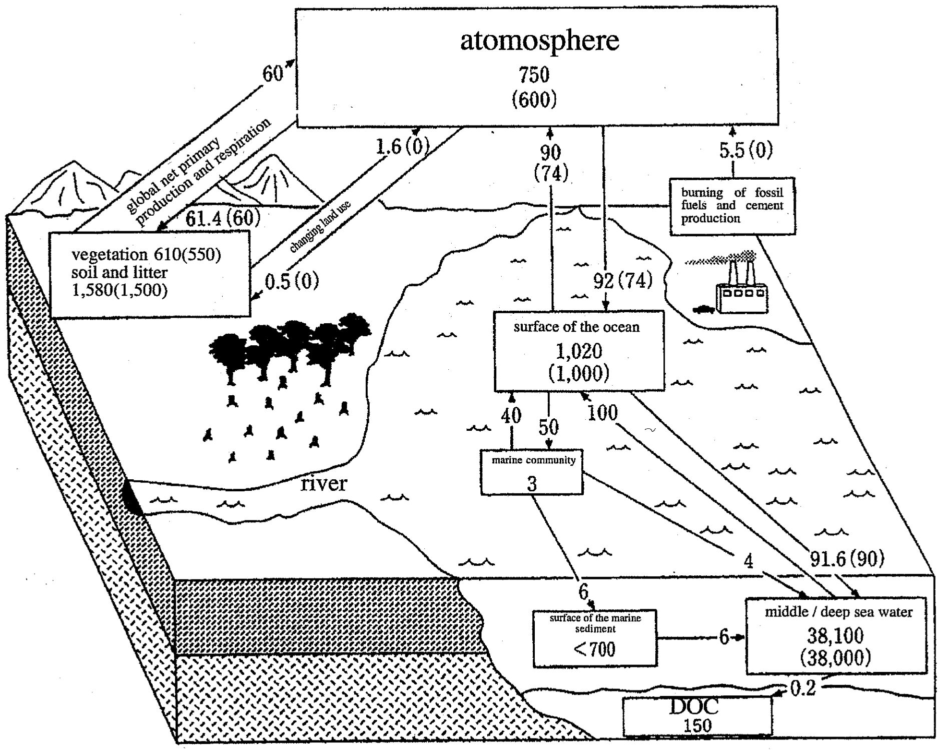


Figure 1-1 Global carbon fluxes and pools. Values in parenthesis mean fluxes and pools before Industrial Revolution. Unit: Gt C (Suzuki 1997).

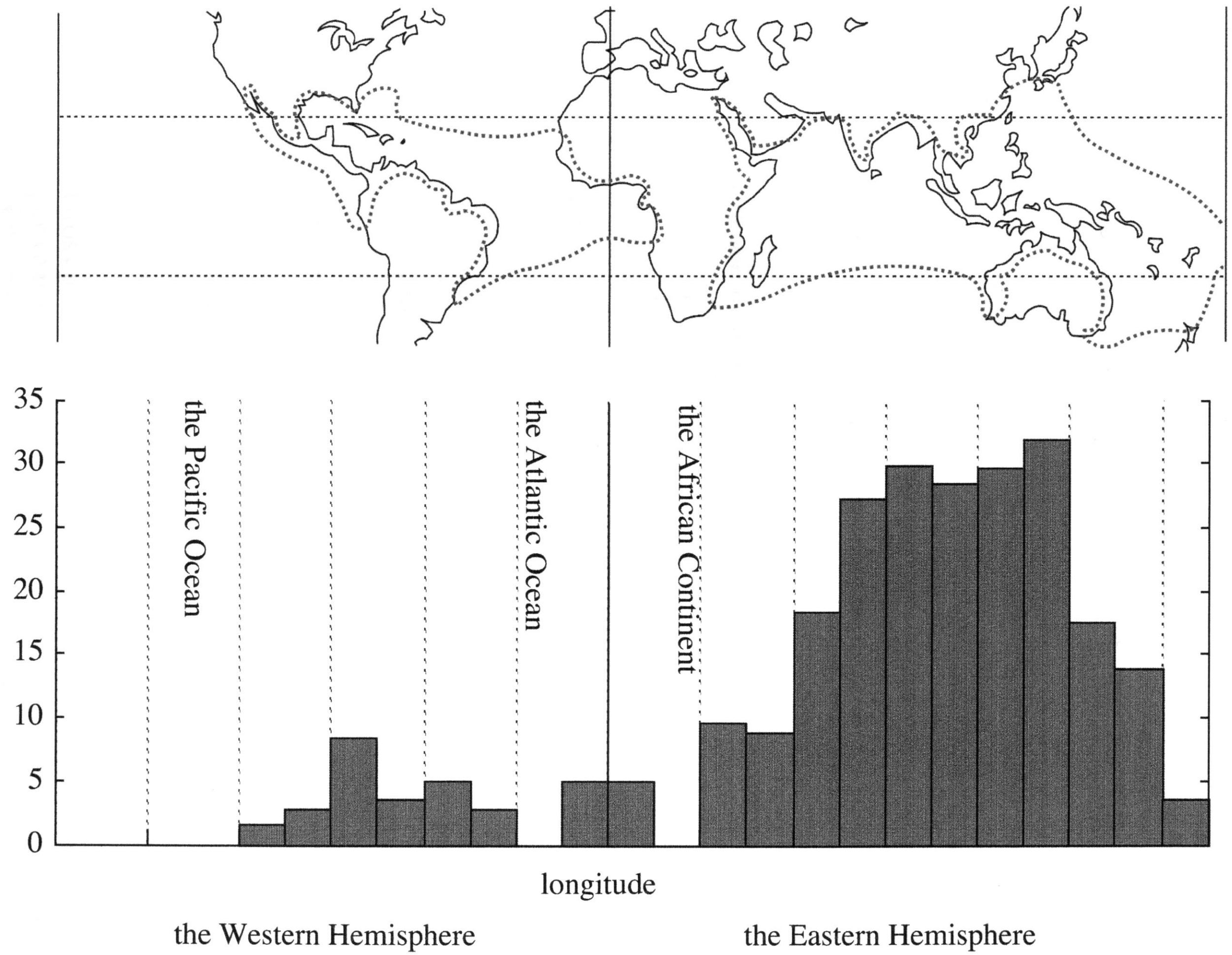


Figure 1-2 Global distribution of species of mangrove vegetation to global longitude (Suzuki 1997).

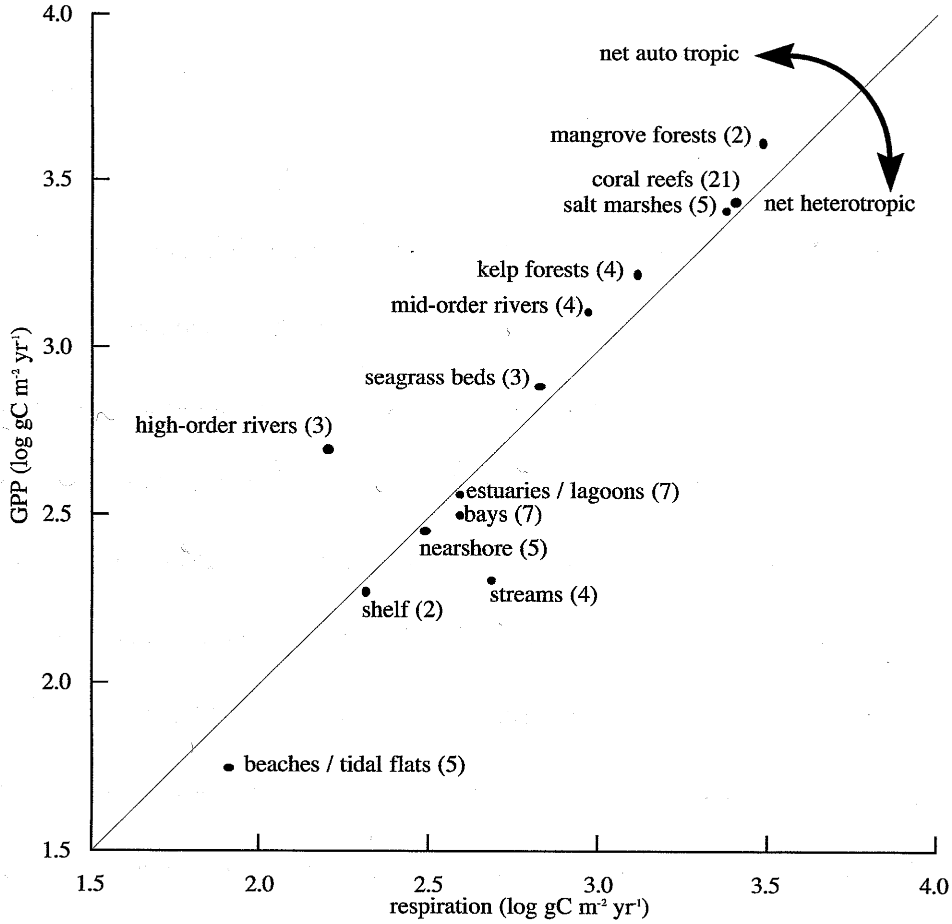


Figure 1-3 Gross primary production (GPP) and total respiration per square meter per year in various aquatic ecosystems, including streams and rivers. Note that data are log10 transformed (Alongi 1998).

CHAPTER II: INORGANIC AND ORGANIC NITROGEN CONCENTRATIONS IN FUKIDO MANGROVE ESTUARY

Introduction

The chemical and biological links between mangroves and near-shore waters are still poorly understood (Boto and Wellington 1988). Some studies have showed that export of large amounts of organic material has a recognizable effect on food webs in coastal waters (Odum and Heald 1975, Alongi *et al.* 1989 and Alongi 1990). Coastal outwelling of dissolved and suspended organic matter and nutrients from mangrove swamps can also affect considerably the biogeochemical cycles of marine environments (Dittmar and Lara 2001b). However, the information available on this phenomenon is confined to few regions in the world and often controversial (Dittmar and Lara 2001b). Adjacent mangrove areas in Hinchinbrook Island (Australia) were a source and effective sink for dissolved nutrients and organic carbon (Boto and Bunt 1981, Boto and Wellington 1988, Alongi 1996, Alongi *et al.* 1998 and Ayukai *et al.* 1998). Twilley (1985) determined net-export of dissolved and suspended organic carbon from mangroves in Rookery Bay (Florida, U.S.A). Wattayakorn *et al.* (1990) reported outwelling of inorganic nutrients from mangroves in Klong Ngao (Thailand). In Terminos Lagoon (Mexico), the mangrove seems to be rather an importing system for dissolved nitrogen species (Rivera-

Monroy *et al.* 1995). Simpson *et al.* (1997) showed the balance of net nitrate exchange rate between the mangrove forests and adjacent coastal waters were nearly 0 in Malaysia. In Baganca (North Brazil), strong outwelling of nutrients and organic matter was measured, exceeding that of other mangroves in the world (Dittmar and Lara 2001a).

Most studies represented the mangrove forests are a source of organic carbon to near-shore waters via tidal exchange, but estimate of balance of nutrients, especially nitrogen, have large variability of fluxes between mangrove forest and adjacent coastal waters. Boto and Wellington (1988) indicated large and random variations of material concentrations over space and time prevented their estimates of fluxes. Ayukai *et al.* (1998) indicated variations of tidal range, topography, sediment chemistry or community structure in their two study sites may introduce the inconsistencies in their results of material fluxes in Hinchinbrook Island, Australia. Dittmar and Lara (2001a) showed that many inconsistencies in the published data were introduced by methodological differences and difficulties in accurately determining material fluxes in mangrove areas.

The objective of the present chapter is to pre-analyze the concentrations of inorganic and organic nitrogen for determining of the fluxes of those between the mangrove ecosystem along Fukido River and the adjacent coastal water. This objective includes following subjects as: (1) analysis of the data sets of inorganic and organic nitrogen concentrations in mangrove estuary obtained by the investigation carried out by NEDO/JOIA project (2) To clarify the characterization of horizontal and temporal distribution of inorganic and organic nitrogen concentrations in the mangrove ecosystem and the adjacent coastal water.

The data sets of present study were obtained by investigations of NEDO/JOIA project, development of technical fixation and utilization of carbon dioxide.

Materials and Methods

Observations were carried out from 1999 to 2002 (March 1999, September 2000, November 2001 and April 2002). The research area, mangrove forest along Fukido River, is located in northeastern Ishigaki Island, South-west Japan (Fig. 2-1). Ishigaki Island belongs to the subtropical climate zone, the annual average temperature and annual rainfall in 1999 were about 24 °C and about 2000 mm, respectively (Fig. 2-2: Kurosawa *et al.* 2003). In Ishigaki Island, rainy season is from May to September, and latter in the season, typhoons bring heavy storms.

Fukido mangrove forest spreads along Fukido River and covers an area of about 18.7 ha. Fukido River is about 1 km long and joined by many small creeks in the mangrove forest (Fig. 2-1). Fukido mangrove forest connected to the coastal sea with only one channel. Fukido River is a tidal creek. In flood tide, sea water flows backward of the river and inundated into the mangrove forest. In ebb tide, sea water flows out through the channel to the coastal sea. The vegetations in Fukido mangrove forest are mainly occupied by *Rhysophora Stylosa*, and *Buruguiera Gymnorrhiza* grew patchily in the forest (Yamaki *et al.* 2001, Yamaki *et al.* 2002). In this study, the mangrove ecosystem was defined as a system which was comprised creeks (Fukido River and its tributaries) and swamps, and the coastal water was defined as the lagoonal water.

To collect water samples temporally, two sampling stations were fixed along Fukido River; Stn A was at the mouth of the creek and Stn B was at the mid creek (Fig. 2-1). There are some differences in environment between Stns A and B. The mean depth of the water column is about 1.1 m at Stn A and about 1.3 m at Stn B, respectively. The width of the creek in mean tidal level is about 30 m at Stn A and less than 20 m at Stn B (Nihei *et al.* 2001). The sampling point at Stn A was located below the bridge, and the sediment of the creek is composed of gravel and sand. Both shores at the mouth of the creek are protected with concrete structure. On the other hand, the sediment at Stn B composed of sand and mud. Many mangrove stand on the creek banks, and their branches have grown above the creeks at the mid creek. I collected water samples every 3 or 1 hour in the both stations.

To collect water samples horizontally, nine to ten sampling stations were located that fan out from the mouth of the creek toward the coral reef in the lagoon (Fig. 2-1). There were some seagrass beds or patched coral reefs near the sampling points in the lagoon. I collected water samples within 2 hours in flood and ebb in nine to ten stations in the lagoon.

To collect water samples flowing into the Fukido mangrove forest, the collection of water sample was carried out in the upstream of the Fukido River in April 2002 (Fig. 2-1). This station is located out of Fukido mangrove forest, so vegetation among this station was belonging to the terrestrial vegetation. The sediment of water column composed of gravel and sand. The depth of the water column was about 0.8 m, and the width of the river was about 3 m in the point.

Fig. 2-3 shows the flow chart of collection, separation and storage until laboratory analysis of water samples. Water samples were collected from surface of water column with a stainless bucket and filled into one litter poly carbonate bottle. After the collection, water samples were immediately brought back to the laboratory. Particulate matters were separated on pre-combusted (500 °C, 1 hour) Watman GF/F filter pads and they were used for determination of particulate organic nitrogen (PON) concentration. Filters for determination of PON were kept frozen until laboratory analyses. Filtrated water was divided and filled into pre-combusted (500 °C, 1 hour) glass ampules for determination of dissolved organic nitrogen (DON)) concentration and prewashed (3N HCl) plastic bottles for determination of nutrient concentrations. They were kept frozen until laboratory analysis. Except investigation in March 1999 and November 2001, I had lost some GF/F filter pads so I filled unfiltered water sample into pre-combusted glass ampules for determination of TON concentration (PON + DON).

The GF/F filters containing particulate organic matter were acidified with HCl to remove inorganic carbon, and then dried (50 °C, 12 hours) for analyses of PON. Analyses of PON concentration were carried out by high temperature flash combustion with C/N analyzer (Sumigraph NC-90A). Analysis of concentrations of nutrients (NO_3^-+NO_2^- or NO_3^-, NO_2^- and NH_4^+) was carried out with The Flow Solution (ALPKEM inc.) or

TRACCS 2000 (Bran Luebe Inc.). Determining of concentrations of nutrients was based on the methods of Wood *et al.* (1967) (NO_3^-+NO_2^- or NO_3^-), Bendschneider and Robinson (1952) (NO_2^-) and Koroleff (1970) (NH_4^+), respectively. The summation of concentrations of nutrients was defined as total inorganic nitrogen (TIN) concentrations. TDN and TN concentrations were determined by high-temperature catalytic oxidation method with Sumigraph TOC-90A by high temperature catalytic method (Suzuki and Tanoue 1991, Suzuki *et al.* 1992, Suzuki 1993 and Suzuki *et al.* 2000). DON and TON concentrations were estimated by subtract TIN from TDN or TN, respectively. The reproducibility of method is within ±5 %, except the concentrations of nutrients determined using The Flow Solution (±10 %).

The physicochemical parameters (tidal level, current velocity, water temperature, salinity and dissolved oxygen) were obtained by Tateda personal communications, except those in upper Fukido River and temperature, salinity and dissolved oxygen in March 1999. Tidal level was measured by ADL tide gauge (Alec Electronics Co. Ltd.) at the mouth of the creek (March 1999, September 2000, November 2001) and the mid creek (September 2000, November 2001). Current velocity was determined by ACM-8M current meter (Alec Electronic Co. Ltd.) at Stn A (March 1999, September 2000, November 2001) and Stn B (September 2000, November 2001). Water temperature, salinity and dissolved oxygen were measured by MWQ meter (Sanyo-Sokki Co. Ltd.) at Stns A and B in September 2000 and November 2001. All gauges were moored in the constructed pipe as regular tetrahedron shape, and are installed 0.15 m above the bottom at the mouth of the creek and the mid creek.

Water temperature and salinity at the surface of water column were measured by CSTD gauge at Stns 1 to 9 in September 2000 and November 2001.

Current velocity and salinity in upper Fukido River were determined by ACM1000 current meter (Alec Co. Ltd.) and U-10 water quality checker (Horiba Ltd.) in April 2002, respectively.

Water temperature, salinity and concentration of dissolved oxygen in March 1999 were obtained by Ikeda personal communications. Water temperature was measured by mercury thermometer. Salinity (chlorinity) and concentration of dissolved oxygen were determined by silver nitrate titration method and Winkler method, respectively.

Results

Fig. 2-4 shows spatial distribution of temperature and salinity as a typical example at Stns 1 ~ 9 in the lagoon. Salinity and temperature at Stns 1 ~ 6 were lower than that at Stns 7 ~ 9 in ebb tide, and gradient of those from the mouth of Fukido River to the reef were formed in the lagoon. This means that low saline and thermal water was flowed from the mangrove ecosystem to the lagoon in ebb tide. Low saline and thermal water was found at northern Stns in flood tide, however, salinity at Stns 1 and 3 were lower than any other Stns. This means that the coastal water was intermingled with the low saline and low thermal water by tidal change near the mouth of the Fukido River, and part of those flowed into the mangrove ecosystem.

Figs. 2-5 ~ 7 show spatial distribution of concentrations of inorganic and organic nitrogen at Stns 1 ~ 9 in the lagoon. Concentrations of organic nitrogen (TON, PON and DON) and NO_3^- (NO_3^-+NO_2^- in 1999) at Stns 1 ~ 3 were higher than Stns 7 ~ 9 in ebb tide, and high concentrations of those were still observed near the mouth of Fukido River in flood tide. The gradient of those were formed from the mouth of Fukido River to the reef. The distribution of high concentrations of organic nitrogen and NO_3^-+NO_2^- were approximately correspond to the distribution of low salinity and temperature in the lagoon. These mean that organic nitrogen and NO_3^-+NO_2^- are supplied with low saline and thermal water from the mangrove ecosystem to the lagoon, however, those may be removed from the water column near Stns 4 ~ 6 because concentrations of those were not higher than Stns 7 ~ 9 despite low salinity in Stns 4 ~ 6.

Fig. 2-8 shows the diel change of physicochemical parameters as a typical example in the creek. Water temperature, salinity and concentration of dissolved oxygen in creek water were strongly influenced by tidal change. Those reached a peak in high tide, and those reached a bottom in low tide. The decrease of salinity in low tide shows that the creek water was influenced by freshwater loading from upper Fukido River (Fig. 2-15). The decrease of concentration of dissolved oxygen in low tide means that dissolved oxygen may be consumed by respiration activity by organisms in the creek.

Figs. 2-9 ~ 11 show the diel change of concentrations of inorganic and organic nitrogen in the creek. Those were influenced by tidal change too, however, those trends of change were opposite to the physicochemical parameters in the creek. Concentrations of inorganic and organic nitrogen in the creek reached a peak in low tide and reached a bottom in high tide, especially concentrations of NO_3^- (NO_3^-+NO_2^- in March 1999) and NH_4^+ in low tide were several times higher than those in high tide. For example, concentration of NO_3^-+NO_2^- in flood tide was 0.4 ~ 0.9 μmol l^{-1}, and that increased 6.8 ~ 7.0 μmol l^{-1} in ebb tide at Stn A on 16th March 1999.

Concentrations of inorganic and organic nitrogen in ebb tide were higher than those in flood tide. For example, concentrations of inorganic and organic nitrogen at 7:00 were several times higher than those at 13:00 (TON: about two fold higher, NO_3^-: about seven fold higher, NH_4^+: about three fold higher) although tidal level at 7:00 at Stn A (0.64 m) were approximately equal to that at 13:00 (0.66 m) (Fig. 2-13). This indicates that nitrogen compounds flows out from the creek to the adjacent coastal water.

On 18th March 1999, 12th and 15th September 2000, DON or NH_4^+ concentrations greatly increased (Figs. 2-10, 11 and 12). Those concentrations were ten or hundred timer higher than those on other day, and the maximum concentrations of those were 23 ~ 221 μmol l^{-1}. Those reached a peak in flood tide or high tide, and those concentrations weren't shown common change like those in any other days. However, the other concentrations of inorganic and organic nitrogen were observed common change, and those range were approximately equal to those in any other day. For example, on 16th and 18th March 1999, the range of concentrations of TON and NO_3^-+NO_2^- were 2.9 ~ 12 and 5.0 ~ 19 μmol l^{-1}, 0.9 ~ 7.0 μmol l^{-1} and 1.3 ~ 16.7 μmol l^{-1}, respectively.

Discussion

The correlation between physicochemical parameters and concentrations of inorganic and organic nitrogen

Tables 2-3 to 5 show the correlation between physicochemical parameters and concentrations of inorganic and organic nitrogen. The tidal level show significant negative correlation to some inorganic nitrogen concentrations, but there was not significant positive correlation with concentrations of inorganic and organic nitrogen. This could mean differences of mechanisms which contributed to nutrient concentrations or organic nitrogen concentrations. Most results of inorganic nitrogen concentrations didn't show significant negative correlation to TON concentrations. This indicates inorganic nitrogen in creek waters wasn't affected by mineralization or primary production in water column strongly, and remineralization of organic nitrogen in the water column was not main source of inorganic nitrogen in the water column in Fukido mangrove creek. Dittmar and Lara (2001b) and Lara and Dittmar (1999) showed that DON and inorganic nitrogen concentrations in the creeks oscillated with tidal level, but DON concentration didn't have significant correlation to the tidal level in Furu do Meio, Brazil. Boto and Wellington 1988 found that DOC in water column of the creeks didn't appear to be linked with primary production in a tropical mangrove system at Hinchinbrook Island. In mangrove forest, dissolved organic matter (DOM) concentrations could not be contributed by biochemical mechanisms in water column of mangrove creeks.

Salinity and the concentrations of nutrients in Fukido mangrove creek and the lagoon

Figs. 2-16 to 18 showed mixing diagram for concentrations of inorganic and organic nitrogen in Fukido River Estuary. The lines in the graphs represented conservative mixture of Fukido River water and adjacent coastal water. Representative concentrations of fresh water were used the concentrations of water column in Stn C (upper Fukido River: Table 2-2) and representative concentrations of adjacent coastal waters were used the average concentration at Stns 7 ~ 9 in flood tide. Concentrations of inorganic and organic nitrogen and physicochemical parameters in upper Fukido River are shown in Tables 2-1 to 2. TN and TIN in Fukido mangrove creeks deviated from conservative mixing. Some TON plots are below conservative mixing. This might show that TON was consumed by heterotrophic organism in the water column and released inorganic nitrogen.

Figs. 2-19 to 21 show box graphs for the results of physicochemical parameters and inorganic and organic nitrogen concentrations in spatial and temporal collection of water samples. The physicochemical parameters in the lagoon have a small range to the parameters in the Fukido mangrove creek. The average concentrations of TON and TIN in the mangrove creeks were higher than the average of the concentrations of those in the adjacent coastal waters (TON: 1 - 10 fold higher, TIN: 1 - 2 fold higher, respectively). Data sets at the mouth of the creek and the mid creek have a wide range. The average concentration of TN in Fukido mangrove creeks has a significant difference from the average concentration of TN in lagoon.

High concentration of DON or NH_4^+ on 18th March 1999, 12th and 15th September 2000

On 18th March 1999, 12th and 15th September 2000, DON or NH_4^+ concentration greatly increased (Figs. 2-10, 11 and 12), and the maximum concentrations of those were 23 ~ 221 μmol l^{-1}. However, such high concentrations of those were not observed in the lagoon and upper Fukido River (Table 2-2 and Figs. 2-5 ~ 7). The source of these nitrogen compounds could be the mangrove ecosystem.

Hagawa *et al.* (2003) showed that surface concentrations of DON and NH_4^+ were 1600 and 170 μmol l^{-1} in pore water of the swamp, respectively. These concentrations were from hundred to thousand fold higher than the average concentrations in the creek water, and pore water may be a source of high concentrations in the creek water.

Some studies about nutrient dynamics in mangrove ecosystem reported about high concentrations of inorganic and organic nitrogen in creek water. Nixon *et al.* (1984) showed that NH_4^+ concentration was up to 24 μmol l^{-1} in Sangga River, Malaysia. Dittmar and Lara (2001b) reported that the average concentrations of PON and NH_4^+ were 670 and 20 μmol l^{-1} in April 1997 in Furu do Meio, North Brazil. However, evidence against high concentrations of inorganic and organic nitrogen in creek water were not clear yet. Further research would be required to analyze how to originate these high concentrations in creek water.

Conclusion

The results of this chapter are concluded as follows: (1) Low salinity and high concentrations of organic matter and NO_3^- (NO_3^-+NO_2^-) were spreaded out in Stns 1 ~ 3 in ebb tide, and those were still shown in some Stns near the mouth of Fukido River in flood tide in the lagoon. These mean that the mangrove ecosystem supplies low saline water, organic nitrogen and NO_3^- to the adjacent coastal water. (2) Concentrations of inorganic and organic nitrogen reached a peak in low tide and reached a bottom in high tide. Concentrations of inorganic and organic nitrogen in ebb tide were higher than those in flood tide in the creek. These mean that nitrogen compounds were flowed out from the creek to the adjacent coastal water. (3) NO_3^- and NH_4^+ were significantly correlated to the tidal level. On the other hand, the concentration of TON or DON changes independently to the tidal level, and those were not significantly correlated to the tidal level. (4) Concentrations of inorganic and organic nitrogen in the creeks were deviated from conservative mixing of fresh waters and coastal sea waters. Some results of TON concentrations were below conservative mixing. This might reflect consumption of organic nitrogen by heterotrophs in Fukido Mangrove Estuary. (5) On 18th March 1999, 12th and

15th September 2000, DON or NH_4^+ concentration greatly increased. Those sources might be pore water of sediment in the swamp because those concentrations in the pore water were from hundred to thousand times higher than those in creek water.

Table 2-1 Physicochemical parameters at Stn C (upper Fukido River).

cross section of the river	current velocity	salinity
5.0	0.85±0.43	0
m^2	$cm\ sec.^{-1}$	

Table 2-2 Concentrations of inorganic and organic nitrogen at Stn C (upper Fukido River).

	concentration (μmol l^{-1})
TN	9.6
PON	1.5
DON	5.1
NO_3^-	0.5
NO_2^-	0.00
NH_4^+	2.5

(a)

1999.3.16 the mouth of the creek	tidal level	current velocity	temperature	salinity	DO	PON	DON	$NO_3^-+NO_2^-$	NH_4^+
tidal level	1.000	0.619	0.485	0.852	0.651	0.083	-0.970	-0.940	-0.889
current velocity		1.000	0.179	0.683	0.925	-0.071	-0.481	-0.503	-0.559
temperature			1.000	0.338	0.594	-0.015	-0.461	-0.416	-0.313
salinity				1.000	0.808	0.071	-0.944	-0.960	-0.865
DO					1.000	-0.516	-0.778	-0.692	-0.702
PON						1.000	-0.037	-0.201	0.151
DON							1.000	0.970	0.897
$NO_3^-+NO_2^-$								1.000	0.875
NH_4^+									1.000

(b)

1999.3.16 the mid creek	temperature	salinity	DO	PON	DON	$NO_3^-+NO_2^-$	NH_4^+
temperature	1.000	-0.035	0.717	-0.531	-0.483	-0.046	0.425
salinity		1.000	0.154	-0.821	-0.016	-0.636	0.354
DO			1.000	-0.636	-0.226	0.682	0.949
PON				1.000	0.128	0.250	-0.659
DON					1.000	0.114	-0.493
$NO_3^-+NO_2^-$						1.000	0.100
NH_4^+							1.000

(c)

1999.3.18 the mouth of the creek	tidal level	current velocity	temperature	salinity	DO	PON	DON	$NO_3^-+NO_2^-$	NH_4^+
tidal level	1.000	0.628	-0.796	0.958	0.668	-0.685	-0.237	-0.907	0.469
current velocity		1.000	-0.754	0.898	0.754	-0.543	-0.388	-0.837	0.629
temperature			1.000	-0.719	-0.291	0.446	-0.069	0.629	0.075
salinity				1.000	0.510	-0.756	-0.096	-0.982	0.415
DO					1.000	-0.155	-0.798	-0.438	0.888
PON						1.000	-0.468	0.852	-0.188
DON							1.000	-0.017	-0.600
$NO_3^-+NO_2^-$								1.000	-0.411
NH_4^+									1.000

(d)

1999.3.18 the mid creek	temperature	salinity	DO	PON	DON	$NO_3^-+NO_2^-$	NH_4^+
temperature	1.000	-0.755	-0.518	-0.392	0.348	0.289	-0.011
salinity		1.000	0.717	0.441	-0.601	-0.770	0.102
DO			1.000	0.570	-0.630	-0.905	0.435
PON				1.000	-0.275	-0.610	0.695
DON					1.000	0.614	-0.610
$NO_3^-+NO_2^-$						1.000	-0.463
NH_4^+							1.000

(e)

1999.3.17 flood	temperature	salinity	DO	TON	$NO_3^-+NO_2^-$	NH_4^+
temperature	1.000	0.316	-0.296	-0.227	-0.684	-0.329
salinity		1.000	-0.110	0.094	-0.742	0.195
DO			1.000	-0.187	0.005	0.061
TON				1.000	0.542	0.545
$NO_3^-+NO_2^-$					1.000	0.216
NH_4^+						1.000

(f)

1999.3.17 ebb	temperature	salinity	DO	TON	$NO_3^-+NO_2$	NH_4^+
temperature	1.000	0.687	0.698	-0.648	0.087	0.165
salinity		1.000	0.195	-0.360	-0.204	-0.172
DO			1.000	-0.867	0.286	0.352
TON				1.000	0.040	-0.038
$NO_3^-+NO_2$					1.000	-0.010
NH_4^+						1.000

Table 2-3 Correlation between physicochemical parameters and concentrations of inorganic and organic nitrogen in water column in March 1999. (a) Stn A on 16th March, 1999 (b) Stn B on 16th March, 1999 (c) Stn A on 18th March, 1999 (d) Stn B on 18th March, 1999 (e) Stns 1-9 in flood tide on 17th March, 1999 (f) Stns 1-9 in ebb tide on 17th March, 1999.

(a)

2000.9.12 the mouth of the creek	tidal level	current velocity	temperature	salinity	DO	PON	DON	NO_3^-	NO_2^-	NH_4^+
tidal level	1.000	0.353	0.536	0.697	0.526	-0.772	0.609	-0.709	-0.752	0.623
current velocity		1.000	0.182	0.202	0.041	-0.514	-0.032	-0.405	-0.103	0.166
temperature			1.000	0.201	-0.155	-0.837	0.414	0.145	-0.254	0.314
salinity				1.000	0.914	-0.296	0.523	-0.747	-0.914	0.785
DO					1.000	-0.024	0.494	-0.763	-0.774	0.760
PON						1.000	-0.570	0.216	0.285	-0.495
DON							1.000	-0.339	-0.417	0.869
NO_3^-								1.000	0.777	-0.481
NO_2^-									1.000	-0.557
NH_4^+										1.000

(b)

2000.9.12 the mid creek	tidal level	current velocity	temperature	salinity	DO	PON	DON	NO_3^-	NO_2^-	NH_4^+
tidal level	1.000	0.368	0.541	-0.135	-0.336	0.640	-0.576	-0.751	-0.367	0.708
current velocity		1.000	0.234	0.350	-0.154	-0.372	-0.719	-0.540	-0.362	0.328
temperature			1.000	-0.167	-0.561	0.016	-0.188	-0.669	-0.648	0.095
salinity				1.000	-0.405	-0.526	0.063	-0.103	-0.212	-0.460
DO					1.000	0.032	-0.021	0.658	0.902	-0.018
PON						1.000	0.365	0.588	0.714	-0.034
DON							1.000	0.293	0.065	-0.649
NO_3^-								1.000	0.821	-0.481
NO_2^-									1.000	-0.192
NH_4^+										1.000

(c)

2000.9.15 the mouth of the creek	tidal level	current velocity	temperature	salinity	DO	PON	DON	NO_3^-	NO_2^-	NH_4^+
tidal level	1.000	0.979	0.706	0.767	0.882	-0.907	-0.031	-0.959	-0.932	-0.335
current velocity		1.000	0.614	0.816	0.943	-0.959	-0.040	-0.974	-0.920	-0.323
temperature			1.000	0.246	0.334	-0.378	-0.377	-0.475	-0.636	0.084
salinity				1.000	0.927	-0.914	0.512	-0.859	-0.901	-0.771
DO					1.000	-0.998	0.195	-0.967	-0.884	-0.508
PON						1.000	-0.163	0.980	0.895	0.486
DON							1.000	-0.109	-0.258	-0.930
NO_3^-								1.000	0.905	0.448
NO_2^-									1.000	0.594
NH_4^+										1.000

(d)

2000.9.15 the mid creek	tidal level	current velocity	temperature	salinity	DO	PON	DON	NO_3^-	NO_2^-	NH_4^+
tidal level	1.000	0.979	-0.101	0.427	-0.368	-0.873	-0.856	-0.694	-0.288	0.582
current velocity		1.000	-0.120	0.393	-0.352	-0.791	-0.748	-0.656	-0.385	0.410
temperature			1.000	0.796	0.945	-0.174	0.263	0.467	0.454	-0.031
salinity				1.000	0.567	-0.701	-0.183	-0.153	0.024	0.236
DO					1.000	0.155	0.516	0.712	0.525	-0.264
PON						1.000	0.786	0.715	0.215	-0.680
DON							1.000	0.643	-0.007	-0.887
NO_3^-								1.000	0.714	-0.393
NO_2^-									1.000	0.362
NH_4^+										1.000

(e)

2000.9.16 flood	temperature	salinity	PON	DON	NO_3^-	NO_2^-	NH_4^+
temperature	1.000	0.741	-0.840	-0.852	0.312	0.487	-0.342
salinity		1.000	-0.886	-0.977	0.107	0.435	-0.530
PON			1.000	0.967	-0.235	-0.468	0.562
DON				1.000	N.A.	-0.902	0.515
NO_3^-					1.000	0.721	-0.083
NO_2^-						1.000	N.A.
NH_4^+							1.000

(f)

2000.9.16 ebb	temperature	salinity	PON	DON	NO_3^-	NO_2^-	NH_4^+
temperature	1.000	0.989	-0.630	0.121	-0.102	0.161	-0.950
salinity		1.000	-0.552	0.160	-0.204	0.036	-0.935
PON			1.000	-0.110	-0.102	-0.361	0.631
DON				1.000	N.A.	-0.608	-0.262
NO_3^-					1.000	0.855	-0.025
NO_2^-						1.000	-0.182
NH_4^+							1.000

Table 2-4 Correlation between physicochemical parameters and concentrations of inorganic and organic nitrogen in water column in September 2000. (a) Stn A on 12th September, 2000 (b) Stn B on 12th September, 2000 (c) Stn A on 15th September, 2000 (d) Stn B on 15th September, 2000 (e) Stns 1-9 in flood tide on 16th September, 2000 (f) Stns 1-9 in ebb tide on 16th September, 2000.

(a)

2001.11.25 the mouth of the creek	tidal level	current velocity	temperature	salinity	TON	NO_3^-	NO_2^-	NH_4^+
tidal level	1.000	0.528	0.540	0.806	-0.226	-0.743	-0.709	-0.665
current velocity		1.000	0.483	0.581	-0.373	-0.594	-0.607	-0.495
temperature			1.000	0.329	-0.093	-0.451	-0.286	-0.323
salinity				1.000	-0.489	-0.855	-0.906	-0.884
TON					1.000	-0.063	0.232	0.203
NO_3^-						1.000	0.764	0.790
NO_2^-							1.000	0.886
NH_4^+								1.000

(b)

2001.11.25 the mid creek	tidal level	current velocity	temperature	salinity	TON	NO_3^-	NO_2^-	NH_4^+
tidal level	1.000	0.757	0.516	0.663	-0.424	-0.686	-0.436	-0.615
current velocity		1.000	0.638	0.470	-0.444	-0.377	-0.393	-0.734
temperature			1.000	0.059	-0.082	-0.378	-0.612	-0.520
salinity				1.000	-0.058	-0.794	-0.300	-0.745
TON					1.000	-0.052	-0.127	-0.080
NO_3^-						1.000	0.745	0.765
NO_2^-							1.000	0.665
NH_4^+								1.000

(c)

2001.11.30 the mouth of the creek	tidal level	current velocity	temperature	salinity	TON	NO_3^-	NO_2^-	NH_4^+
tidal level	1.000	0.815	0.373	0.908	0.091	-0.783	-0.176	-0.676
current velocity		1.000	0.260	0.738	0.279	-0.725	-0.230	-0.673
temperature			1.000	0.407	0.166	-0.465	-0.147	-0.365
salinity				1.000	-0.200	-0.682	-0.187	-0.638
TON					1.000	-0.460	-0.125	-0.385
NO_3^-						1.000	0.381	0.899
NO_2^-							1.000	0.600
NH_4^+								1.000

(d)

2001.11.30 the mid creek	tidal level	current velocity	temperature	salinity	TON	NO_3^-	NO_2^-	NH_4^+
tidal level	1.000	0.734	0.469	0.842	-0.295	-0.858	-0.381	-0.884
current velocity		1.000	0.283	0.504	-0.082	-0.716	-0.340	-0.726
temperature			1.000	0.466	0.065	-0.395	-0.392	-0.463
salinity				1.000	-0.364	-0.878	-0.458	-0.766
TON					1.000	0.024	-0.133	0.165
NO_3^-						1.000	0.569	0.893
NO_2^-							1.000	0.677
NH_4^+								1.000

(e)

2001.12.1 flood	temperature	salinity	PON	DON	NO_3^-	NO_2^-	NH_4^+
temperature	1.000	0.779	-0.598	-0.419	0.269	0.216	0.511
salinity		1.000	-0.255	-0.471	0.362	0.384	0.588
PON			1.000	-0.205	0.135	0.304	-0.009
DON				1.000	-0.629	-0.929	-0.951
NO_3^-					1.000	0.469	0.657
NO_2^-						1.000	0.885
NH_4^+							1.000

(f)

2001.12.1 ebb	temperature	salinity	PON	DON	NO_3^-	NO_2^-	NH_4^+
temperature	1.000	-0.177	0.097	-0.114	0.249	0.159	0.217
salinity		1.000	0.046	-0.280	-0.180	0.181	0.080
PON			1.000	-0.243	0.693	0.207	0.360
DON				1.000	-0.709	-0.985	-0.943
NO_3^-					1.000	0.707	0.857
NO_2^-						1.000	0.952
NH_4^+							1.000

Table 2-5 Correlation between physicochemical parameters and concentrations of inorganic and organic nitrogen in water column in November 2001. (a) Stn A on 25 - 26th November, 2001 (b) Stn B on 25 - 26th November, 2001 (c) Stn A on 30th November, 2001 (d) Stn B on 30th November, 2001 (e) Stns 1-9 in flood tide on 1st December, 2001 (f) Stns 1-9 in ebb tide on 1st December, 2001.

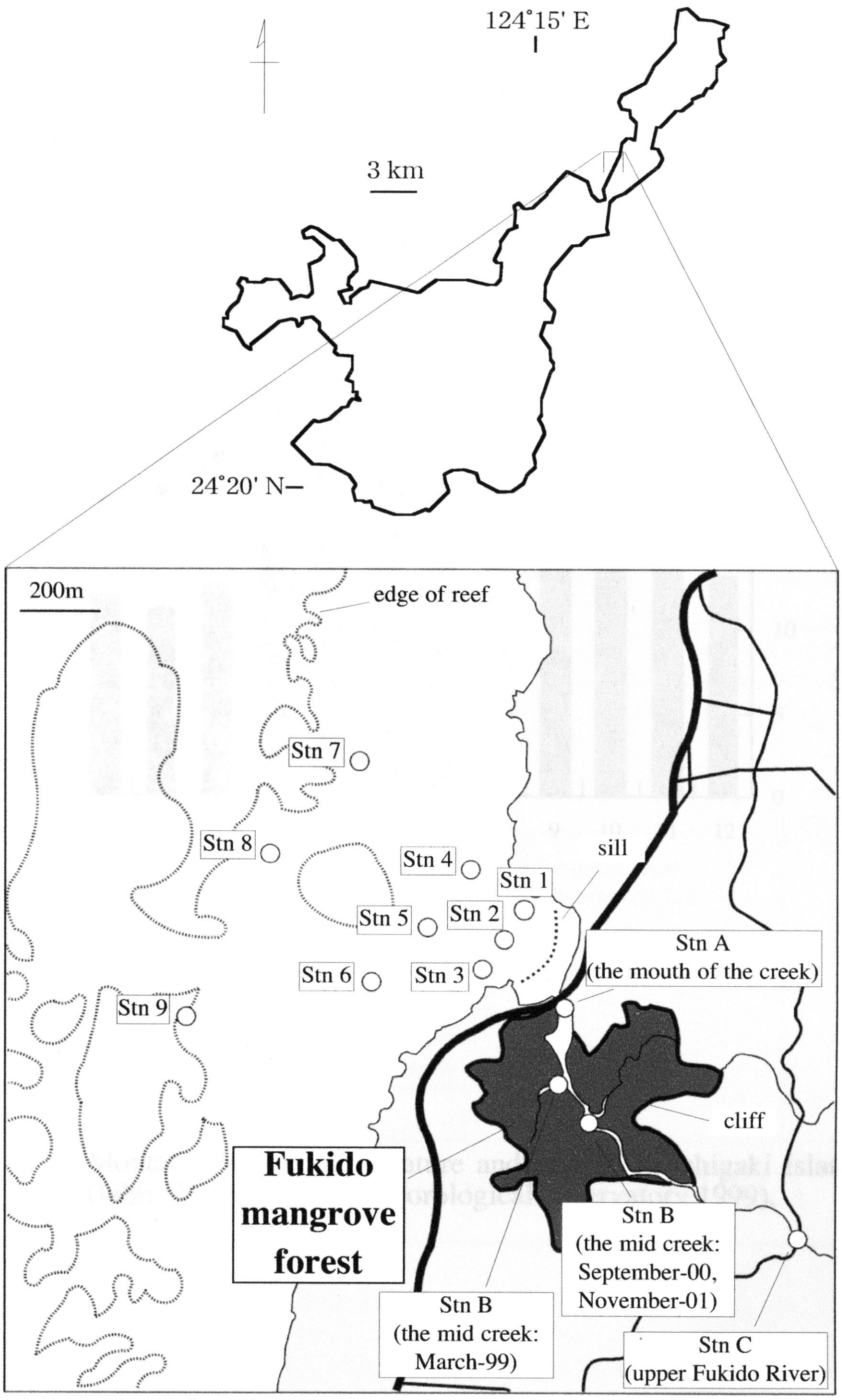


Figure 2-1 Location of the study site and the system of Fukido mangrove forest.

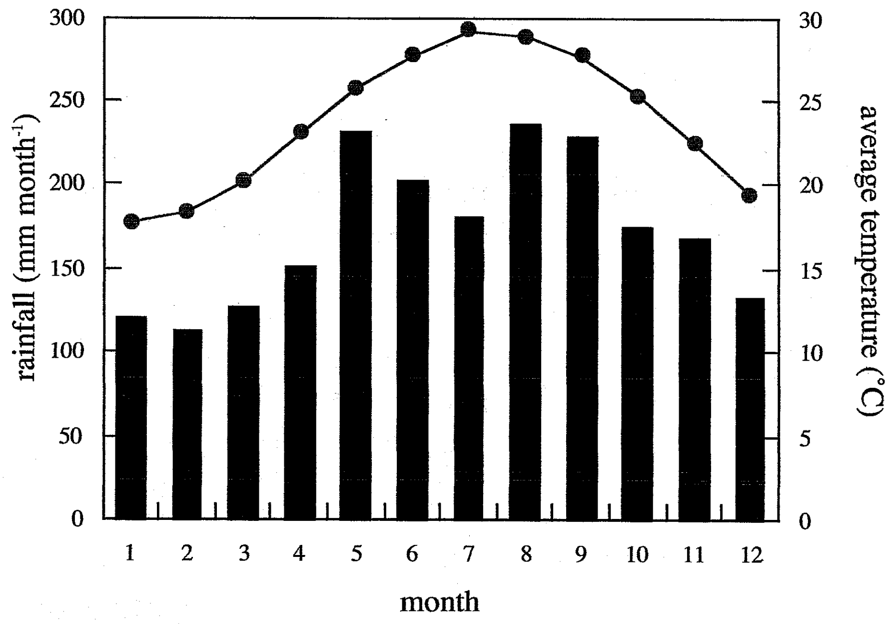


Figure 2-2 Monthly .average temperature and rainfall in Ishigaki Island in 1999 (Iahigaki-Jima local meteorological observatory 1999).

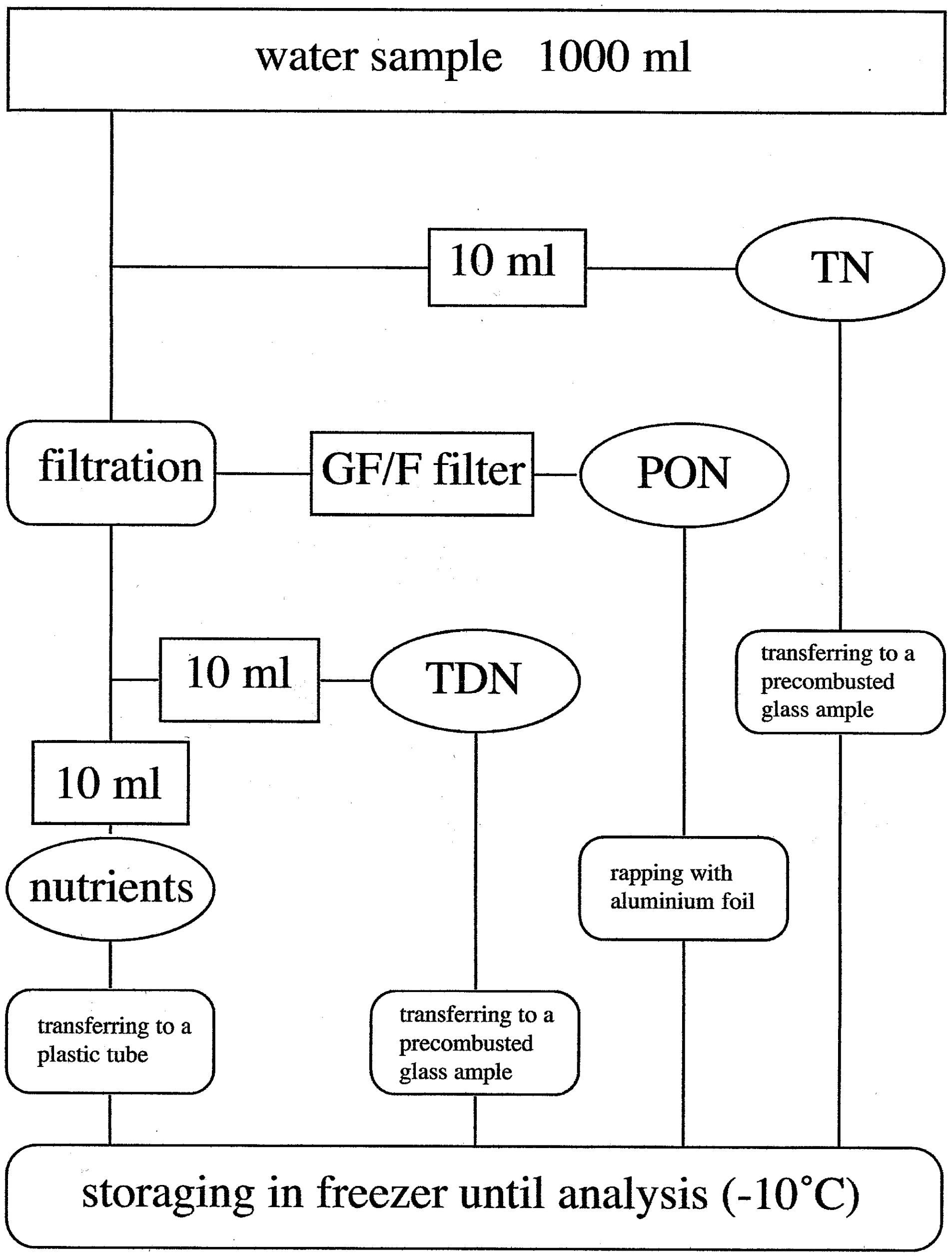


Figure 2-3 Flow diagram for the separation and the storage of sample. TN, TON, TIN and TDN mean total nitrogen, total organic nitrogen, total inorganic nitrogen, total dissolved nitrogen, respectively.

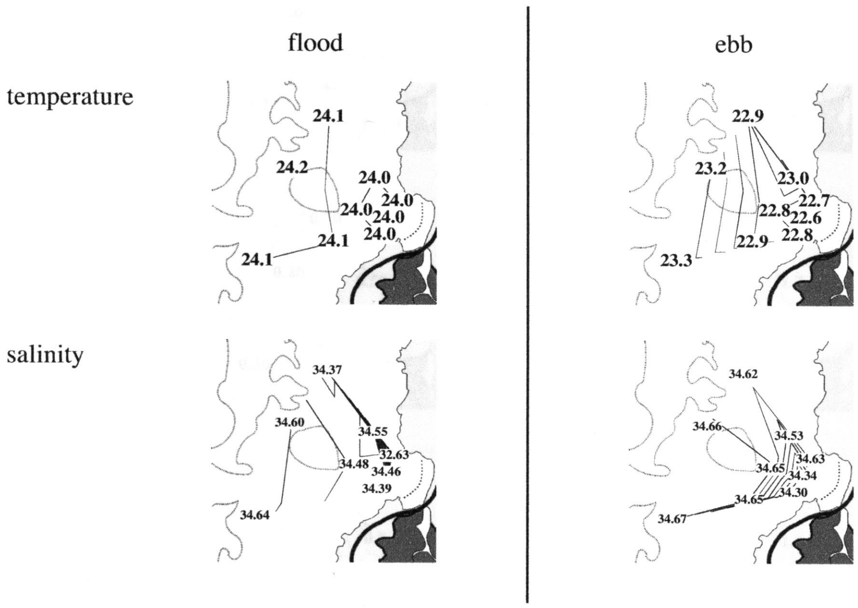


Figure 2-4 Spatial distribution of temperature and salinity at Stns 1 ~ 9 in the lagoon on 17th March, 1999. The datas are cited from Ikeda personal communications. The interval of constant isothermal line are 0.1 °C. The interval of constant salinity line are 0.1.

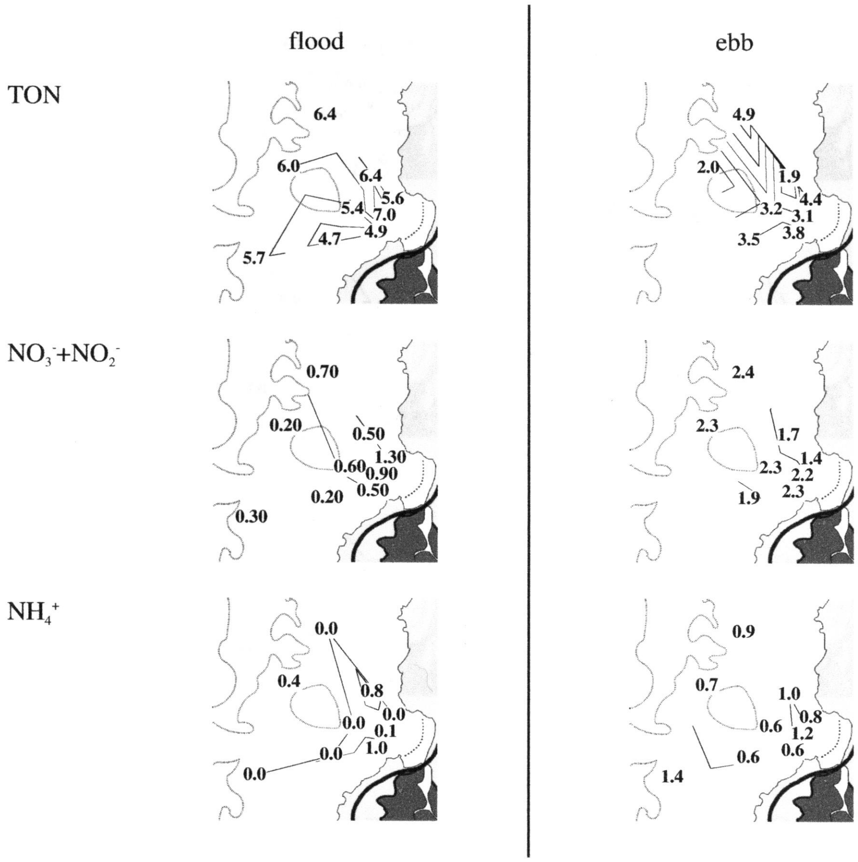


Figure 2-5 Spatial distribution of concentrations of inorganic and organic nitrogen st Stns 1 ~ 9 in the lagoon on 17th March, 1999. All intervals of constant concentration line are 0.5 μmol l^{-1}.

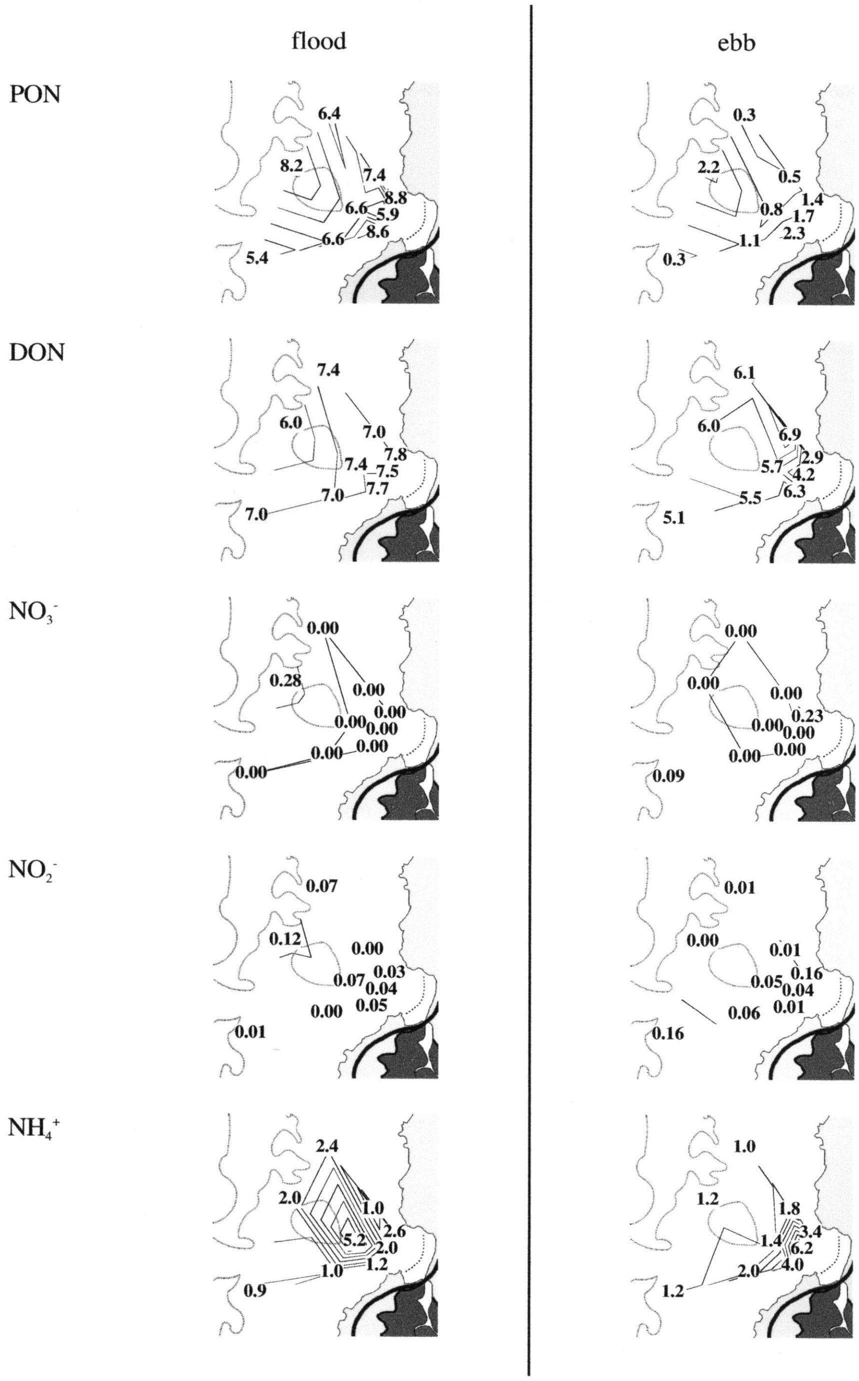


Figure 2-6 Spatial distribution of concentration of inorganic and organic nitrogen st Stns 1 ~ 9 in the lagoon on 16th September, 2000. The intervals of constant concentration line are 0.5 (PON, DON and NH_4^+), 0.2 (NO_3^-) and 0.1 (NO_2^-) μmol l^{-1}, respectively.

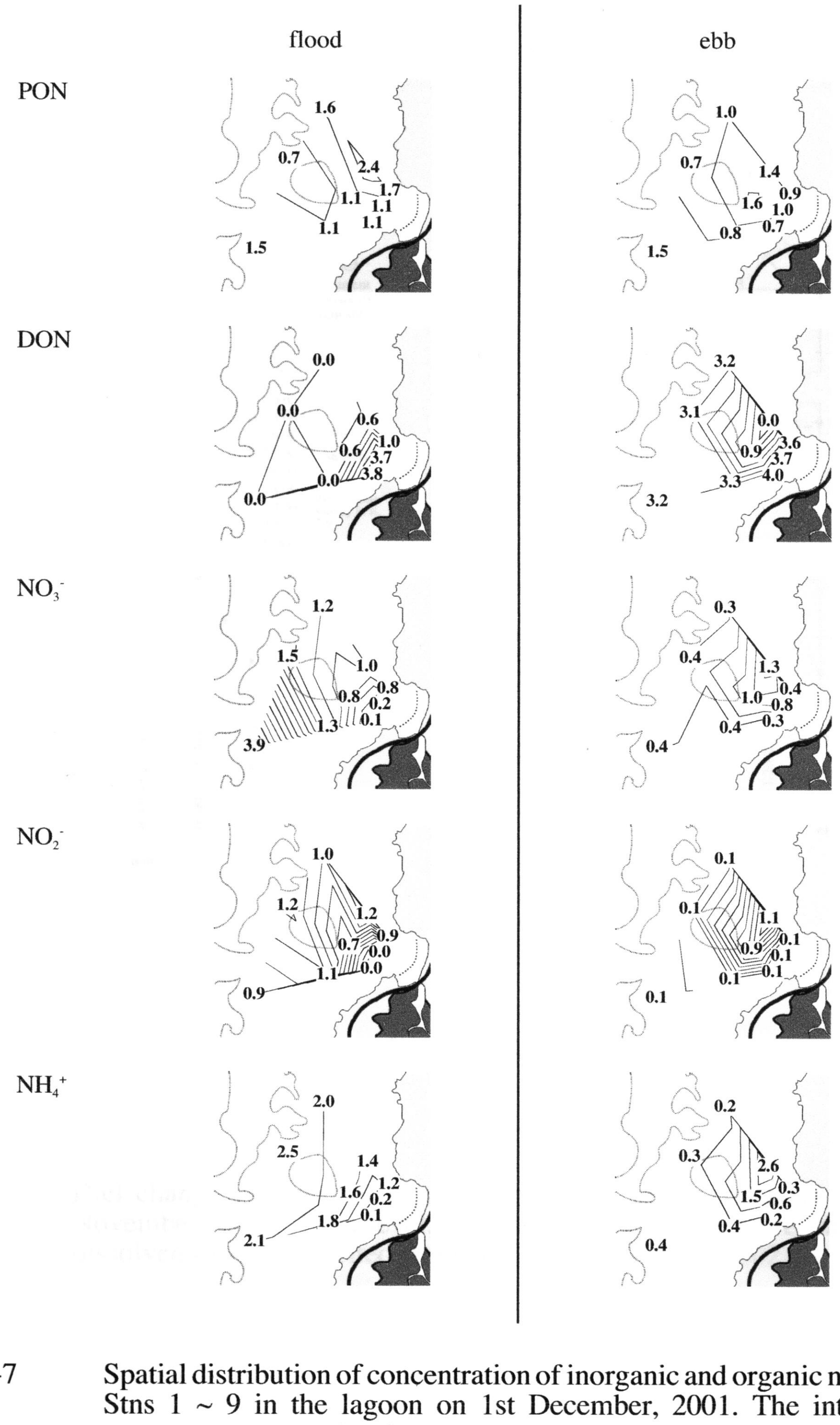


Figure 2-7 Spatial distribution of concentration of inorganic and organic nitrogen at Stns 1 ~ 9 in the lagoon on 1st December, 2001. The intervals of constant concentration line are 0.5 (PON, DON and NH_4^+), 0.2 (NO_3^-) and 0.1 (NO_2^-) $\mu mol\ l^{-1}$, respectively.

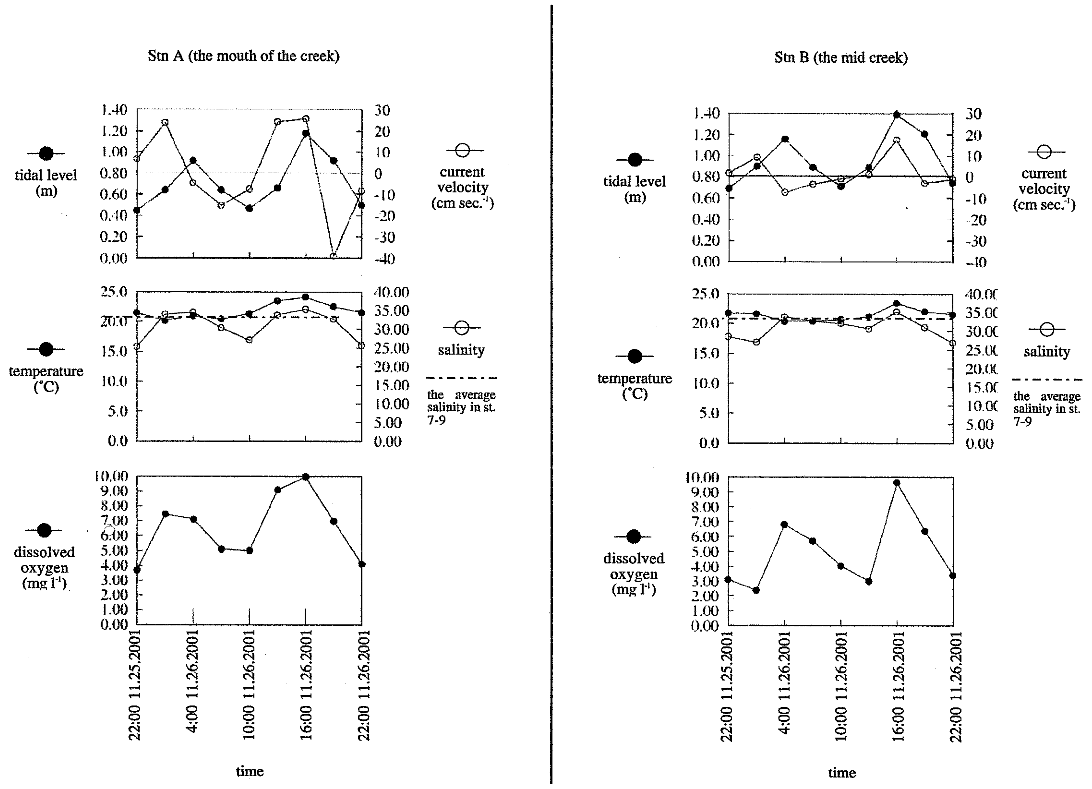
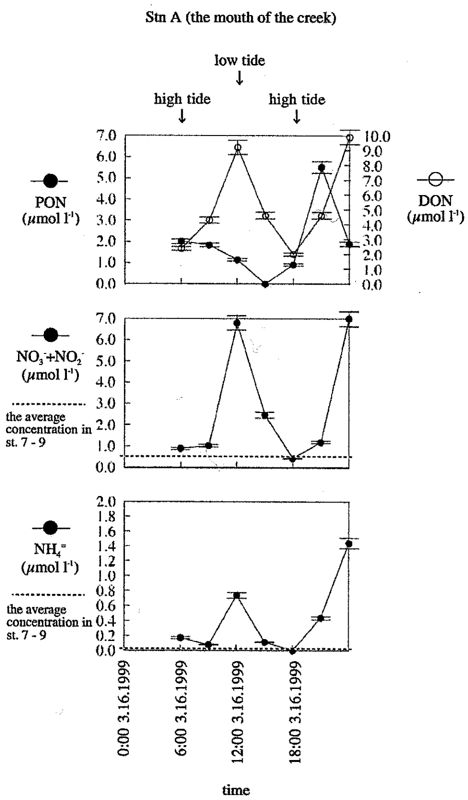


Figure 2-8 Diel change of physicochemical parameters in the creek on 25 - 26th November, 2001. Tidal level, current velocity, temperature, salinity and dissolved oxygen are cited from NEDO/JOIA report (2002).



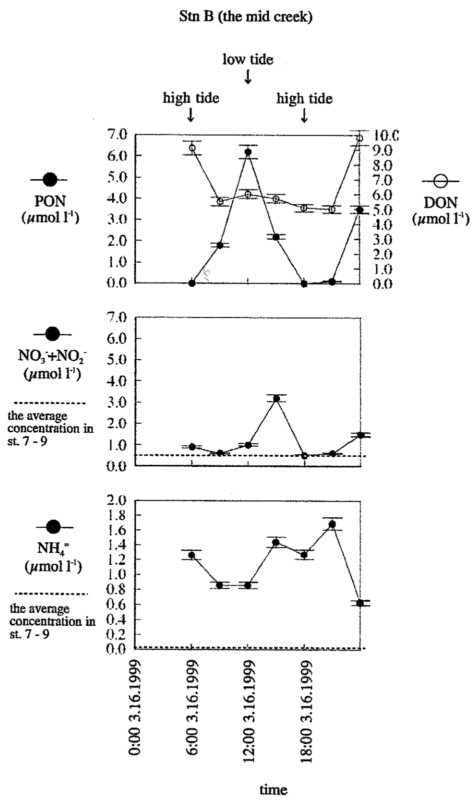


Figure 2-9 Diel change of concentrations of inorganic and organic nitrogen at the mouth of the creek on 16th March, 1999.

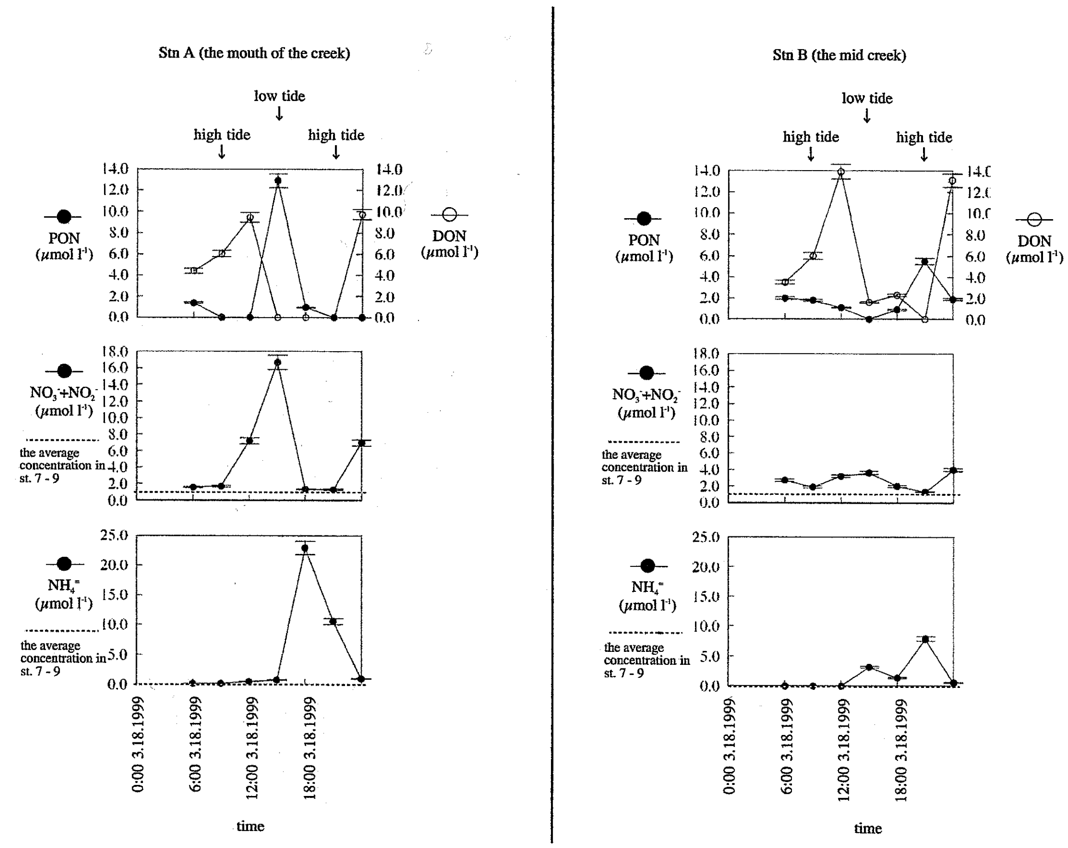


Figure 2-10 Diel change of concentrations of inorganic and organic nitrogenat the mouth of the creek on 18th March, 1999.

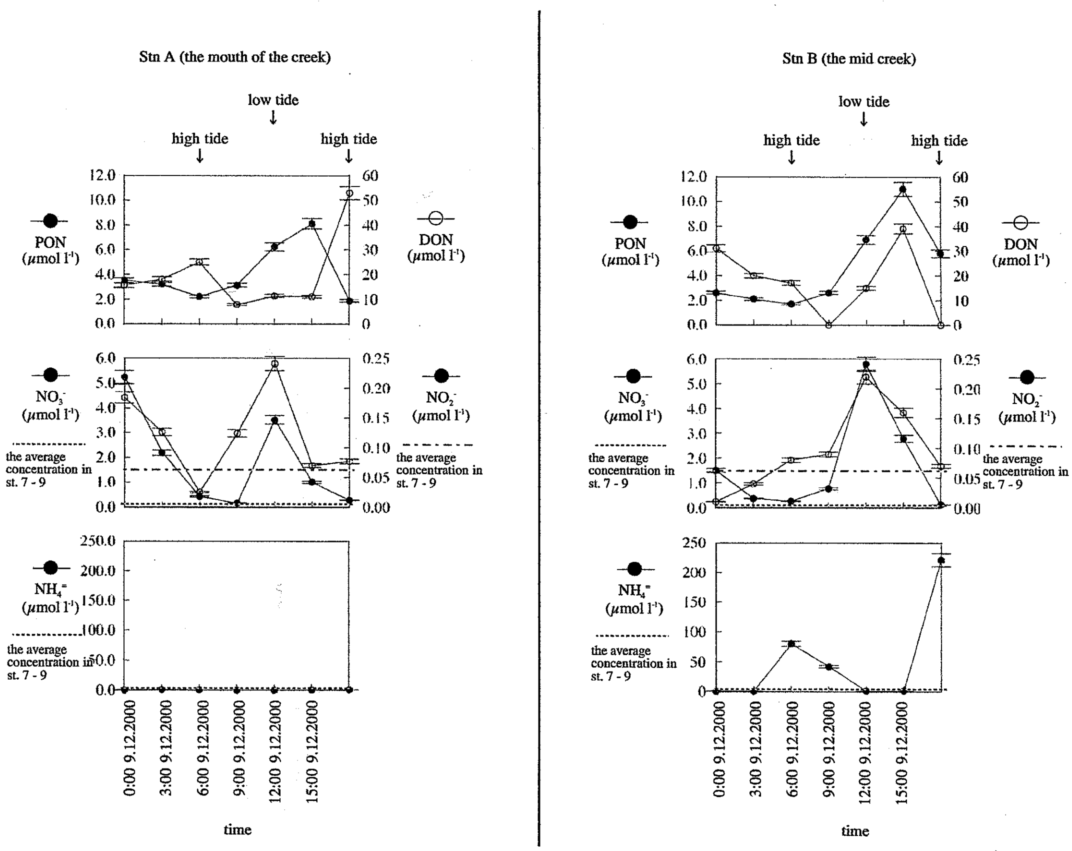


Figure 2-11 Diel change of concentrations of inorganic and organic nitrogen at the mouth of the creek on 12th September, 2000.

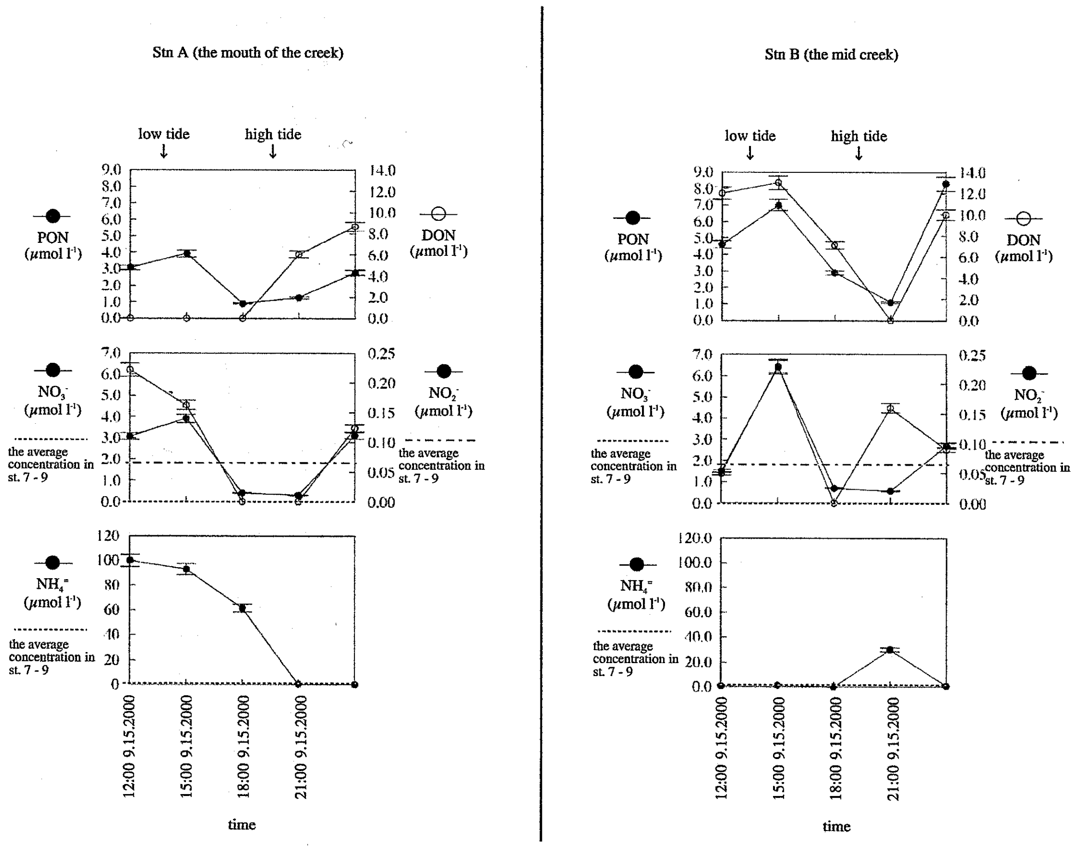


Figure 2-12 Diel change of concentrations of inorganic and organic nitrogen at the mouth of the creek on 15th September, 2000.

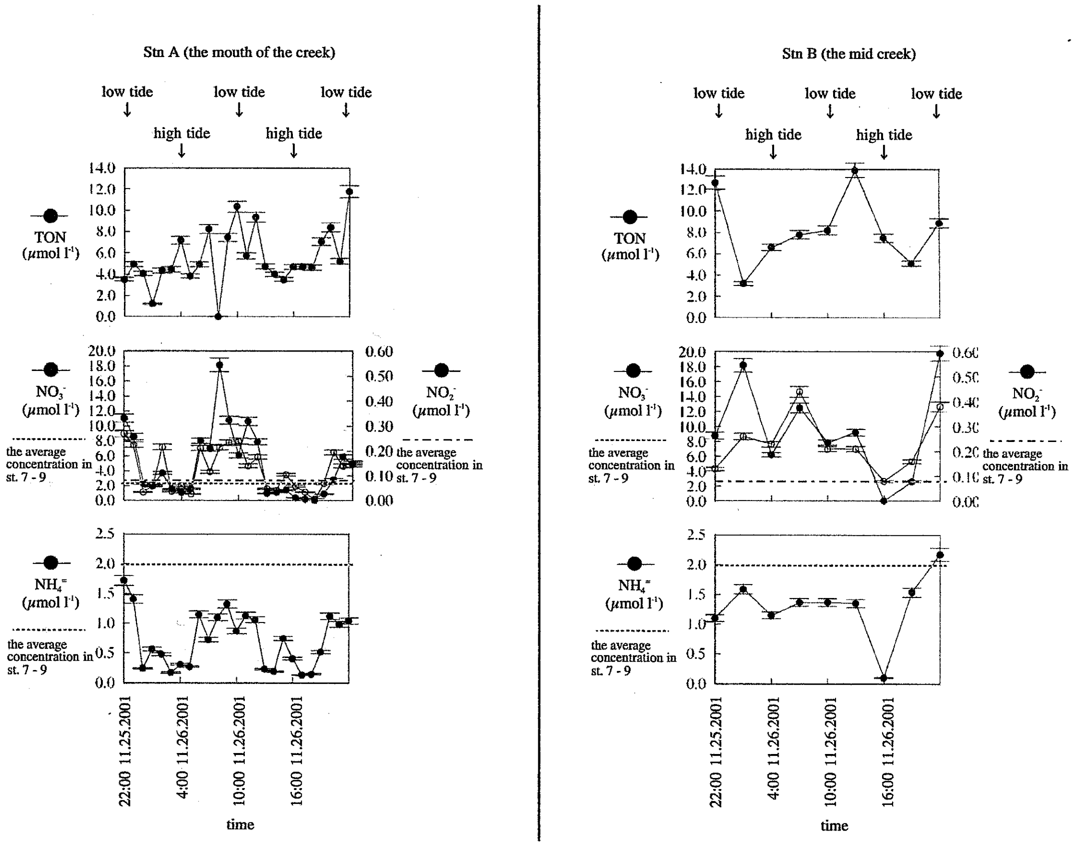


Figure 2-13 Diel change of concentrations of inorganic and organic nitrogen at the mouth of the creek on 25 - 26th November, 2001.

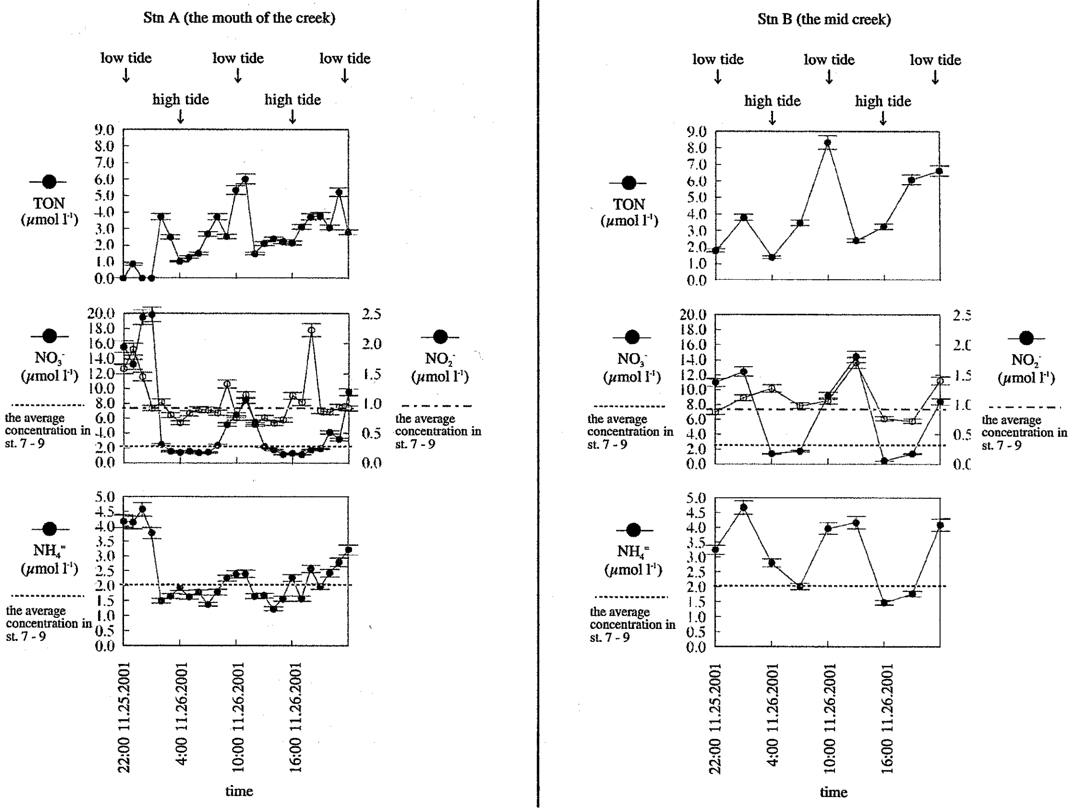


Figure 2-14 Diel change of concentrations of inorganic and organic nitrogen at the mouth of the creek on 30th November, 2001.

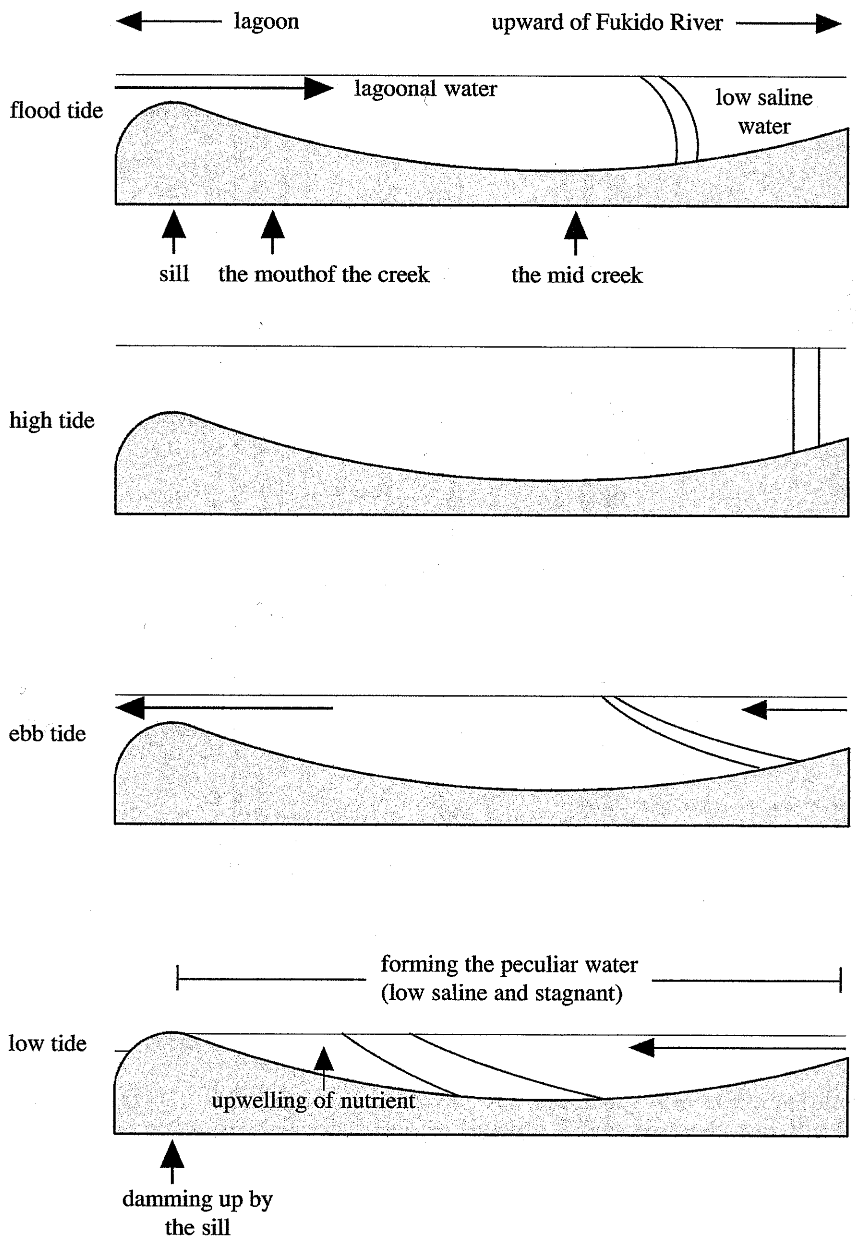


Figure 2-15 Sea water exchange in riverine mangal with sill (Mazda 1997).

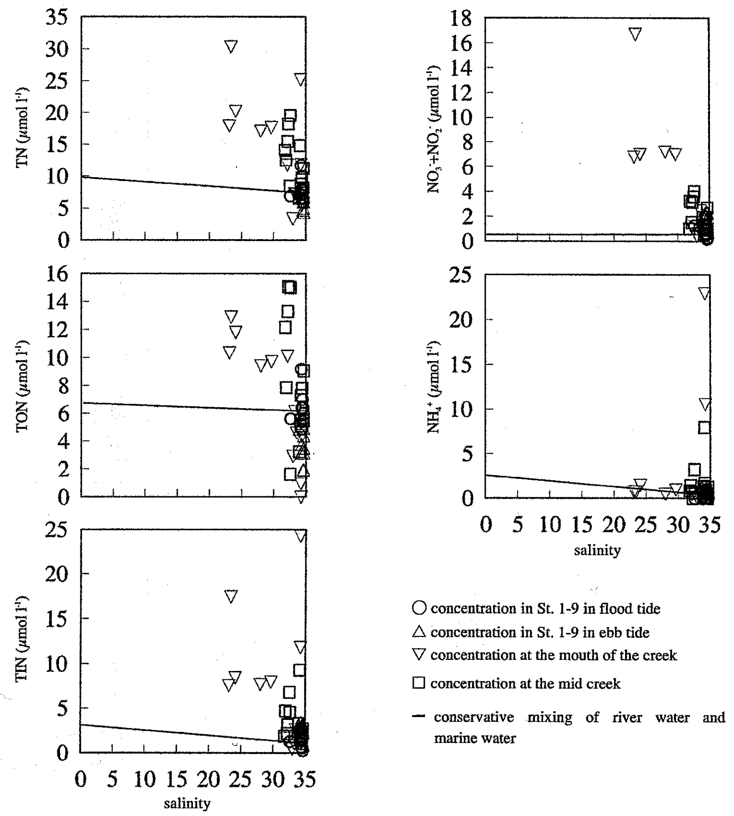


Figure 2-16 Mixing diagrams between salinity and concentrations of inorganic and organic nitrogen in Fukido River Estuary in March 1999.

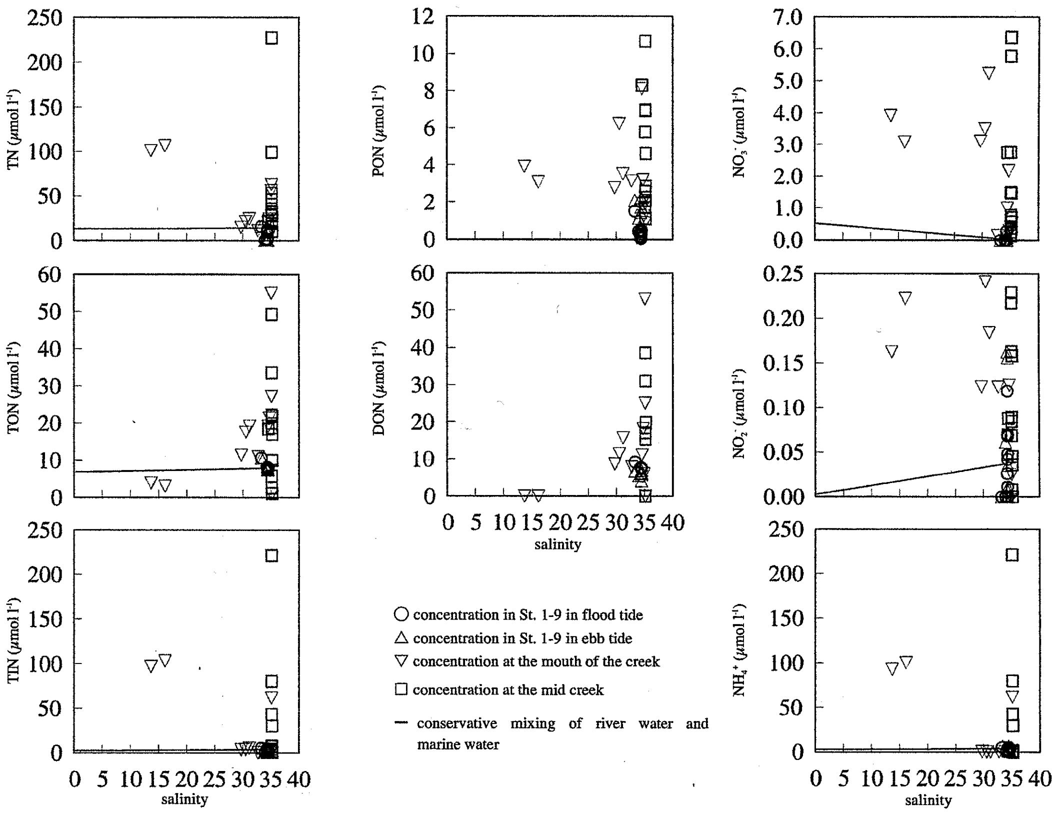


Figure 2-17 Mixing diagrams between salinity and concentration of inorganic and organic nitrogen in Fukido River Estuary in September 2000.

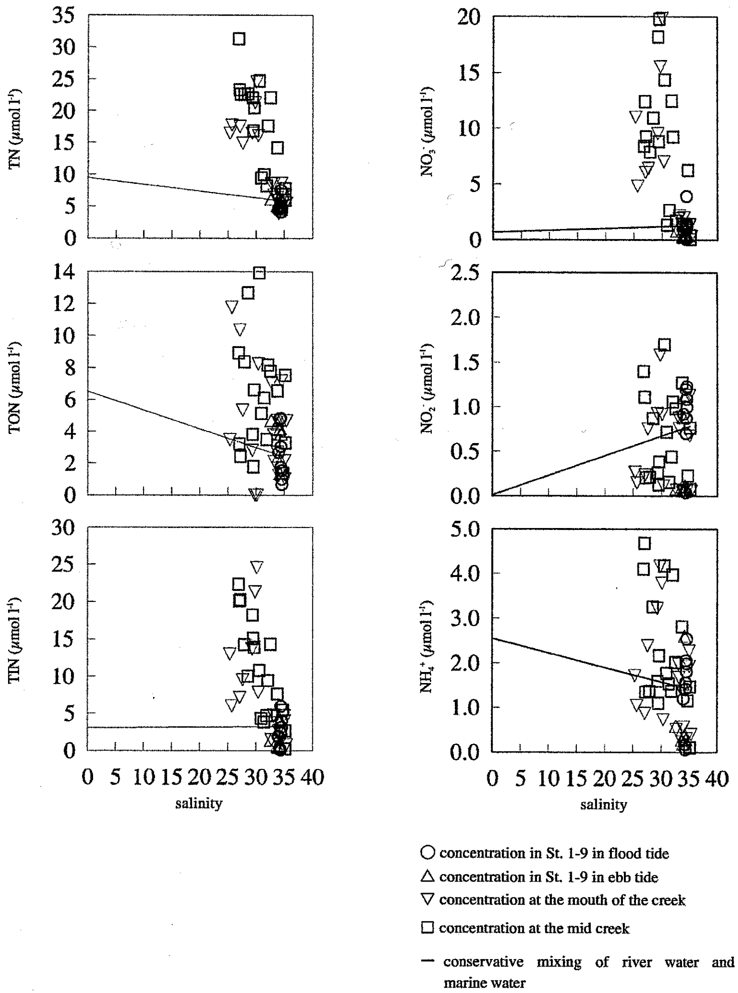


Figure 2-18 Mixing diagrams between salinity and concentration of inorganic and organic nitrogen in Fukido River Estuary in November 2001.

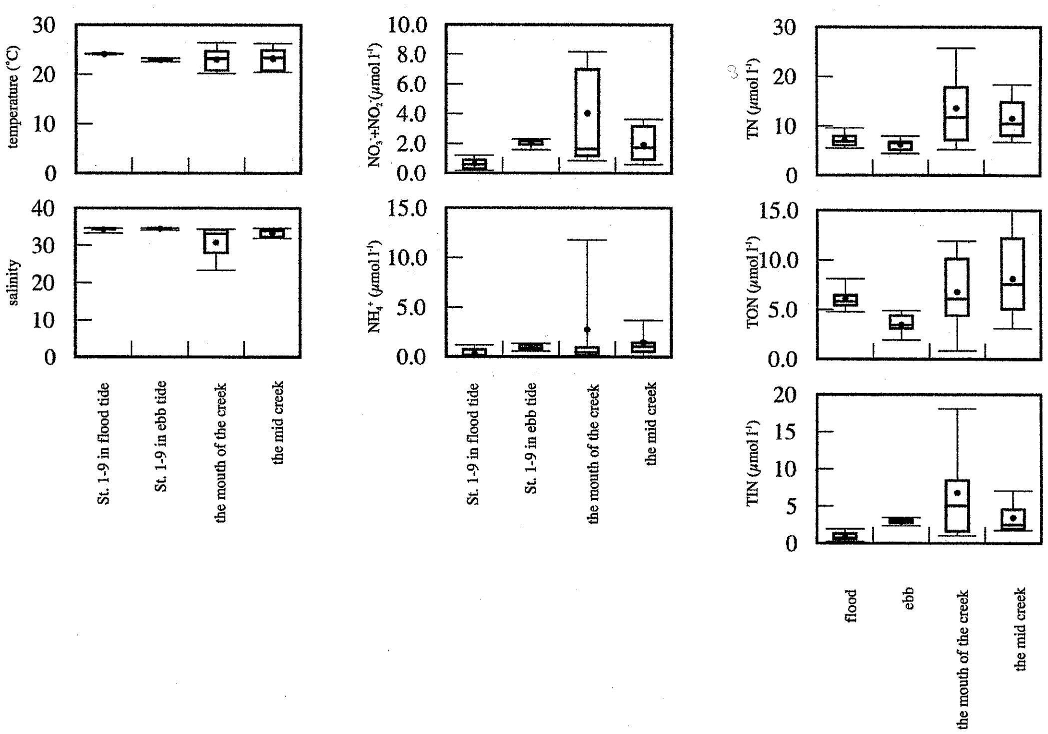


Figure 2-19 Box and whisker plots of physicochemical parameters and concentrations of inorganic and organic nitrogen in Fukido River Estuary in March 1999. The symbols show the average, the center horizontal lines are the median, the top and bottom of the box are 25th and 75th percentiles, and the ends of the whiskers are the 10th and 90th percentiles.

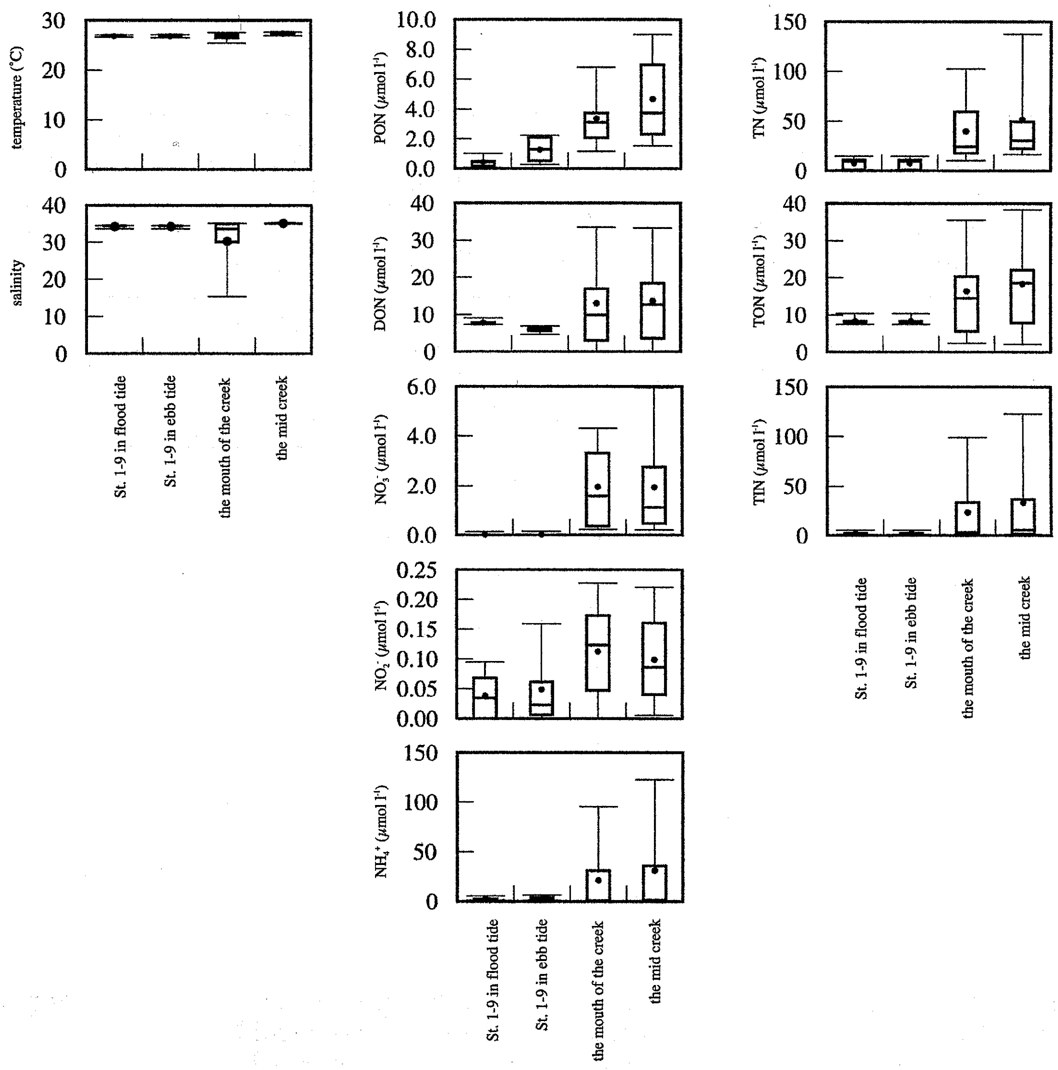


Figure 2-20 Box and whisker plots of physicochemical parameters and concentration of inorganic and organic nitrogen in Fukido River Estuary in September 2000. The symbols show the average, the center horizontal lines are the median, the top and bottom of the box are 25th and 75th percentiles, and the ends of the whiskers are the 10th and 90th percentiles.

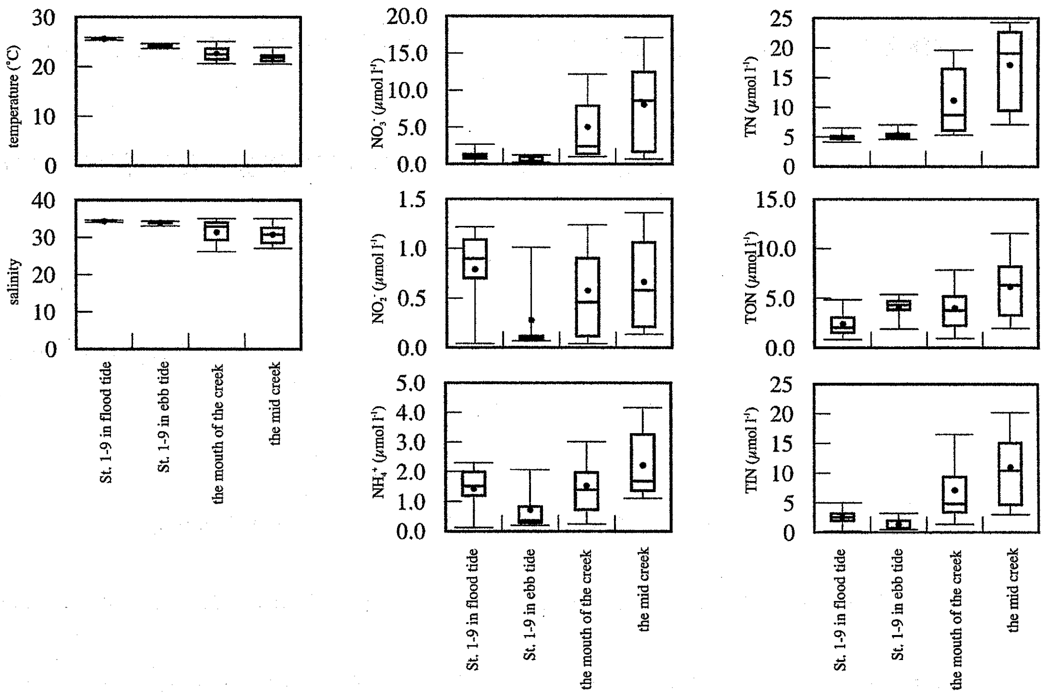


Figure 2-21 Box and whisker plots of physicochemical parameters and concentration of inorganic and organic nitrogen in Fukido River Estuary in November 2001. The symbols show the average, the center horizontal lines are the median, the top and bottom of the box are 25th and 75th percentiles, and the ends of the whiskers are the 10th and 90th percentiles.

Chapter III: Fluxes of inorganic and organic nitrogen between the mangrove ecosystem along Fukido River and the adjacent coastal water

Introduction

Mangrove forest is a relatively open system compared with terrestrial forests because water in the creeks and swamps within the area is exchanged with seawater by tide (Suzuki 1997). Dissolved and suspended materials in the mangrove area are carried into the adjacent coastal area by outflow water from the creeks and swamps. The fluxes are defined as net fluxes. Several studies reported the net flux of organic carbon from the mangrove area (e.g. Boto and Bunt 1981, Twilley 1985 and Robertson *et al.* 1992). On the other hand, there are very few studies which estimated the net fluxes of inorganic and organic nitrogen from the mangrove area and their research regions were restricted (Dittmar and Lara 2001b). The Hinchinbrook Island (Australia) is the only mangrove area where the net fluxes of both inorganic and organic nitrogen have been studied (Boto and Wellington 1988, Alongi 1996, Alongi *et al.* 1998, Ayukai *et al.* 1998). Wattayakorn *et al.* (1990) studied the net fluxes of total nitrogen and inorganic nitrogen in Klong Ngao

(Thailand).

Most of the above studies applied 'Eulerian approach' to estimate the net fluxes from the mangrove area (Wellington 1988, Wattayakorn *et al.* 1990, Ayukai *et al.* 1998 and Dittmar and Lara 2001a). In Eulerian approach, fluxes are calculated as an integration of the product of the discharged water mass and material concentrations at the mouth of the river over one tidal cycle (Ayukai *et al.* 1998). For example, Boto and Bunt (1981) estimated the export fluxes of particulate organic carbon during the flood and ebb tides at the Coral Creek (Hinchinbrook Island, Australia) using Eulerian approach and show the exponential increase in the fluxes with water discharge.

However, the inflow of the riverine freshwater into the creeks and swamps increases concentrations of the materials within the mangrove area which causes possible overestimation of the export flux (Dittmar and Lara 2001a). In R-type mangal (a mangrove area spreading along a river), freshwater continuously flows into the forest and supplies nutrient and organic matter from upstream of the river. When sea level rises up by tidal oscillation, adjacent coastal water upflows the river and takes nutrient and organic matter for mangrove forest. The coastal water intermingles with a freshwater in mangrove area. While the coastal water intermingle with the freshwater, nutrient and organic matter are exchanged between the mangrove forest and the mixed water in the mangrove area. In Fukido mangrove area, the concentrations of inorganic and organic nitrogen in the creek water are above the line of conservative mixing in comparison with salinity and their concentrations (see Chapter II). It means that Fukido mangrove forest supplies inorganic and organic nitrogen for the mixed waters. In ebb tide, all supplied nutrient and organic matter in creek water are flowed out from the mangrove area to adjacent coastal area by tidal oscillation. Thus, the nitrogen compounds in the creek water are supplied from three sources, such as the adjacent coastal area, freshwater supplied from the upper river and the mangrove forest.

This chapter reports (1) an improvement of Eulerian approach to estimate the flux of inorganic and organic nitrogen between the mangrove ecosystem and the adjacent coastal water (2) contribution of the effect of the riverine fresh water to the flux of inorganic and organic nitrogen across the mouth of Fukido River (3) comparison the net fluxes of inorganic and organic nitrogen between the mangrove ecosystem and the adjacent coastal water in Fukido River Estuary and those reported in any other mangrove ecosystem.

Materials and Methods

To correct the export fluxes and estimate the contribution of those sources to nitrogen fluxes via the mouth of the creek, I employed four functions in this study.

The export fluxes of inorganic and organic nitrogen were calculated by traditional Eulerian method. It means that the export fluxes were estimated by product water discharge by concentrations of inorganic and organic nitrogen at time t_k at the mouth of the creek. The fluxes of inorganic and organic nitrogen were described as follows:

$$f = c_t \cdot Q_t \quad (1)$$

f; flux of inorganic and organic nitrogen at time t_k (mmol 10min.$^{-1}$)

c_{tk}; concentrations of inorganic and organic nitrogen at the mouth of the creek at time t_k (mmol m^{-3})

Q_{tk}; volume of water discharge during $[t_{k+1} - t_k]^{-1}$ (m^3 10min.$^{-1}$)

The nitrogen compounds used in the function of the fluxes are following.

March 1999; TON, NO_3^-+NO_2^-, NH_4^+

September 2000; PON, DON, NO_3^-, NO_2^-, NH_4^+

November 2001; TON, NO_3^-, NO_2^-, NH_4^+

The concentrations of inorganic and organic nitrogen at the mouth of the creek at t_k were interpolated between the sampling period by using cubic spline interpolation every in 10 minutes (Dittmar and Lara 2001b).

Volume of water discharge was calculated by the relationship between the tidal level at the mouth of the creek and water volume in the mangrove ecosystem ($y = 9.86 \times 10^4 \times x^2 \times 1.78 \times 10^5 \times x \times 7.98 \times 10^4$, $n = 15$, $r = 0.947$, $p < 0.001$; datas are cited from Mazda 1997). Tidal level at t_k was calculated by data of tidal level in every one hour at

Ishigaki Port (Ishigaki-Jima local meteorological observatory 1999-2001). Figure 3-1 show the flow diagram for calculation of the tidal level at the mouth of the creek. I assumed that sea level at the mouth of the creek was horizontally equated with that at Ishigaki Port except that in low tide, and I estimated the difference (C) of observed tidal level at the mouth of the creek (A') from that at Ishigaki Port (B') in high tide. The tidal level at the mouth of the creek (D) was estimated by subtract the difference (C) from the tidal level at Ishigaki Port (B). However, the tidal level can't decrease under the height of the sill, because the creek water dams up and separate from the lagoonal water by the sill in low tide (Mazda 1997). Therefore, I assumed that the sill height equated the observed minimum tidal level at the mouth of the creek (A") (Nakamura *et al.* 2002). When the difference of B from C is lower than A", the calculated tidal level (D) was translated the observed minimum tidal level at the mouth of the creek (A"). The calculated tidal level was interpolated between the sampling period by using cubic spline interpolation every in 10 minutes (Dittmar and Lara 2001b).

The oceanic fluxes of inorganic and organic nitrogen were assumed as the nitrogen fluxes originated from the adjacent coastal water (high salinity and low nutrient concentrations). The oceanic fluxes of inorganic and organic nitrogen were described as follows:

$$f_o = c_o \cdot Q_t \cdot \frac{s_t}{s_o} \qquad (2)$$

f_o; fluxes of inorganic and organic nitrogen with exchange of sea water at time t_k (mmol 10min.$^{-1}$)

c_o; average concentrations of inorganic and organic nitrogen at Stns 7 - 9 in each observation period (mmol m^{-3})

s_t; salinity at time t_k

s_o; average salinity at Stns 7 - 9

Salinity at t_k was interpolated between the sampling period by using cubic spline interpolation every in 10 minutes (Dittmar and Lara 2001b).

The freshwater fluxes of inorganic and organic nitrogen were assumed as the nitrogen fluxes originated from the upper river water. It means that riverine freshwater intermingles with the creek water that flow out via the mouth of the creek. The freshwater fluxes of inorganic and organic nitrogen were described as follows:

$$f_f = c_u \cdot Q_t \cdot \frac{(s_o - s_t)}{s_o} \qquad (3)$$

f_f; fluxes of inorganic and organic nitrogen with fresh water loading at time t_k (mmol 10min.$^{-1}$)

The fluxes of inorganic and organic nitrogen originated from the mangrove ecosystem were described as the unaccountable fraction in the total fluxes of inorganic and organic nitrogen. It was assumed that increase or decrease of concentrations of inorganic and organic nitrogen in the creek was originated from the physical and biochemical mechanism in the mangrove forest. The mangrove originated fluxes of inorganic and organic nitrogen was described as follows:

$$f_m = f - f_o - f_f \qquad (4)$$

f_m; fluxes of inorganic and organic nitrogen compounds from the mangrove area at time t_k (mmol 10min.$^{-1}$)

Functions (1) to (4) are integrated from the beginning of half-tidal cycle to end of half-tidal cycle, and they were estimated as the fluxes of inorganic and organic nitrogen for ebb tide or flood tide.

$$F = \sum_{t=tb}^{te} f$$

F; fluxes of inorganic and organic nitrogen per half-tidal cycle (mmol $[t_e - t_b]^{-1}$)

t_b; beginning of half-tidal cycle

t_e; end of half-tidal cycle

$$F_o = \sum_{tb}^{te} f_o$$

F_o; fluxes of inorganic and organic nitrogen with exchange of sea water per half-tidal cycle (mmol $[t_e - t_b]^{-1}$)

$$F_f = \sum_{tb}^{te} f_f$$

F_f; fluxes of inorganic and organic nitrogen with fresh water loading per half-tidal cycle (mmol $[t_e - t_b]^{-1}$)

$$F_m = \sum_{tb}^{te} f_m$$

F_m; fluxes of inorganic and organic nitrogen from the mangrove ecosystem per half-tidal cycle (mmol $[t_e - t_b]^{-1}$)

Corrected fluxes of inorganic and organic nitrogen was estimated by subtract F_f from F.

$$F_c = F - F_f$$

F_c; corrected fluxes of inorganic and organic nitrogen per half-tidal cycle (mmol [$t_e - t_b$]$^{-1}$)

Results

Figs. 3-1 to 6 show the time series of discharged water mass and fluxes of inorganic and organic nitrogen originated from three sources (the lagoonal water, freshwater and the mangrove ecosystem) via the mouth of the creek. Positive values in the graphs mean the import of water and nitrogen compounds into Fukido mangrove forest. Negative values in the graphs show the export of those from the forest.

The discharged water mass exponentially increase during flood tide, and it reaches a peak and turns to be negative value in high tide. The flow rate rapidly becomes to zero, and it turns to be positive in low tide. The time series of discharged water mass is sphenoidal shape, and the shape in flood tide is point symmetry to that in ebb tide in Figs. 3-1 to 6. This indicates that flow rate during flood tide is almost equal to that during ebb tide. When the tidal level at the mouth of the creek decreases, the mass of water discharge is rapidly getting low. The maximum flow rate in Fig. 3-5 is the smallest in all our observation period, because 25th November 2001 was a mid tide (Ishigaki-Jima local meteorological observatory 2001) and the volume in the tidal cycle was wholly small.

The fluxes of inorganic and organic nitrogen are mostly sphenoidal shape too, but some of them differently changed. Time series of $NO_3^-+NO_2^-$ flux in second-tidal cycle on 18th March 1999 (Fig. 3-2) is dome shape, because concentration of $NO_3^-+NO_2^-$ in high tide became near zero (see Fig. 1-9 in Chapter II). The fluxes of inorganic and organic nitrogen on 25th November 2001 irregularly changed with time. Their concentrations irregularly changed with time, and the increment of flow rate in high tide is the smallest in our observation period because it was a mid tide on 25th November, 2001. When the tidal level at the mouth of the creek is low, the fluxes of inorganic and organic nitrogen are littl

The fraction of three fluxes are changed with time. The fraction of oceanic fluxes of inorganic and organic nitrogen increased in the total fluxes of those in high tide. The fraction of freshwater fluxes of inorganic and organic nitrogen increased in the total fluxes of those in ebb tide (for example, flux of NH_4^+ on 25th November 2001; see Fig. 3-6), but the fraction is small compared with the fraction of the other fluxes.

Table 3-1 shows the fraction of the freshwater fluxes of inorganic and organic nitrogen in total flux of those. The maximum fraction of the freshwater flux was 35 % (NH_4^+ in 25th November 2001). Fukido River is relatively small compared with any other river in R-type mangal, however, the freshwater fluxes of inorganic and organic nitrogen were significant to the total fluxes of those in some cases. It is important to note that freshwater loading in mangrove ecosystem can be overestimate in study about nutrient dynamics in R-type mangal.

The freshwater fluxes of inorganic and organic nitrogen are deducted from the total flux of those and estimated the normalized fluxes of those between the mangrove ecosystem and the adjacent coastal water. It is defined as the normalized fluxes of inorganic and organic nitrogen per flood tide or ebb tide (Fig. 3-8). The normalized fluxes of NH_4^+ in flood tide on 18th March 1999 and 15th September 2000 are one or two orders higher than any other fluxes in the days. On the contrary, the normalized flux of NH_4^+ in flood on 16th March 1999 is one order lower than any other fluxes. These indicate that fraction of fluxes of inorganic and organic nitrogen in TN flux can change in the mangrove forest

Fig. 3-9 shows the summation of normalized fluxes of inorganic and organic nitrogen during flood tide and ebb tide. DON or NH_4^+ is the main fraction in the normalized fluxes of those during flood tide and ebb tide on 18th March 1999 and 15th September 2000 or 12th September 2000, respectively. The percentage of the normalized fluxes of DON and NH_4^+ in the normalized TN fluxes per half-tidal cycles are 93% (in flood on 18th March 1999), 84% (in flood on 12th September 2000) and 93% (in flood on 15th September 2000), respectively.

Discussion

The contribution of the oceanic fluxes of inorganic and organic nitrogen, the freshwater flux of those and the mangrove originated fluxes of those in the total flux of those

The influence of the freshwater fluxes of inorganic and organic nitrogen to the total flux of those is smaller than the other fluxes of those in a half-tidal cycle, because flow rate and concentrations of inorganic and organic nitrogen in the upper Fukido River are lower than those at the mouth of the creek (see Chapter II). However, the contribution of freshwater flux of NH_4^+ is 35% of the total flux of that in the first tidal cycle on 25th November, 2001 (Fig. 3-6). This indicates that the influence of freshwater fluxes of inorganic and organic nitrogen can be a considerable effect to the estimate of export flux of those in the mangrove ecosystem.

The oceanic fluxes of inorganic and organic nitrogen and the mangrove originated fluxes of those are occupied in the total fluxes of those in the all season (Fig. 3-2 ~ 7). The contribution of the mangrove originated fluxes of inorganic and organic nitrogen changed with the observation season. In March 1999, the mangrove originated fluxes of inorganic nitrogen contributes 34 ~ 98% of the total fluxes of those. On the other hand, in November 2001, the contribution of the mangrove originated fluxes of inorganic nitrogen are 2 ~ 66% of the total fluxes of those.

The net fluxes of inorganic and organic nitrogen in "steady-state" and "non steady-state"

Fig. 3-10 and 11 show the results of cluster analysis per flood tide and ebb tide, respectively. (a), (b) and (c) in those Figs. were the summation of fluxes of inorganic and organic nitrogen, the dendrograms for classification of normalized fluxes during flood tide or ebb tide and 3D plot of normalized fluxes of those during flood tide and ebb tide in each tidal cycle, respectively. To analysis and compare the each normalized fluxes during flood tide or ebb tide, normalized fluxes of organic nitrogen were estimated as TON flux (PON flux + DON flux), and normalized fluxes of NO_3^- and NO_2^- were estimated as NO_3^- $+NO_2^-$ flux. The summation of normalized fluxes during flood tide and ebb tide are analyzed by cluster analysis based on median method, and the dendrograms are drawn by the squared distances between each clusters (Yonezawa *et al.* 1988). To minimize the variance of the clusters, classification was done at the level which the product of average by standard deviation of the vector of distances was the minimum (Souissi *et al.* 2000). (c) in Fig. 3-10 and 11 show the 3D plots of normalized nitrogen fluxes per flood and ebb in each tidal cycle. The X, Y and Z axes mean TON, NO_3^-+NO_2^- and NH_4^+ fluxes per flood tide or ebb tide, respectively. The black marks mean that normalized nitrogen fluxes belong to the same cluster, and the individual gray marks show the independent fluxes. The normalized fluxes on 16th March 1999, 25th and 30th November 2001 were classified as those belong to the same cluster.

The normalized fluxes of inorganic and organic nitrogen during flood tide or ebb tide belong to the same cluster were defined as "steady-state" fluxes of those in this study. On the other hand, each independent fluxes of nitrogen during flood tide or ebb tide were defiined as "non steady-state" fluxes of those in this study because those were quantified by very high concentrations of DON and NH_4^+ in the creek water (see Chapter II).

Table 3-2 shows the net fluxes of inorganic and organic nitrogen between the mangrove ecosystem and the adjacent coastal water. (a) indicates those in steady-state, and (b) shows those in non steady-state. The net fluxes of inorganic and organic nitrogen on

25th and 30th November 2001 were estimated by summation of normalized fluxes during 24 hours. The others were estimated by summation of normalized flux during one tidal cycle and product of those and two. The magnitude of net fluxes of inorganic and organic nitrogen in steady-state were $-3.4\times10^{5} \sim 4.8\times10^{4}$ mmol day^{-1}. Most of those were negative value and were quantified as export fluxes from the mangrove ecosystem to the adjacent coastal water. The net fluxes of NO_3^-+NO_2^- on 16th March 1999 and NH_4^+ on 25th November 2001 were quantified as import fluxes from the adjacent coastal water to the mangrove ecosystem, however, those magnitudes were relatively small compared with the others in steady-state. The net fluxes of TN in steady-state were quantified as export fluxes, and the mangrove ecosystem is concluded as the source of nitrogen to the adjacent coastal water in steady-state. On the other hand, the net fluxes in non steady-state were dominated by the net flux of DON or NH_4^+, and those of TN were quantified as import fluxes. However, those should be indicated the return of DON or NH_4^+ to the mangrove ecosystem because those were dominated by the mangrove origidinated fluxes of those (Figs. 3-3 ~ 5). The overestimate of DON or NH_4^+ flux in non steady-state may be caused by suppose the mouth of Fukido River as the boundary of the mangrove ecosystem, not the sill. Further research would be required to analyze how to originate these fluxes at mangrove ecosystem in non steady-state.

Comparison areal fluxes of inorganic and organic nitrogen in the mangrove ecosystem *and those in the other mangrove ecosystem*

A general consensus on nutrient outwelling from mangrove has not yet been reached (Dittmar and Lara 2001a), however, scope and spatial scale of investigation in mangrove ecosystem were distinctly different in each previous studies about nutrient dynamics in mangrove ecosystem. For example, Rivera-Monroy *et al.* (1995) reported data of fluxes of inorganic and organic nitrogen by using 12m flume on swamp in Terminos Lagoons, Mexico. Davis III *et al.* (2001) reported the datas about nutrient fluxes by using 14m flume constructed along creek in Southern Everglades, U.S.A. In the other previous studies, data of nutrient fluxes were quantifies by Eulerian method which were product of combination of processes both within creeks and swamps in mangrove ecosystem.

Table 3-3 show comparison areal fluxes of inorganic and organic nitrogen in the mangrove ecosystem with those reported in previous studies. The fluxes of those in mangrove ecosystem are demonstrated certain trend by classification of those in Table 3-3. Table 3-3 (a) shows that mangrove ecosystem in Estero Pargo (Mexico) and Coral Creek (Australia) are sink of TN. Table 3-3 (b) indicates that nitrogen compounds are export from the sediment to the creek water in Taylor River (U.S.A). Table 3-3 (c) shows that PON and NO_3^-+NO_2^- are generally exported (PON: -1.4 ~ -0.22 mmol m^{-2} day^{-1}, NO_3^- +NO_2^-: -0.29 ~ 0.00 mmol m^{-2} day^{-1}) from each mangrove ecosystem to adjacent coastal water, however, direction of net fluxes of DON and NH_4^+ were not certain in those mangrove ecosystem. These might be that the magnitude of mechanisms which affect concentrations of DON and NH_4^+ were different in each mangrove ecosystem. TN is exported (-2.3 ~ -0.04 mmol m^{-2} day^{-1}) from each mangrove ecosystems, and those mangrove ecosystem are concluded as the source of nitrogen to those adjacent coastal water. Mangrove ecosystem may be an important source of nitrogen compounds to coastal water in tropical region because surface water in tropical sea is generally oligotrophic. Further research would be required to support these hypothesis.

Driving forces of fluxes of inorganic and organic nitrogen between the mangrove ecosystem and the adjacent coastal water

Boto and Bunt 1981 showed that POC fluxes in ebb and flood increased exponentially to water volume inundated into mangrove forest in Missionary Bay, Australia. Twilley (1985) showed that net organic carbon fluxes increased with cumulative tidal amplitude in Rookery Bay, USA (represented in inundated water volume in the mangrove forest). Their results indicate the material fluxes in mangrove forest via tidal exchange could be controlled by hydrology of tidal exchange.

Fig. 3-12 shows the comparison between the normalized fluxes of inorganic and organic nitrogen during flood tide and ebb tide and the high tide at the mouth of Fukido River, as the representative parameter of the inundated sea water in the mangrove ecocystem in steady-state. Those increase with the high tide, and the normalized fluxes of TON and TN during flood tide and ebb tide were significantly correlate with high tide (TON flux during flood tide: r = 0.897, n = 5, $p < 0.05$, TON flux during ebb tide: r =

0.897, $n = 7$, $p < 0.05$, TN flux during flood tide: $r = 0.931$, $n = 5$, $p < 0.05$, TN flux during ebb tide: $r = 0.931$, $n = 7$, $p < 0.01$). This suggests that the normalized fluxes of TON and TN during flood tide and ebb tide in steady-state depend on discharged water mass across the mouth of Fukido River. On the other hand, concentrations of NO_3^-+NO_2^- and NH_4^+ might be changed by physicochemical mechanism (for example, remineralization, nitrification, and so on) in the creek water because those fluxes were not correlated with the high tide at the mouth of the Fukido River. Further research about nitrogen cycle in the creek water would be required to show this problem.

Fig. 3-13 shows the logarithmic plot between fluxes of TON and TN during flood or ebb and high tide. (a) indicates TON fluxes and (b) shows TN fluxes. To comparison the slopes in flood tide and ebb tide, comparison of each regression slopes was employed (Ichihara 1990). The slope of TON in ebb tide is significantly higher than that in flood tide, and the slope of TN in ebb tide is not significantly higher than that in flood tide. These may indicate that TON was produced by inorganic nitrogen supplied from the adjacent coastal water in the mangrove ecosystem and that TON is effectively supplied to the adjacent coastal water from the mangrove ecosystem.

Conclusion

The results of this chapter are concluded follows: (1) The improved Eulerian Approach was employed for an estimate of normalized fluxes of inorganic and organic nitrogen between the mangrove ecosystem and the adjacent coastal water. (2) Sometimes the mangrove originated fluxes of inorganic and organic nitrogen were the main fraction in the total flux of those. The maximum contribution of freshwater fluxes of inorganic and organic nitrogen to total fluxes of those were up to 35% in the mangrove ecosystem. (3) The magnitude of net fluxes of inorganic and organic nitrogen in steady-state were -$3.4\times10^5 \sim 4.8\times10^4$ mmol day^{-1}. On the other hand, the net fluxes in non steady-state were dominated by the net fluxes of DON or NH_4^+, and those of TN were quantified as import fluxes. However, those should be indicated the return of DON or NH_4^+ to the mangrove ecosystem because those were dominated by the fluxes originated from the mangrove ecosystem. (4) A general consensus on nutrient outwelling from mangrove has not yet been reached because scope and spatial scale of investigation in mangrove ecosystem were distinctly different in each previous studies about nutrient dynamics in mangrove ecosystem. By using Eulerian method, PON and NO_3^-+NO_2^- are generally exported (PON: -1.4 ~ -0.22 mmol m^{-2} day^{-1}, NO_3^-+NO_2^-: -0.29 ~ 0.00 mmol m^{-2} day^{-1}) from mangrove ecosystem to adjacent coastal water. (5) The normalized fluxes of TON and TN during flood tide and ebb tide were significantly correlate with high tide. (5) In analysis of comparison of each regression slopes, the slope of TON in ebb tide is significantly higher than that in flood tide, and the slope of TN in ebb tide is not significantly higher than that in flood tide. These may indicate that TON was produced by inorganic nitrogen supplied from the adjacent coastal water in the mangrove ecosystem and that TON is effectively supplied to the adjacent coastal water from the mangrove ecosystem.

Table 3-1 The fraction of freshwater fluxes of inorganic and organic nitrogen in total flux of those. * means significant fraction to total fluxes of those.

		PON	DON	TON	NO_3^-	NO_2^-	NO_3^-+NO_2^-	NH_4^+
16/3/1999	ebb (1)	—	—	5% *	—	—	1%	27% *
	flood (2)	—	—	4%	—	—	0%	4%
	ebb (2)	—	—	10% *	—	—	1%	8%
3/18/1999	ebb (1)	—	—	4%	—	—	1%	0%
	flood (2)	—	—	4%	—	—	1%	0%
	ebb (2)	—	—	3%	—	—	0%	1%
9/12/2000	flood (1)	2%	1%	1%	1%	0%	1%	0%
	ebb (1)	2%	1%	1%	3%	0%	2%	0%
9/15/2000	flood (2)	5% *	0%	2%	2%	0%	2%	0%
	ebb (2)	2%	1%	1%	1%	0%	1%	0%
11/25/2001	flood (1)	—	—	1%	0%	0%	0%	6% *
	ebb (1)	—	—	10% *	1%	0%	1%	35% *
	flood (2)	—	—	1%	0%	0%	0%	4%
	ebb (2)	—	—	6% *	2%	0%	2%	26% *
11/30/2001	flood (1)	—	—	0%	1%	0%	0%	4%
	ebb (1)	—	—	1%	1%	0%	1%	7% *
	flood (2)	—	—	0%	0%	0%	0%	2%
	ebb (2)	—	—	0%	1%	0%	0%	4%

Table 3-2 The net fluxes of nitrogen compounds between the mangrove ecosystem and the adjacent coastal water. (a) indicates those in steady-state, and (b) shows those in non steady-state. The positive values mean the import to the mangrove ecosystem. The negative values are the export from the mangrove ecosystem. The unit of fluxes are mmol day^{-1}.

(a)

date	TN	TON	PON	DON	NO_3^-+NO_2^-	NO_3^-	NO_2^-	NH_4^+
16th March 1999	-3.2×10^5	-3.4×10^5	—	—	4.8×10^4	—	—	-3.4×10^4
25th November 2001	-7.8×10^4	-3.9×10^4	—	—	-4.1×10^4	-4.1×10^4	-6.5×10	1.2×10^3
30th November 2001	-2.0×10^5	-7.0×10^4	—	—	-7.0×10^4	-1.7×10^4	-5.3×10^4	-2.3×10^4

(b)

date	TN	TON	PON	DON	NO_3^-+NO_2^-	NO_3^-	NO_2^-	NH_4^+
18th March 1999	2.4×10^6	4.8×10^4	—	—	-1.4×10^5	—	—	2.5×10^6
12th September 2000	1.6×10^6	1.3×10^6	-4.3×10^3	1.3×10^6	2.2×10^5	2.2×10^5	-1.1×10^3	6.8×10^4
15th September 2000	7.0×10^6	-1.2×10^6	-1.7×10^5	-1.1×10^6	-1.9×10^5	-1.9×10^5	-6.8×10^3	8.4×10^6

unit: mmol day^{-1}

Table 3-3 Areal net fluxes of nitrogen compounds reported by previous studies and this study. The positive values mean the import of nitrogen to the mangrove forest or the swamp. The negative values are the export of nitrogen from the mangrove forest or the swamp.
(a) Areal fluxes of nitrogen compounds from the swamp to the inundated creek waters.
(b) Areal fluxes of nitrogen compounds in creek water.
(c) Areal fluxes of nitrogen compounds from mangrove ecosystem to adjacent coastal water by quantifying Eulerian method.

(a)

location	TN	TON	PON	DON	NO_3^-+NO_2^-	NH_4^+	reference
Estero Pargo, Mexico	0.014	-0.106	-0.10	-0.006	0.02	0.10	Rivera-Monroy *et al.* 1995
Coral Creek, Australia	0.22 0.14	- -	- -	- -	- -	- -	Alongi 1996

(b)

location	TN	TON	PON	DON	NO_3^-+NO_2^-	NH_4^+	reference
Taylor River estuary,USA	-0.29±5.34	-	-	-	-0.54±1.2	-0.21±0.87	Davis III *et al.* 2001

(c)

location	TN	TON	PON	DON	NO_3^-+NO_2^-	NH_4^+	reference
Missionary bay, Australia	-0.07	-0.08	-0.23	0.15	-0.00	0.02	Alongi 1998
Klong Ngao Estuary,Thailand	-0.09	-	-	-	-0.02	-	Wattayakorn *et al.* 1990
Coral Creek, Australia	-0.04 *3	-0.06	-0.31 *1 (-0.06 ~ -1.4)	0.25 *2	-0.01 *2	0.03 *2	Boto and Bunt 1981 *1 Boto and Wellington 1988 *2 compiled by this study *3
Caeté Estuary, Brazil	-2.3 *6	-2.1 *6	-1.4 *4	-0.74±0.65 *5	0.00 *5	-0.16±0.18 *5	Dittmar and Lara 2001b *4 Dittmar and Lara 2001a *5 compiled by this study *6
Fukido River Estuary, Japan	-0.83	-0.30	-0.22	-0.08	-0.29	-0.23	this study
Coral Creek, Australia	-	-	-	-	-0.004	-	Ayukai *et al.* 1998
Conn Creek, Australia	-	-	-	-	-0.14	-	Ayukai *et al.* 1998

mmol m^{-2} day^{-1}

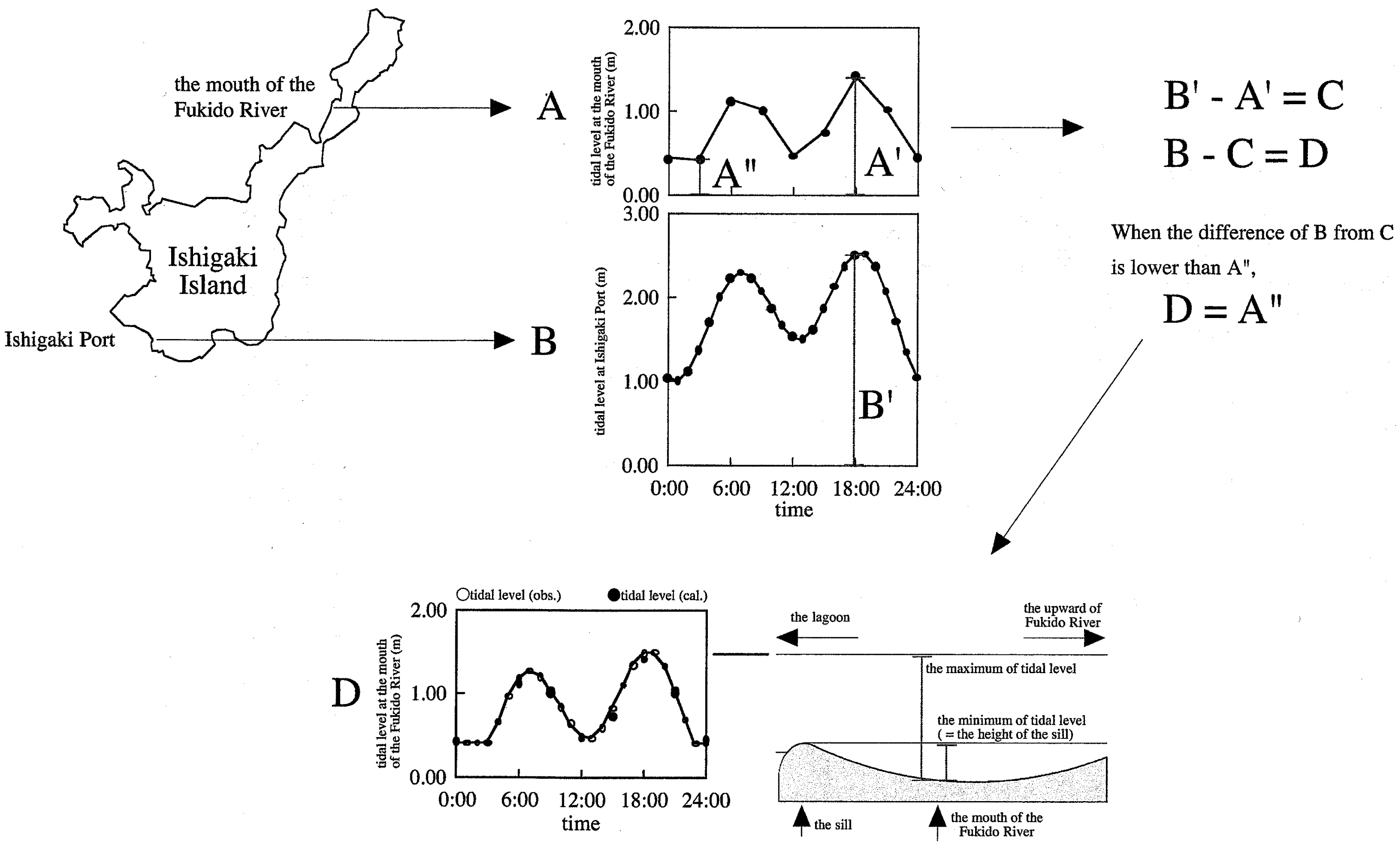


Figure 3-1 Flow diagram for the calculation of the tidal level at the mouth of the Fukido River.

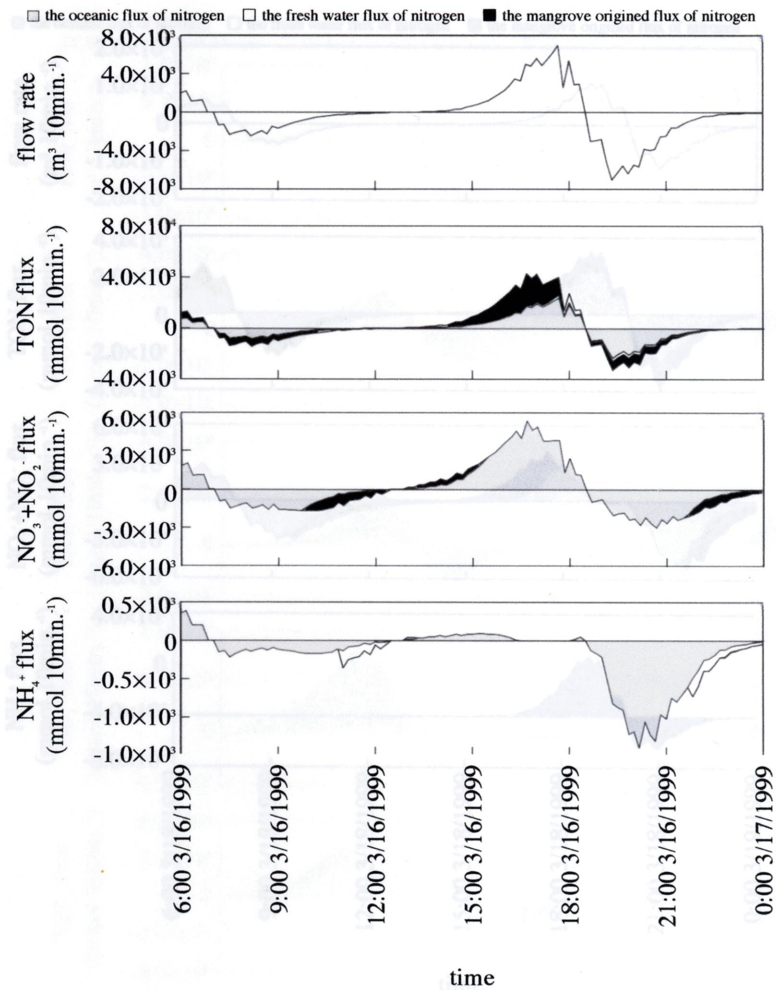


Figure 3-2 Water mass and fluxes of inorganic and organic nitrogen via the mouth of the creek on 16th March, 1999. Positive values in the graphs mean the import of water and nitrogen compounds into Fukido mangrove forest and negative value show the export of those from the forest.

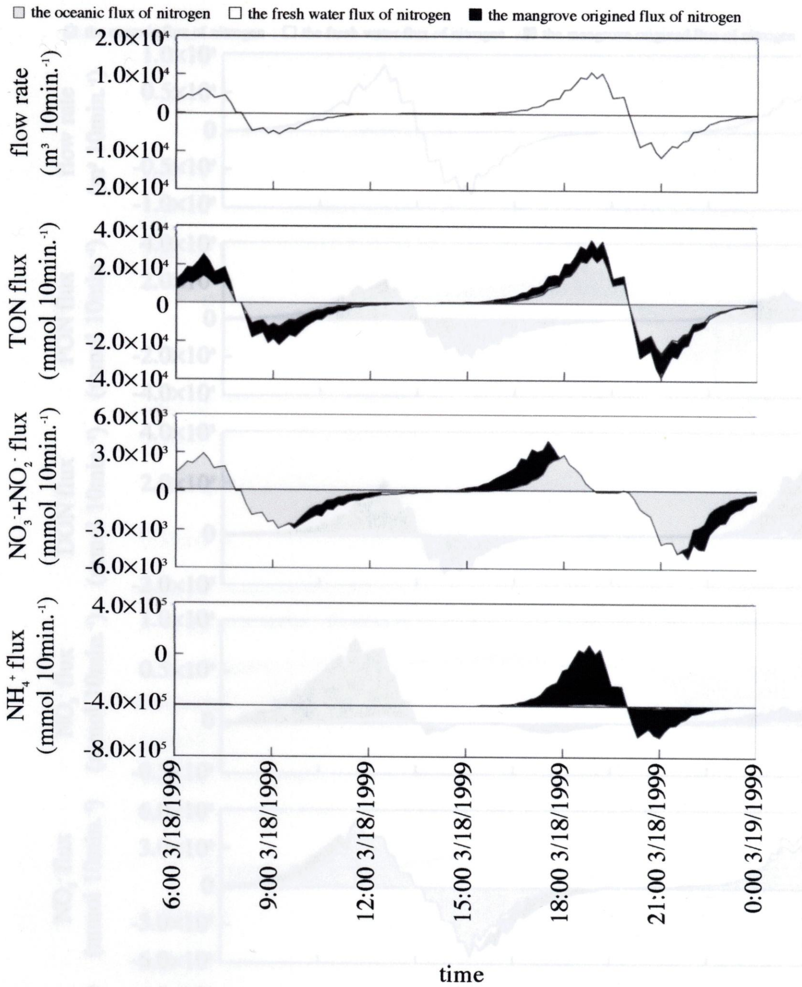


Figure 3-3 Water mass and fluxes of inorganic and organic nitrogen via the mouth of the creek on 18th March, 1999. Positive values in the graphs mean the import of water and nitrogen compounds into Fukido mangrove forest and negative value show the export of those from the forest.

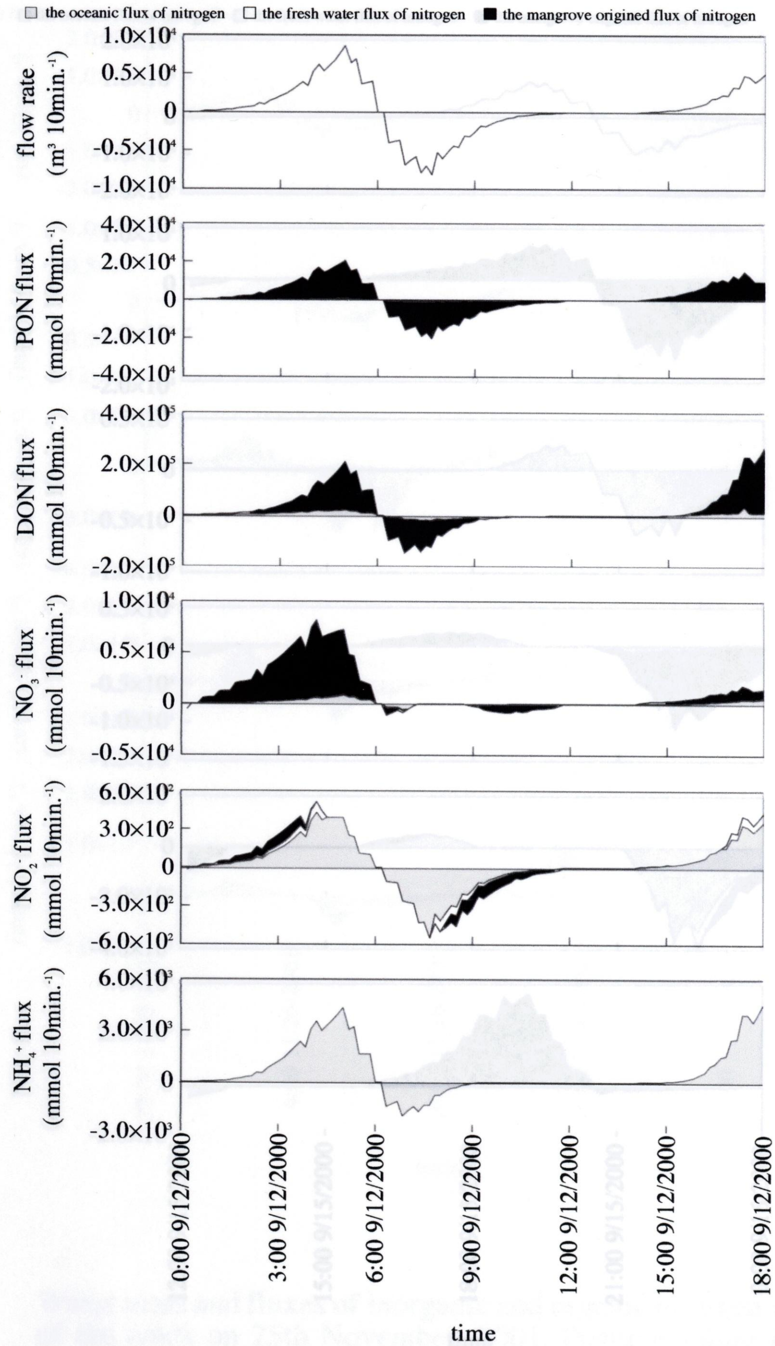


Figure 3-4 Water mass and fluxes of inorganic and organic nitrogen via the mouth of the creek on 12th September, 2000. Positive values in the graphs mean the import of water and nitrogen compounds into Fukido mangrove forest and negative value show the export of those from the forest.

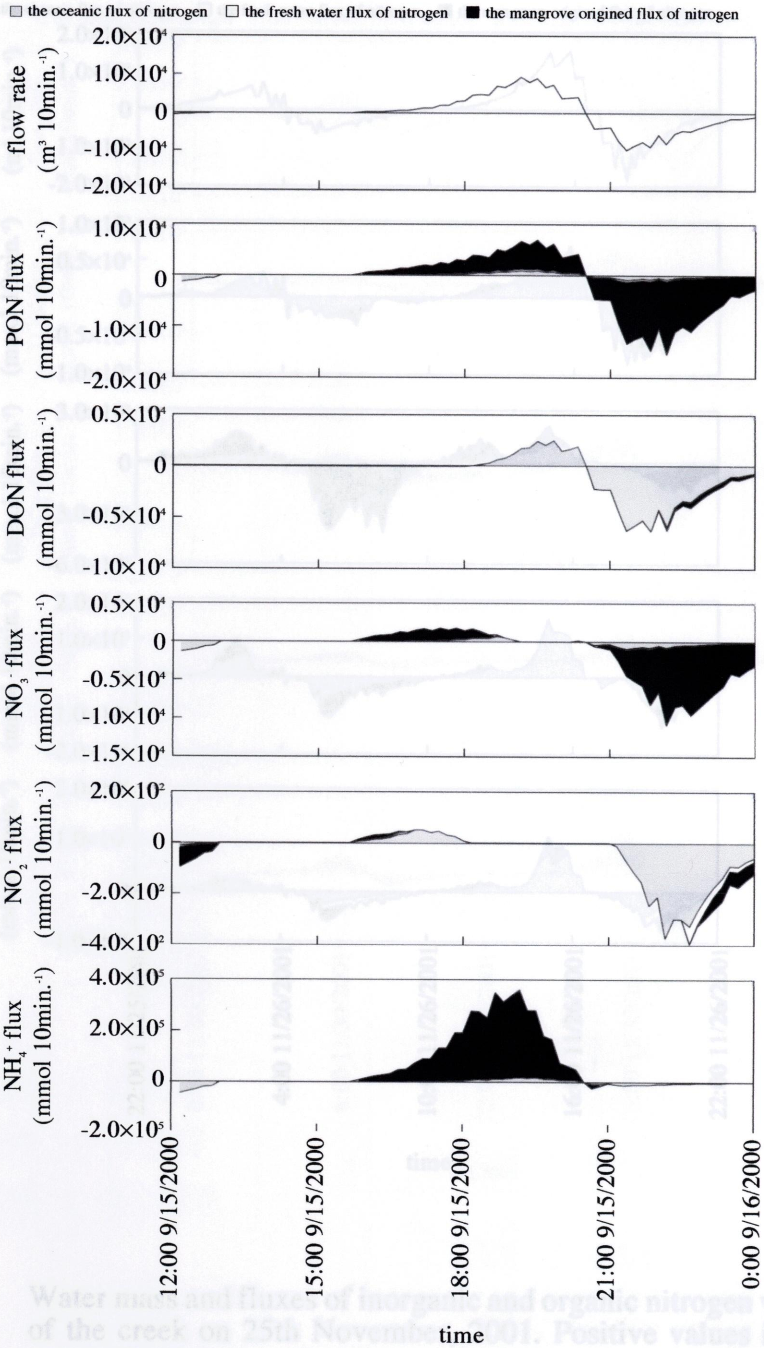


Figure 3-5 Water mass and fluxes of inorganic and organic nitrogen via the mouth of the creek on 15th September, 2000. Positive values in the graphs mean the import of water and nitrogen compounds into Fukido mangrove forest and negative value show the export of those from the forest.

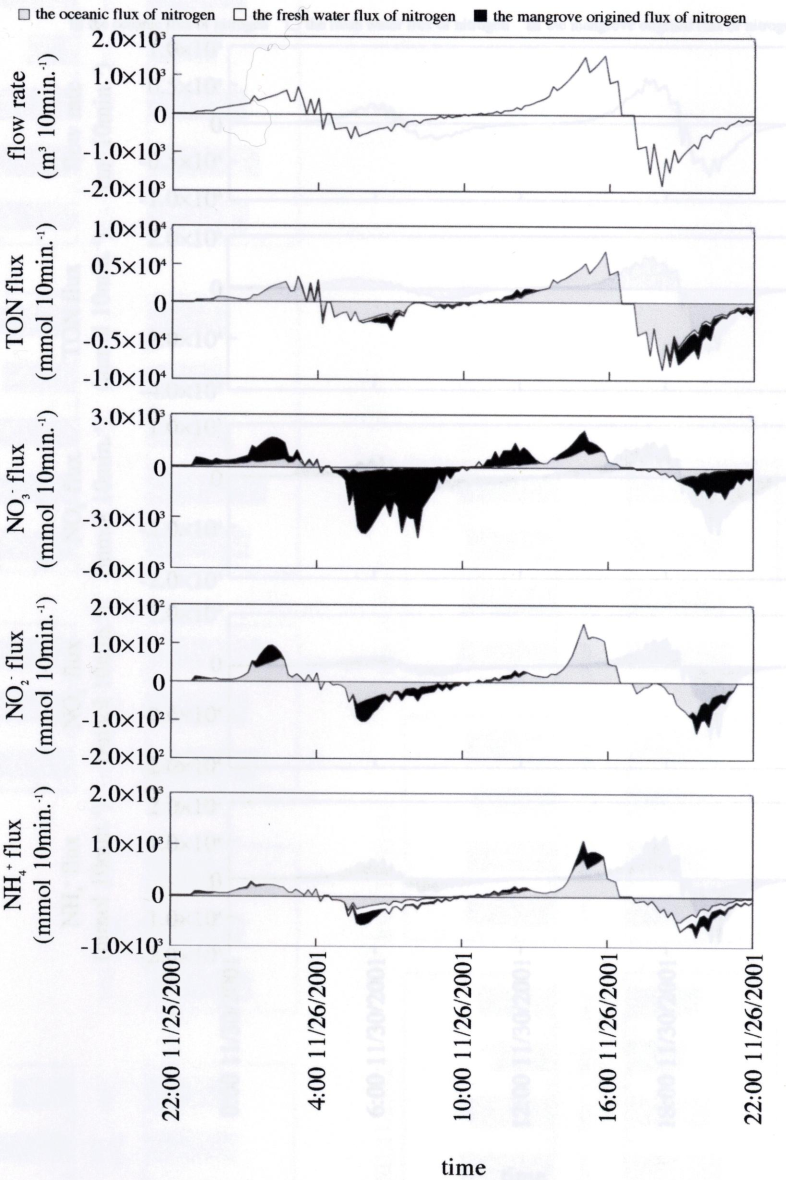


Figure 3-6 Water mass and fluxes of inorganic and organic nitrogen via the mouth of the creek on 25th November, 2001. Positive values in the graphs mean the import of water and nitrogen compounds into Fukido mangrove forest and negative value show the export of those from the forest.

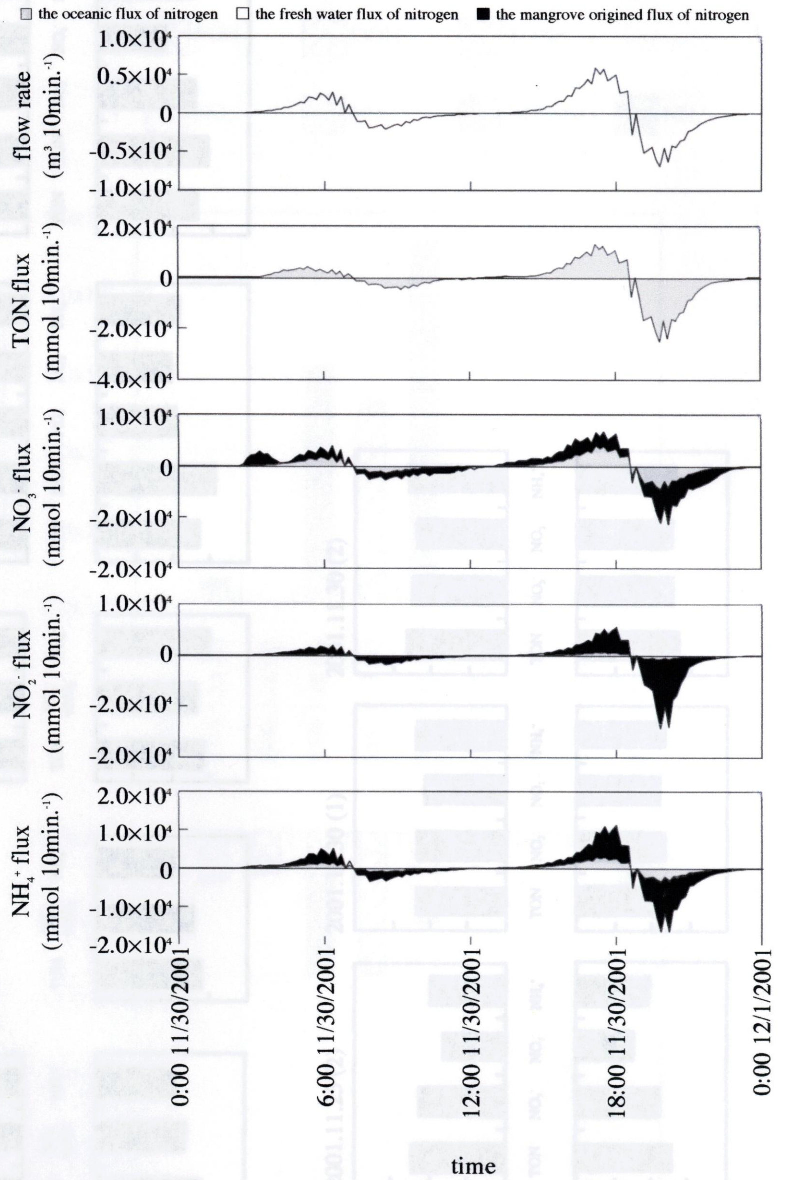


Figure 3-7 Water mass and fluxes of inorganic and organic nitrogen via the mouth of the creek on 30th November, 2001. Positive values in the graphs mean the import of water and nitrogen compounds into Fukido mangrove forest and negative value show the export of those from the forest.

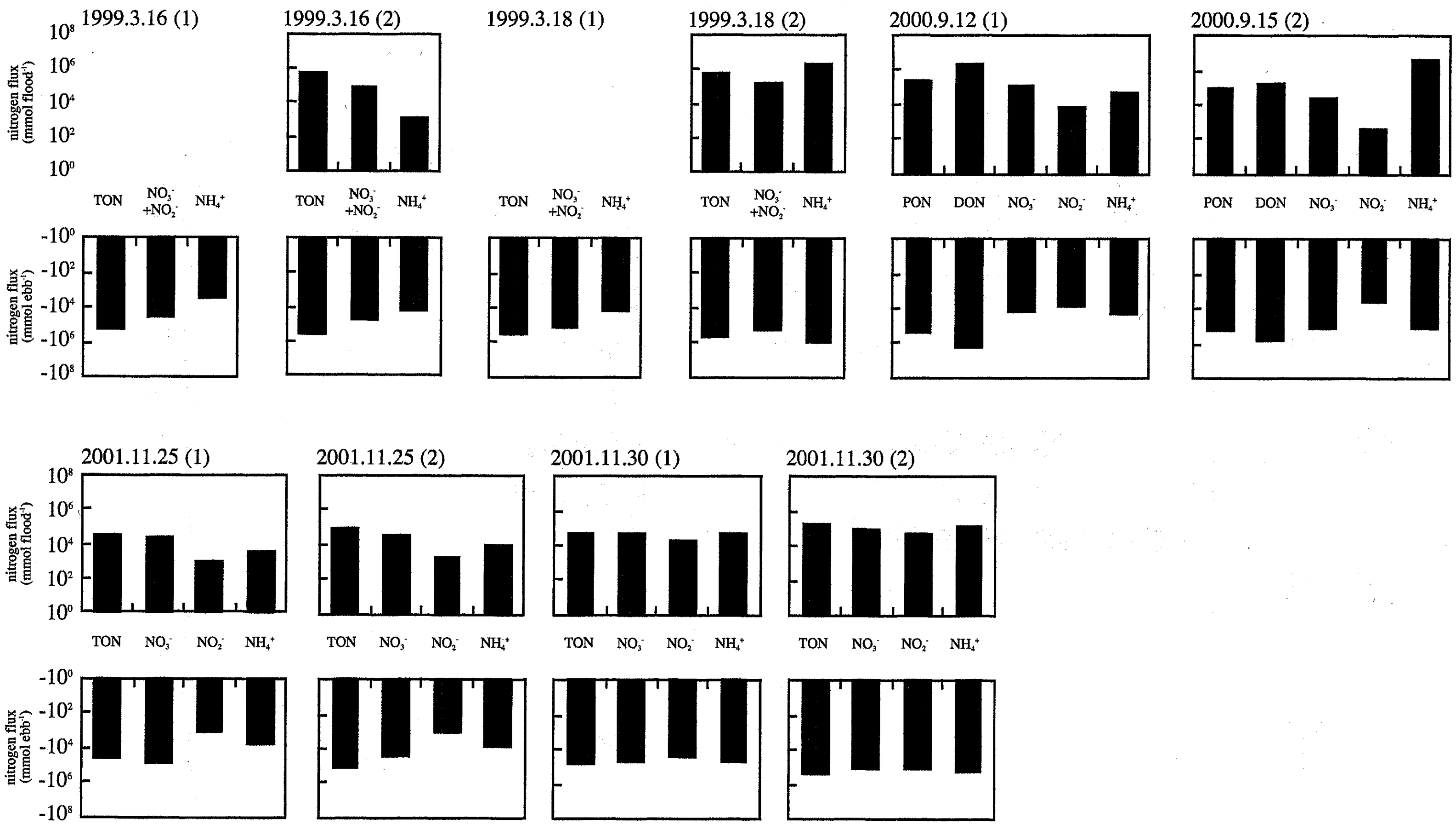


Figure 3-8 Normalized nitrogen fluxes per flood or ebb via the mouth of the creek. (1) and (2) after the date mean the first or the second tidal cycle in the day, respectively.

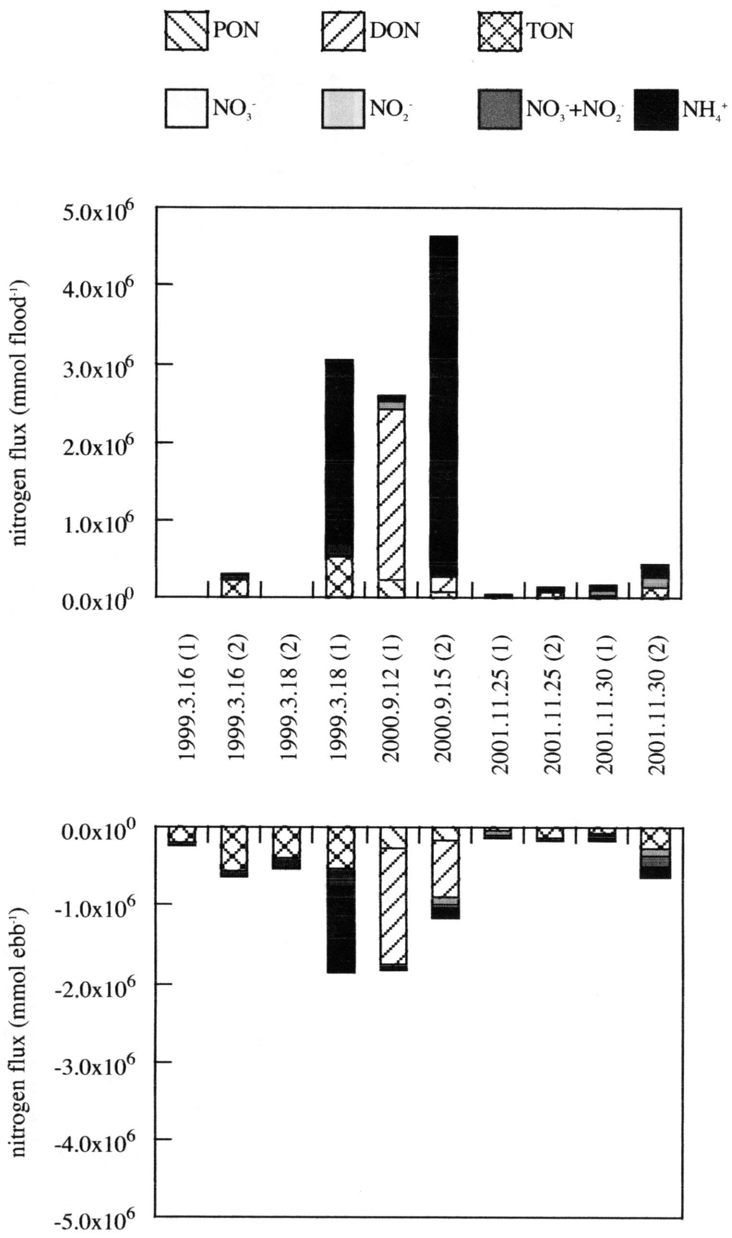


Figure 3-9 Nitrogen fluxes per flood or ebb. (1) and (2) mean that first and second tidal cycle in the day respectively.

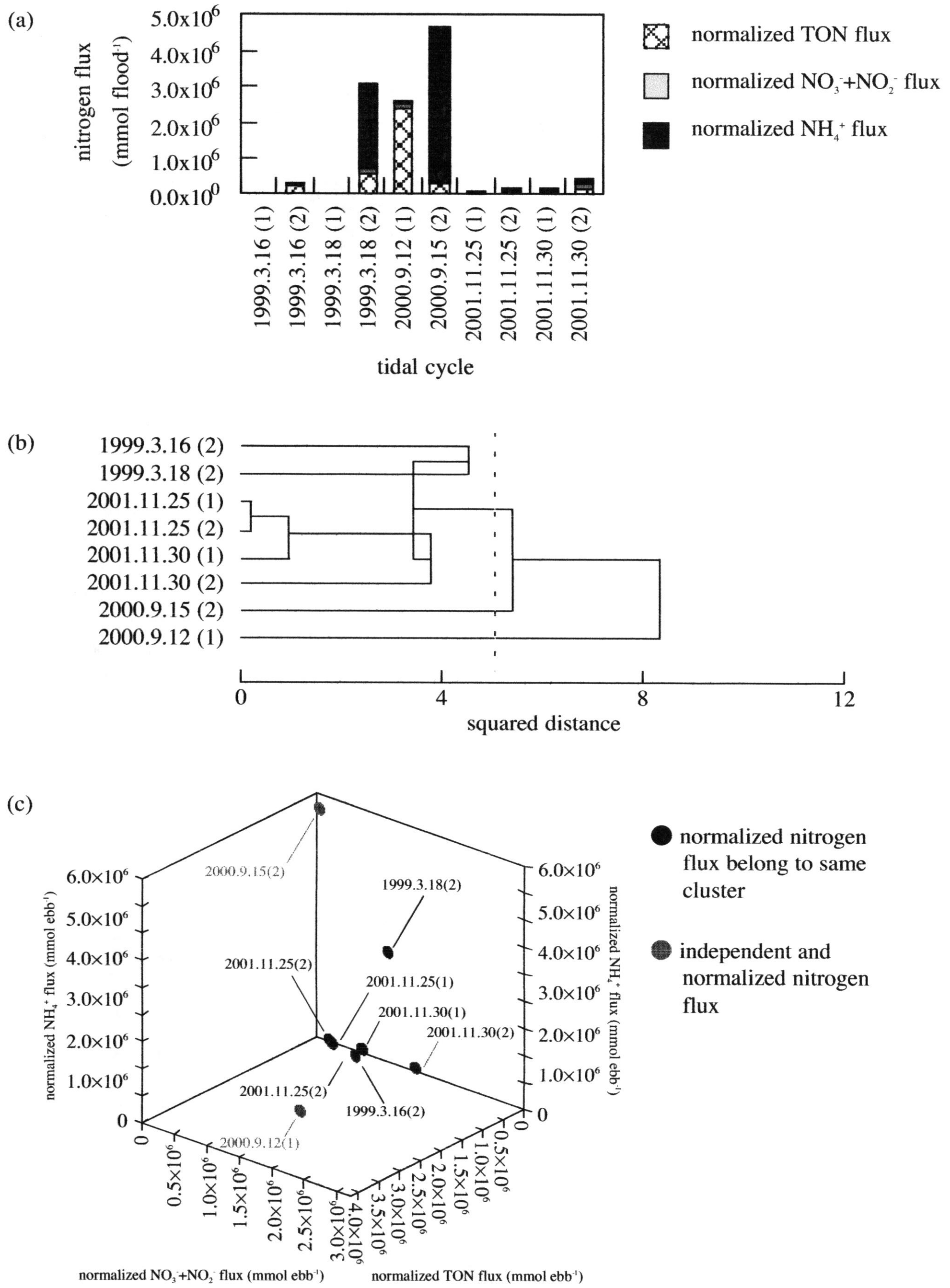


Figure 3-10 (a) Fraction of nitrogen fluxes per flood. (1) and (2) mean that first and second tidal cycle in the day, respectively.
(b) Dendrogram of tidal cycle based on cluster analysis by using centroid method. Dashed line means the optimal level of cutting in the dendrogram (Souissi *et al.* 2000).
(c) 3D plot of the normalized nitrogen fluxes per flood belong to same cluster and independent fluxes.

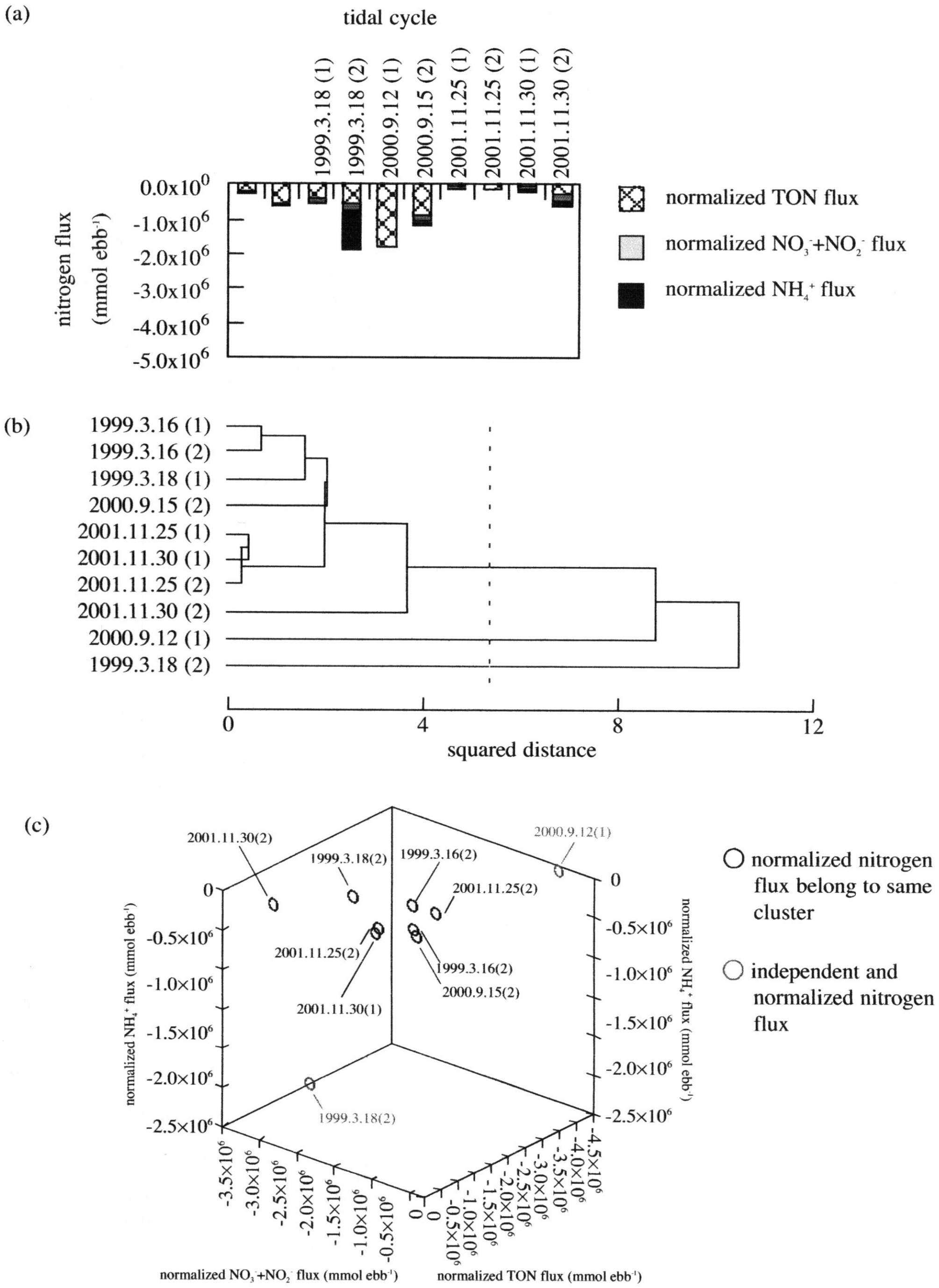


Figure 3-11 (a) Fraction of nitrogen fluxes per ebb. (1) and (2) mean that first and second tidal cycle in the day, respectively.
(b) Dendrogram of tidal cycle based on cluster analysis by using centroid method. Dashed line means the optimal level of cutting in the dendrogram (Souissi *et al.* 2000).
(c) 3D plot of the normalized nitrogen fluxes per ebb belong to same cluster and independent fluxes.

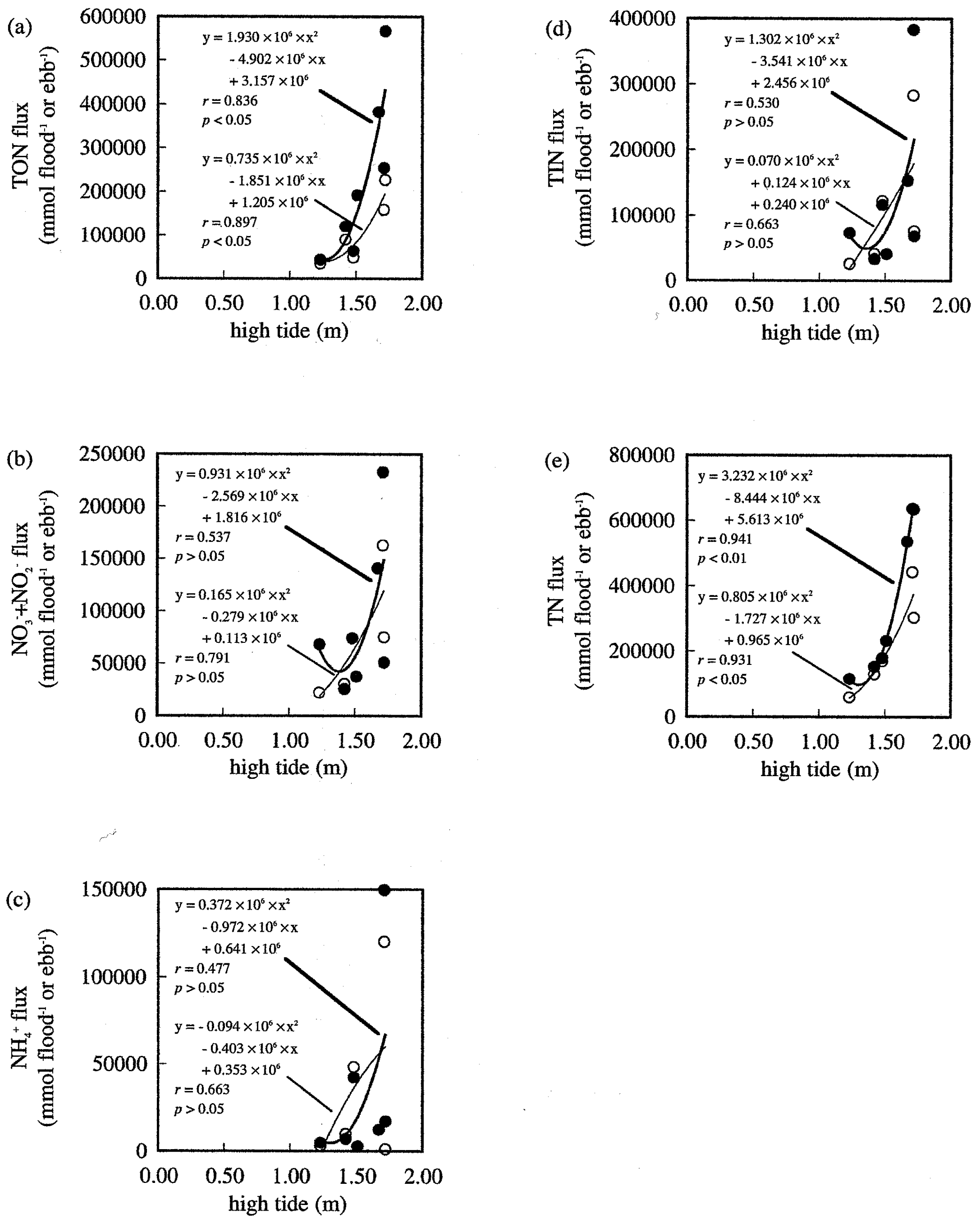
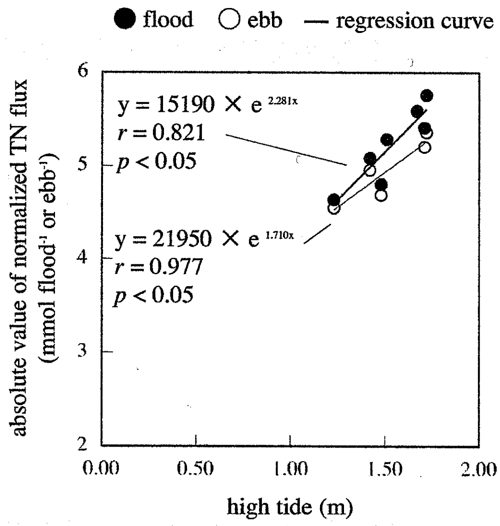


Figure 3-12 Correlation between high tide and the fluxes of inorganic and organic nitrogen per flood tide or ebb tide in steady-state. (a) TON (b) $NO_3^-+NO_2^-$ (c) NH_4^+ (d) TIN (e) TN

(a)



(b)

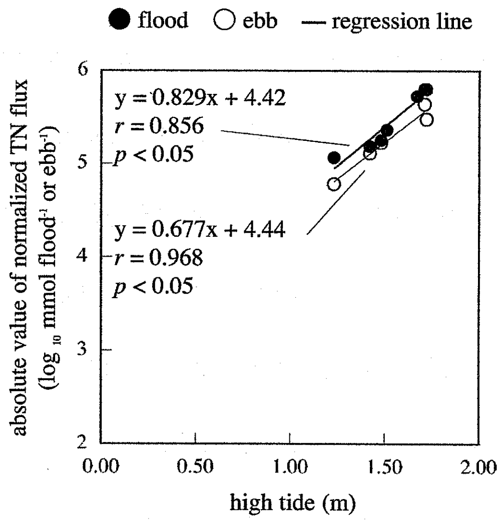


Figure 3-13 Logarithmic plot between fluxes of TON and TN per flood or ebb and high tide. (a) TON (b) TN

CHAPTER IV: A MODEL OF THE NITROGEN CYCLING IN FUKIDO MANGROVE SYSTEM

Introduction

Mangrove forests are valuable resources for multiple economic and ecological reasons (Alongi 1998). People living in coastal region in tropical countries have utilized the resource of various natural products from mangrove, such as building houses, bridges, boats, and so on (Lalli and Parsons 1993). Mangrove leaves have been consumed as fodder for breeding cows or goats by Arabian nomads. Mangrove forests supply fishing grounds in the tidal creeks and coastal sea, such as fishes, crabs, lobsters, shellfishes, and so on (Lalli and Parsons 1993). Mangrove forests play a role of protector to coastal topography in tropical region. Suspended matters and organic matters (especially mangrove litter) in water column are resident or sedimented to mangrove swamp (Lalli and Parsons 1993). Alongi 1998 showed that mangrove forests provide control of floods, storm surges and coastal erosion and filters for nutrients. Especially in Indonesia, great amount of detritus and muds sedimented in mangrove forest and the mangrove swamp spreads about 100 - 200 m to the coastal sea per year (Lalli and Parsons 1993).

However, mangrove forests have been lost by anthropogenic activities, such as for logging, development for shrimp pond, and so on. Especially in Vietnam, mangrove forest has lost by defoliants during the war, and more recently (Alongi 1998). Cebrian (2002) reported 47,839 km^2 of mangrove forest has been lost over the last 20 years due to coastal deforestation generated by human activities.

For the purpose of restoration and protection of environment in coastal region, transplanting or replanting of mangroves has been carried out by governments of South East Asian countries or civilian organizations. In India, Malaysia, Thailand, Bangladesh and Burma, restoration of mangrove forests has been practiced for many years (Alongi 1998). Especially in Bangladesh, the government made and carried out the program of restoration of mangrove forest since 1966, and then they have been successful to plant more than 120,000 ha mangrove forests. Vietnam has also been the site of extensive restoration of mangrove forest. Minh Hai province in southern Vietnam has been the site of most of the country's restoration efforts, where over 360,000 ha have been replanted (Alongi 1998).

On the other hand, growth and support of mangrove forest after restoration requires a large amount of nutrients (especially inorganic nitrogen), because mangrove forest is a productive community compared with other aquatic communities (Fig. 1-2, Alongi 1998). However, it is poorly understood that mangrove forest can uptake enough nitrogen. And if mangrove forest is a source of nitrogen for adjacent coastal water, what mechanism supplies nitrogen for mangrove forests is poorly understood too. Because most studies for nitrogen balance in mangrove forest have not estimated as the whole mangrove system.

To estimate fluxes and budgets of nitrogen with more certainly, we should consider two main parts: creeks and swamps (Wolanski *et al.* 1992). Previous reports did not consider this point (Dittmar and Lara 2001a, Alongi 1996).

The purposes of this chapter are: (1) whole estimate of nitrogen balance in creeks and swamp of Fukido mangrove forest (2) estimate of nitrogen fluxes within mangrove forest (3) discussion about what mechanism supplies nitrogen for mangrove forests.

Materials and Methods

I construct nitrogen cycle model based on Kurosawa *et al.* 2003 (Fig. 4-1). PON, DON, NO_3^-+NO_2^- and NH_4^+ pools in the creek are calculated by product of water volume in average tidal level and average concentrations of inorganic and organic nitrogen at the mouth of the creek on 16th March 1999.

The annual net fluxes of inorganic and organic nitrogen were quantified by the summation of net fluxes of inorganic and organic nitrogen per day during 1999 ~ 2001. The net fluxes of inorganic and organic nitrogen per day were calculated by summation of the fluxes of inorganic and organic nitrogen per flood tide and ebb tide during a day, and the fluxes of inorganic and organic nitrogen per flood tide and ebb tide were product of discharged water mass and average concentrations of inorganic and organic nitrogen at the mouth of Fukido River in steady-state (see Chapter II and III). The discharge water mass per flood tide and ebb tide were estimated by the relationship between between the tidal level at the mouth of Fukido River and water volume in the mangrove ecosystem (see Chapter III) and high tide at Ishigaki Port (Fig. 4-2: Ishigaki-Jima local meteorological observatory 1999, 2000 and 2001). The inflow of riverine fresh water was calculated by product of flow rate and concentrations of inorganic and organic nitrogen (Tables 3 and 4: see Chapter II). Litter fall was calculated by the carbon fluxes per month and C/N ratio of living mangrove leaves in Fukido mangrove forest (Tateda *et al.* 1999, Yamaki unpublished data). The nitrogen requirement is calculated with the net CO_2 fixation rate (Nose *et al.* (2001), Okimoto (2002)) and the molecular ratio of carbon/nitrogen of the trunk of a mangrove (Yamaki unpublished data) in the mangrove ecosystem. The accumulation rate is calculated by carbon accumulation rate reported by Tateda *et al.* 2002 and C/N ratio of the sediment in Fukido mangrove forest (Yamaki *et al.* 2001, Yamaki *et al.* 2002). N_2O emission rate is cited by the emission rate reported in Imamura 2002. N_2 fixation - denitrification rate (net N_2 exchange rate) is calculated by method of Dittmar and Lara (2001b) and Morell and Corredor (1993). They assumed the mangrove sediment was in a steady-state of nitrogen balance and calculated balanced fluxes for nitrogen in the sediment.

Results and discussion

Fig. 4-3 shows the annual nitrogen fluxes and pools in Fukido mangrove forest. The magnitude of annual fluxes of inorganic and organic nitrogen were 0.5 ~ 1.8 t N yr^{-1} (import) and 0.7 ~ 2.2 t N yr^{-1} (export), respectively. The summation of those was -0.8 t N yr^{-1}, thus, it suggested that the mangrove ecosystem is a source to the adjacent coastal water in steady-state.

If the nitrogen pools in the mangrove ecosystem were steady-state, the net N_2 exchange rate would be estimated 0.75 t N yr^{-1} (0.78 mmol m^{-2} day^{-1}). This estimate may be same order to that in the mangrove ecosystem because the range of net N_2 exchange rate reported by previous studies is -1.6 ~ 2.3 mmol m^{-2} day^{-1} (Table 4-1). The examination of N_2 exchange rate in the mangrove ecosystem would be required to support this estimate.

To discuss magnitude of fluxes of nutrient in mangrove forest, we have been using the rate of the nutrient fluxes to a nutrient requirement by mangrove vegetation in studies about nutrient dynamics in mangrove ecosystem. The summation of annual net fluxes of inorganic and organic nitrogen and net N_2 exchange rate were same order to the nutrient requirement by mangrove vegetation in the mangrove ecosystem. Boto and Wellington 1988 described that net flux of TN by tidal exchange reached only 5.4 % to areal nutrient requirement in the Coral Creek, Australia. Boto & Robertson (1990) has reported that the average flux of areal net N_2 fixation rate was 3.5 % to forest net primary production (FPPN) in Coral Sea, Australia. These differences of the rates were introduced by the characterization of each mangrove forest. Clough (1998) represented that total canopy carbon fixation was estimated to be about 29 t C ha^{-1} $year^{-1}$ in mangrove forest in Hinchinbrook Island, Australia. Okimoto (2002) showed that net carbon fixation rate was estimated to be about 1.69 t C ha^{-1} $year^{-1}$ in Fukido mangrove forest. The amount of nutrient requirement by vegetation in the mangrove ecosystem is calculated by the amount of net carbon fixation rate (net primary production rate). So the rate of nutrient fluxes to the nutrient requirement has potentially about 17-fold difference between Fukido mangrove forest and mangrove forest in Hinchinbrook Island. Furthermore, the magnitude of net fluxes of inorganic and organic nitrogen in the mangrove ecosystem is about ten times higher than those in Coral Creek, Australia (see Chapter III: Table 3-3).

We must focus detail character of net N_2 exchange between mangrove sediment and the atmospheric N_2 in mangrove ecosystem. Because we have already recognized that primary production is a beginning of carbon cycle, but we have not clarified what is the beginning of nitrogen cycle and trap in mangrove forests. In the mangrove ecosystem, the net N_2 exchange rate has been estimated, and it would be a beginning of nitrogen cycle in the mangrove ecosystem. Further reseach would be require to support this hypothesis.

Conclusion

The results of this chapter are concluded follows: (1) The annual net fluxes of inorganic and organic nitrogen by tidal exchange in the mangrove ecosystem was quantified as 0.8 t N yr^{-1}. This suggests that the mangrove ecosystem is a source of nitrogen compounds to the adjacent coastal water. (2) The annual net N_2 exchange rate was estimated as 0.75 t N yr^{-1} (0.78 mmol m^{-2} day^{-1}) in the mangrove ecosystem. This estimate may be same order to that in the mangrove ecosystem because the range of net N_2 exchange rate reported by previous studies. (3) The tidal exchange and the net N_2 exchange rate were same order to nitrogen requirement by the vegetation of mangrove in the mangrove ecosystem.

Table 4-1 Net N_2 exchange rate in mangrove ecosystem.

reference	site	method	N_2 fixation	denitrification	Net N_2 exchange rate
Alongi 1998	Missionary Bay, Australia	acetylene reduction, *in situ* incubation	0.17	-0.01	0.16
Alongi *et al.* 2000	Mekong delta, Vietnam	acetylene reduction, *in situ* incubation	0.63 ±1.00	-2.2±1.2	-1.6±2.2
Boto and Robertson 1990	Coral Creek, Australia	acetylene reduction	0.12±0.14	-	-
Dittmar and Lara 2001	Caeté Estuary, Brazil	caluculated, assuming balanced fluxes for nitrogen in the sediment	-	-	2.3
this study	Fukido Estuary, Japan	caluculated, assuming balanced fluxes for nitrogen in the sediment	-	-	0.75

mmol m^{-2} day^{-1}

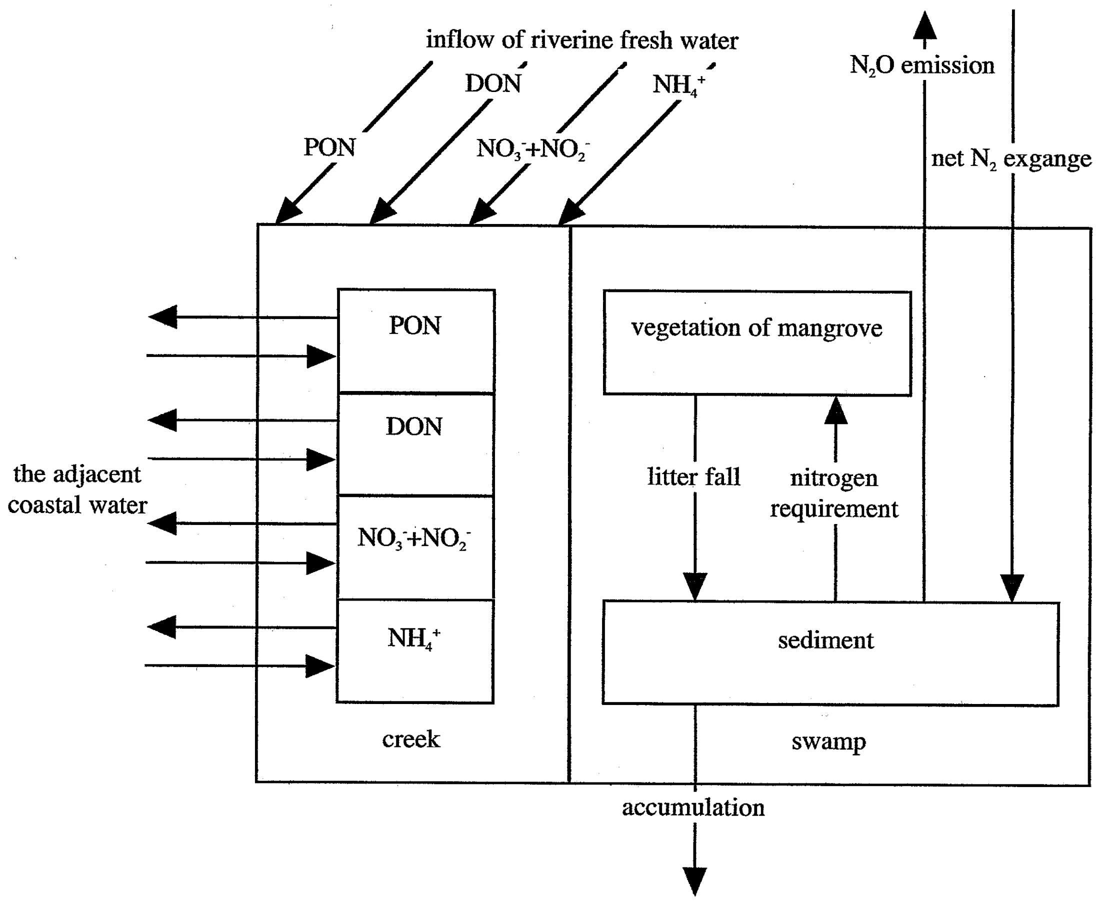


Figure 4-1 Nitrogen fluxes and pools of nitrogen in the mangrove ecosystem.

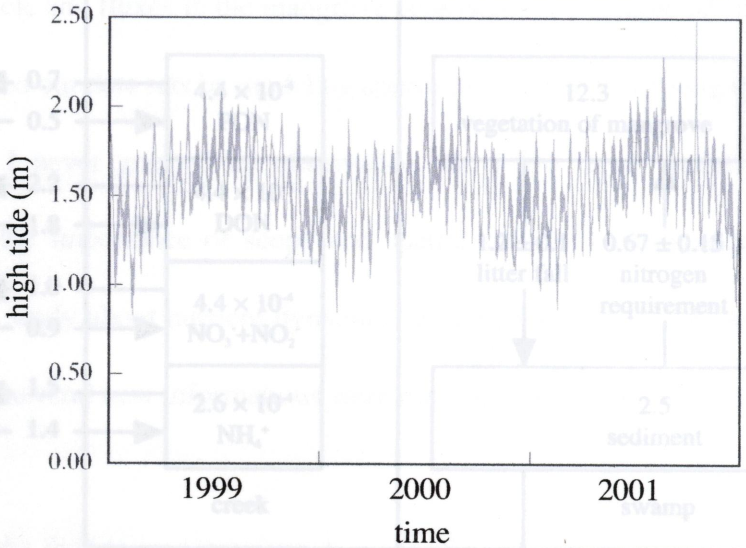


Figure 4-2 Normalized high tide at the mouth of the Fukido River. The data of high tide were observed by meteorologic observatory at Ishigaki Port, Japan (Ishigaki-Jima local meteorological observatory 1999, 2000, 2001).

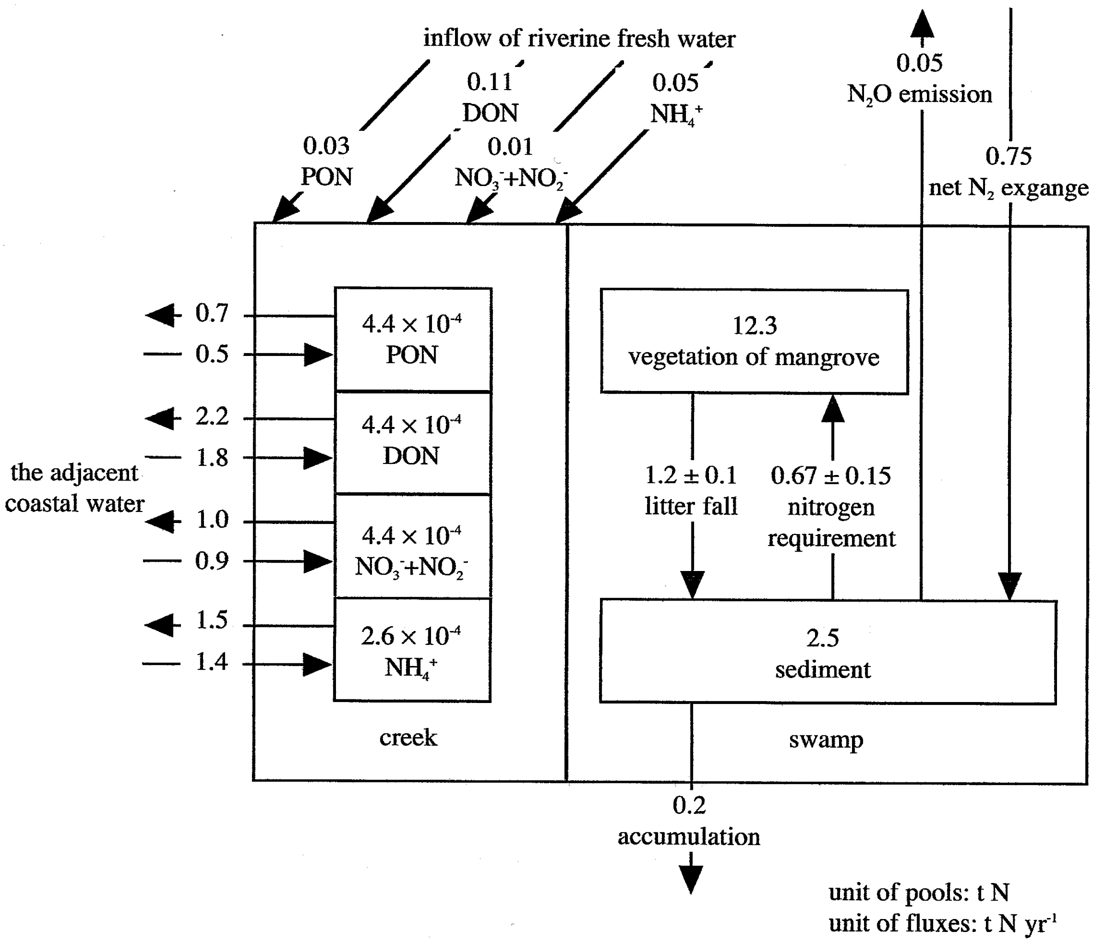


Figure 4-3 Annual nitrogen fluxes and pools in the mangrove ecosystem.

CHAPTER V: GENERAL CONCLUSION

From 1999 to 2002, several field observations were carried out for the evaluation of nitrogen cycle and fluxes in the mangrove ecosystem as a sample of mangrove forest. Then, I analyzed our data sets by modeling approach to evaluate the long term budget and fluxes which I never grasped by observation for a few days. Attentions were paid especially to the importance of scope and spatial scale of investigation in mangrove ecosystem for study about nutrient dynamics in mangrove ecosystem. As the results of present study, several new informations were obtained, which are summarized as follows.

(1) In the Fukido mangrove creek, inorganic and organic nitrogen concentrations changed with tidal oscilation in the creek water. Comparing the average concentrations in the mangrove creeks with the average concentrations in the adjacent coastal waters, concentrations of TON and TIN in mangrove creek waters were higher than the adjacent coastal waters (TON:1-10 fold higher, TIN: 1-2 fold higher, respectively). The average concentration of TN in Fukido mangrove creeks has a significant difference to the average concentration of TN in lagoon ($p > 0.05$, ex. 2001.11).

(2) Fukido mangrove forest was concluded as a source of inorganic and organic

nitrogen to the water body in the creeks by analysis of the mixing diagram.

(3) To divide the total fluxes of inorganic and organic nitrogen into the oceanic flux of those, the freshwater flux of those and the mangrove originated flux of those, and the improved Eulerian Approach was employed. The maximum contribution of freshwater fluxes of inorganic and organic nitrogen was 35% to the total fluxes of inorganic and organic nitrogen. The normalized fluxes of inorganic and organic nitrogen were occupied by the oceanic flux of those and the mangrove originated flux of those in steady-state, and the magnitude of those were $-3.4\times10^{5} \sim 4.8\times10^{4}$ mmol day^{-1}.

(4) In non steady-state, the normalized flux of TN was occupied by DON or NH_4^+ flux in flood and ebb, and it reached about 90 % of normalized TN flux, and those of TN were quantified as import fluxes. However, those should be indicated the return of DON or NH_4^+ to the mangrove ecosystem because those were dominated by the mangrove originated fluxes of those. The overestimate of DON or NH_4^+ flux in non steady-state may be caused by suppose the mouth of Fukido River as the boundary of the mangrove ecosystem, not the sill.

(5) PON and $NO_3^-+NO_2^-$ are generally exported (PON: $-1.4 \sim -0.22$ mmol m^{-2} day^{-1}, $NO_3^-+NO_2^-$: $-0.29 \sim 0.00$ mmol m^{-2} day^{-1}) from each mangrove ecosystem to

adjacent coastal water in previous studies about nitrogen dynamics in mangrove ecosystem investigated by Eulerian method, however, directions of net fluxes of DON and NH_4^+ were not certain in those mangrove ecosystem. These might be that the magnitude of mechanisms which affect concentrations of DON and NH_4^+ were different in each mangrove ecosystem. TN is exported (-2.3 ~ -0.04 mmol m^{-2} day^{-1}) from each mangrove ecosystems, and those mangrove ecosystem are concluded as the source of nitrogen to those adjacent coastal water. Mangrove ecosystem may be an important source of nitrogen compounds to coastal water in tropical region because surface water in tropical sea is generally oligotrophic.

(6) The annual net fluxes of inorganic and organic nitrogen were calculated by the high tide and the average concentrations of those in steady-state at the mouth of Fukido River. It reached 0.8 t N yr^{-1} and suggested that inorganic and organic nitrogen were exported from the mangrove ecosystem to the adjacent coastal water.

(7) A nitrogen cycle model was formulated comparing the annual net fluxes of inorganic and organic nitrogen in mangrove forest. I estimated, assuming balanced fluxes for nitrogen in the sediment, net N_2 exchange rate between the atmosphere and the mangrove ecosystem (denitrification - N_2 fixation). The annual net N_2 exchange rate and the normalized net nitrogen fluxes per year are same order to the nitrogen requirement in the mangrove ecosystem. Some studies represented that the net fluxes of TN and the net

N_2 exchange rate to the nutrient requirement (uptake) in mangrove forests were 5.4 and 3.5 %, respectively. These differences were introduced by the characterization of each mangrove forest. For example, total canopy carbon fixation rate in mangrove forest in Hinchinbrook Island was 17-fold to the carbon fixation rate in Fukido mangrove forest. So the rate of nitrogen fluxes to the nutrient requirement in Fukido mangrove forest has potentially 17-fold difference to the rate in Hinchinbrook Island.

ACKNOWLEDGMENT

I would like to express my thanks to Professor Yoshimi Suzuki, Department of Biology and Geoscience, Shizuoka University. He gave me the present subject, valuable scientific guidance and encouragement during this study. Gratitude is also expressed to Doctor Yutaka Tateda, Abiko Research laboratory, Central Research Institute of Electric Power Industry (CRIEPI), as the chief of present research project. He gave me occasion to join the observations of this project and gave me some scientific guidance.

I wish to express my thanks to Professor Hideki Wada, Professor Yoshihisa Kato, Doctor Rumi Sohrin and Doctor Satish=Kumar, Department of Biology and Geoscience, Shizuoka University. They discussed with me and told me what I should focus in present study. I also wish to express my thanks to Professor Kimio Fukami (Department of Agriculture, Kochi University), Yoshihiro Mazda (Department of Marine Science, Tokai University) and Kiyohiko Nakasaki (Department of Engineering, Shizuoka University). They reviewed my paper and told me what I should express in present study.

I am indebted to the staffs of Global Biogeochemistry laboratory, Department of Biology and Geoscience, Shizuoka University, especially to Miss Yuka Ohnishi for her advices and kind help in completion of this manuscript. I am indebted to the scientists and their students joined in present research project. They helped my brainstorming for a discussion about mangrove study and tell me what I focussed in present study.

This study used the results of program system carbon dioxide fixation / effective utilize with technical development research of Japan Oceanic Industrial Association (JOIA) / New Energy and Industrial Technology Development (NEDO), and was carried out with their financial support. Captain Sasaki and Mr. Hirano assisted our observations in Fukido mangrove river in Ishigaki Island. JOIA staff, particularly Mr. Akimoto supported our observations. I thank also Dr. Lan Smith of FRSGC (Frontier Research System for Global Change) for supporting English correction. I thank them all and appreciate all their support.

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