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Seasonal variability of estuarine dynamics due to freshwater discharge and its influence on biological productivity in Yeongsan River Estuary, Korea

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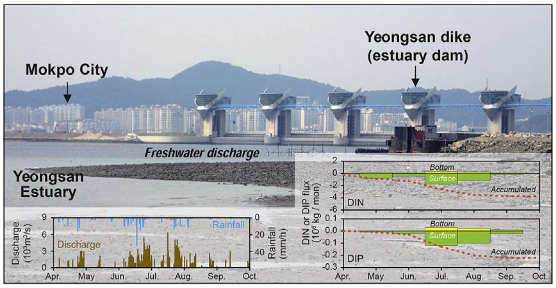
HIGHLIGHTS

- Seasonal dynamics of water quality characterized in closed estuarine system.
- Simulation supported the strong seasonal trends of nutrients with dominated outfluxes.
- Vertical fluxes of nutrients and OM primarily controlled by the freshwater discharge.
- Numerical dye experiment revealed fast nutrient flushing followed by lesser productivity.

GRAPHICAL ABSTRACT



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ABSTRACT

In order to evaluate water quality and biological productivity, observation data sets were collected and analyzed in Yeongsan River Estuary, Korea. We also set up a numerical model to resolve hydrodynamics and fate of water quality variables in the system. Results show that most of nutrients loading are trapped in the lake and higher concentrations of nutrients and organic matters (OM) are present only inside of the artificial sea dike. There exist episodial discharges at the dam, which coincide mostly with rainfall events during summer monsoon periods. During this discharge event, lower salinity and higher suspended solids, nutrients, and OM are observed in surface layer of the estuarine section. Hydrodynamic model results show that circulation in the estuarine section is governed by freshwater discharge from the lake, resulting in an enhanced two-layer estuarine circulation being dominated, during and after the freshwater is discharged. Such two-layer estuarine circulation combined with higher concentration of nutrients in the surface layer results in that outfluxes of nutrients in the surface layer dominate over the influxes in the bottom layer during summer high precipitation periods. Meanwhile, numerical dye experiment results show that the discharged water with elevated nutrients levels have a short residence time (~5–10 days) in the estuarine section. Due to this fast flushing rate, excessive nutrient loadings are not used to produce biological matters in the estuarine section. This limited biological productivity,

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characterized by seaward side of the artificial sea dike, makes Yeongsan estuarine system excluded from acting as an active carbon sink.

1. Introduction

Estuary is a linkage between terrestrial and ocean systems and involves major biogeochemical pathways for freshwater as well as materials including nutrients, organic matters, and sediments. By its definition in Cameron and Pritchard (1963), a typical estuary is characterized by a semienclosed body of water wherein ocean water is diluted by freshwater derived from the land. This mechanism generates a horizontal geochemical gradient with salinity decreasing from the ocean toward the land. The horizontal salinity gradient is one of the most important driving forces in the lotic estuarine system, which establishes and maintain vertically stratified structures being mixed by wind, wave and tidal forcings (Valle-Levinson, 2010 and references therein). Thus, the horizontal salinity gradient, depending on freshwater inflow to an estuarine system, plays a key role in determining the fluxes of salt and other materials in an estuary (Geyer, 2010).

The Yeongsan River drains freshwater from the area of about 3371 km^2 in southwestern part of Korea to Yellow Sea. The river mouth used to have a well-developed estuary and extensive tidal flats (ca. 280 km^2) due to macrotidal characteristics of the tidal range up to 6 m in the eastern Yellow Sea. In 1982, in order to provide consistent freshwater for agricultural and industrial uses, the sea dike was constructed in the middle part of the estuary, about 8 km from the estuary mouth. Since then it is composed of an artificial lake inside the dam and the estuarine section, now defined as the region between sea dike and river mouth, which is strongly influenced by the freshwater discharge control at the sea dike. Although the freshwater discharge via the dike gate is controlled artificially, large discharge events are still related to the natural cycle of summer monsoon, i.e., high precipitation concentration during summer. More than 80% of rainfall is concentrated during July to September, so is freshwater discharge through the sea dikes (Rhew and Lee, 2011; Kim et al., 2013). Cho et al. (2004) and Kim et al. (2013) reported the seasonal variability of hydrographic and hydrodynamic structures depending on the freshwater discharge in the Yeongsan River Estuary. They found that two-layer estuarine circulation pattern is intensified during and right after freshwater discharge events, whereas well-mixed or multi-layer structures are present during low discharge periods.

Different mixing and circulation regimes induced by intermittent freshwater discharge would have a critical impact on the biogeochemical settings in an estuary (Goñi et al., 2009; Lucas, 2010). High sediment and nutrient loadings from terrestrial and anthropogenic sources along with freshwater input and subsequent excessive biological production of organic matters have been reported in wide spectrum of estuaries (Lohrenz et al., 2008, 2013; Cai et al., 2011). Goñi et al. (2009) showed the cycling of biogeochemical materials, particulate organic matter in particular, is strongly influenced by discharge and thus circulation and flux patterns in an estuary. Bang et al. (2013) and Cho et al. (2015) reported, in the Yeongsan River Estuary, the variability in sediment transport and hypoxia formation is fundamentally controlled by freshwater discharge events. Cai et al. (2011) and Lohrenz et al. (2013) demonstrated that the riverine/estuarine coastal environments receive the massive fluxes of carbon, nutrients, and sediments from freshwater, but also it can act as strong sinks for atmospheric carbon dioxide due to high productivity. Having a large, stagnant freshwater lake just inside reach of the sea dike, the Yeongsan lake and estuary system might also act as an efficient place for atmospheric CO_2 sink. Thus, it would be critical to evaluate the fate of those organic matters in the system including artificial lake and estuary like Yeongsan.

In this study, we analyzed year-round field-observed data to depict the variability in biogeochemical characteristics in the Yeongsan River Estuary, especially with respect to different discharge conditions. To better understand the variability of the fate of such biogeochmical components, we also developed a numerical model to simulate the estuarine flushing and mass fluxes of major water quality variables, including nutrients and organic matters. We estimated the material flux for those variables to show the seasonal flushing pattern of the Yeongsan lake-estuarine system. Finally, we compared our study results with long-term data sets from one of Korean national ocean observatory networks, named the Marine Environmental Monitoring System, to understand long-term flux of nutrients and organic matters in the Yeongsan River Estuary.

2. Study area

The Yeongsan River Estuary is located in the southwestern tip of Korean peninsula. The southwestern part of Korea has extensive agricultural areas, especially wide rice fields that use massive freshwater. The Yeongsan River flows through the rice fields and provides majority of water for them. In order to maintain consistent freshwater source for agricultural and industrial uses, a sea dike was constructed in 1982, approximately 8 km from the mouth of the Yeongsan River Estuary (Fig. 1).

The Yeongsan River has a drainage area of about 3371 km^2, with an annual mean discharge of about 1.5×10^8 m^3 (Cho et al., 2004). More than 80% of the rainfall occurs during summer months (July, August, and September) due to the summer monsoon season (Rhew and Lee, 2011). When the water level of the freshwater lake inside of the sea dike during those months, the dike gates are open to discharge fresh water mostly during low tide. Accordingly, the majority of freshwater discharge occurs during the summer.

The estuarine section, up to 8 km from the sea dike, shows relatively straight east-west direction with about 2 km widths. The water depths ranges 10–20 m in the middle of estuary. The tides in the estuary are principally semidiurnal, with mean spring range of up to 6 m (i.e., macrotidal; Cho et al., 2004). It has been reported that the tidal amplitudes have increased and tidal currents have decreased since the construction of sea dike (Choi, 1984; Kang, 1999). Of note, the wide open estuaries and tidal flats of ca. 280 km^2 developed in this area have been disappeared by the series of embankment since early 1980s (Fig. S1).

3. Materials and methods

3.1. Study design and sampling

Study design in the present study was presented in Table 1, and data sets can be divided into three categories according to the specific objectives. Four liters of water samples were collected from

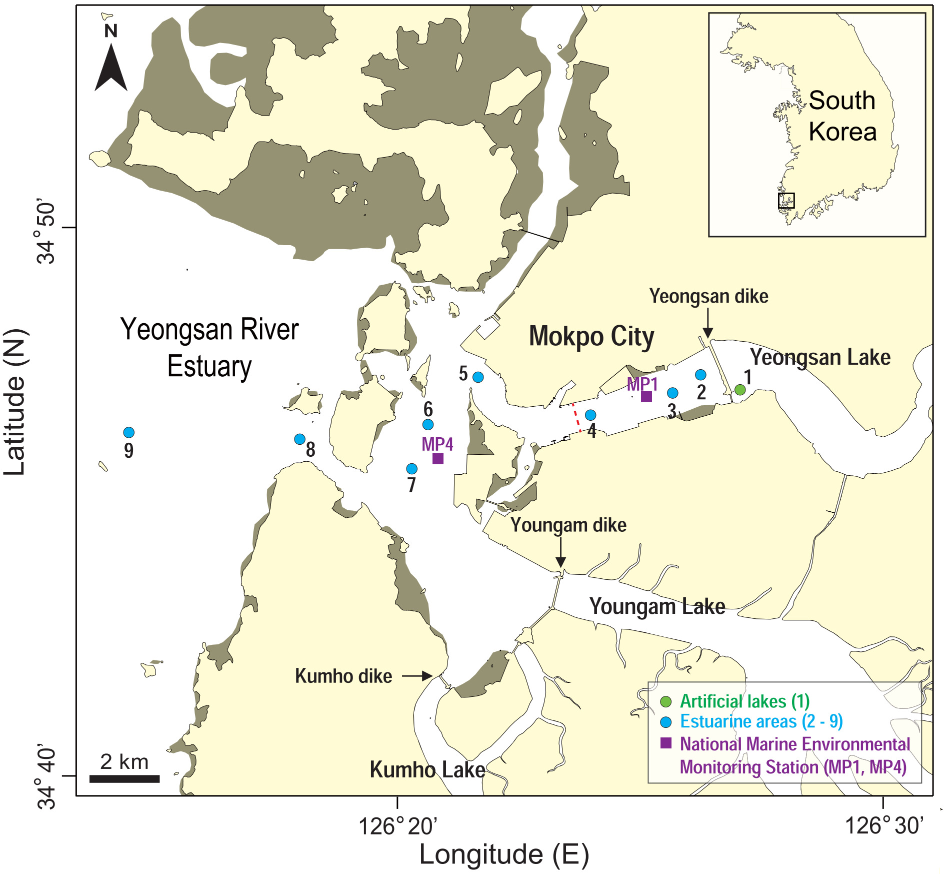


Fig. 1. Map showing the sampling stations in Yeongsan River Estuary, Korea. Location of estimating net flux and flushing rate of water quality is presented as red dotted line by St. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Design of the present study for water quality dynamics in Yeongsan River Estuary, Korea, summarized by data set 1 to 3 with specific objectives.

	Data set 1 (Shipborne)	Data set 2 (Shipborne)	Data set 3 (Long-term monitoring)
Objectives	Establishment of water quality model in estuarine area at freshwater discharge periods	Water quality model validation in estuarine area	Long-term trends of water quality in estuarine area
Survey year	2011	2013	2000–2013
# of sampling	5	5	4
	March, May, August, September, and December	May and June	February, March, August, and November
# of locations			
Artificial lakes	1 (Station 1)		
Estuarine areas	5 (Stations 3, 4, 5, 6, 8)	4 (Stations 2, 5, 7, 9)	2 (MP1 and 2)
Depth	Surface and bottom	Four depths (included surface and bottom)	Surface
Water quality parameters	Temp., Salinity, pH, DO, SS, COD, TOC, TN, TP	Temp., Salinity, pH, DO, SS, TN, TP	Temp., Salinity, pH, DO, SS, COD, TOC, TN, TP
Data obtained from	This study	This study	National Marine Environmental Monitoring
Data present in	Fig. 2	Fig. 3	Fig. 4

the nine stations along the Yeongsan River Estuary (Fig. 1) using a Van Dorn water sampler in 2011 and 2013, based on the amount of rainfall and freshwater discharge. Surface and bottom water samples were collected in March, May, August, September, and December in 2011 and water samples of four depths included surface and bottom were collected in May and June 2013 (details in Table 1). Samples were immediately transferred to laboratory and target water qualities were analyzed. Water temperature (T), salinity (S), pH, and dissolved oxygen (DO) were measured in situ using a calibrated multi-probe (YSI-556 MPS, YSI Incorporated, OH).

3.2. *Water quality analysis*

Water quality parameters such as suspended solids (SS), chemical oxygen demand (COD), total organic carbon (TOC), total nitrogen (TN), and total phosphorus (TP) in water samples were determined. In brief, SS were determined on pre-weighted filter papers (GF/F, Whatman, Maidstone, UK). COD was measured using the $KMnO_4$-based titration method according to the Marine Official Testing Method in Korea (MLTM, 2010). TOC was measured following high-temperature combustion in a TOC analyzer (Shimadzu TOC-VCPH, Shimadzu Co., Japan). TN and TP analyses were based on persulfate digestion method.

3.3. Long-term monitoring system

In order to determine the long-term trends of water quality in Yeongsan River Estuary, water quality data (SS, COD, TN, and TP) in two stations (MP1 and MP4, 2001 to 2013) were obtained from the Marine Environment Information System (MEIS, 2016). In addition, amount of freshwater discharge through Yeongsan water gate and amount of precipitation during those periods were collected from the Water Resources Management Information System (WAMIS, 2016) and the Korea Meteorological Administration (KMA, 2016), respectively.

3.4. Model description

The Environmental Fluid Dynamics Code (EFDC), also referred to as HEM3D, was applied to analyze estuarine flushing rate and mass fluxes for major water quality variables. EFDC has been applied in many estuarine and river systems. Seo and Song (2015) used this model to reproduce the phyto-plankton dynamics in Yeongsan River. Cho et al. (2015) constructed a three-dimensional particle transport model to investigate summer hypoxia formation in bottom water of the Yeongsan River Estuary using EFDC. The EFDC model solves the continuity equation, horizontal momentum equations, vertically hydrostatic momentum equations, and mass balance equations for salt, temperature, and sediment.

EFDC consists of a hydrodynamic model and a water quality model linked internally. Mass balance equations for salt and temperature are linked with the momentum equations by baroclinic term (Park et al., 2005). And the water quality model solves mass balance equations for the 21 state variables. The model uses a sigma coordinate in vertical direction, and a rectilinear or an orthogonal curvilinear grid system in horizontal direction. To provide the vertical turbulent viscosity and diffusivity, the level 2.5 turbulent closure scheme is used (Mellor and Yamada, 1982; Galperin et al., 1988). To provide the horizontal turbulent viscosity and diffusivity, Smagorinsky type diffusivity is used. A more detailed description of the model can be found in Hamrick (1992).

3.5. Model configuration and experimental design

The model used in this study is mainly derived from the one constructed by Cho et al. (2015) in Yeongsan River Estuary and adjacent sea (64×80 km^2). The model was configured a rectilinear and curvilinear grid system comprised of 32,317 surface water cells with grid spacing varying from 50 to 400 m and equidistant 11 vertical sigma layers. Cho et al. (2015) conducted a model-data comparison for tide, tidal current, salinity, and water temperature over August 2011. The results seem to reflect field data successfully. On top of Cho et al. (2015)'s model, we constructed the water quality and sediment transport model. Modeling period was chosen as one year in 2011. Initial conditions were specified with the data from January 2011 and open boundary conditions were specified with national marine environmental information system data. Freshwater discharge and the concentrations of water quality variables from the Yeongsan River Estuary dam were specified with Yeongsan River model results of Seo and Song (2015).

The model results were presented on the basis of two layers. Cho et al. (2015) defined S-depth as an isopycnic, $\sigma_\theta = 19$ kg m^{-3} that was used to identify the surface and bottom layers. The net budget of salt, suspended sediment, DIN, DIP, and TOC were calculated during one year simulation period across the entrance of Yeongsan River Estuary for each layers. And the exchange rates of estuary were calculated using the mass of the dye. It may be expressed as;

$$\gamma\_S = (\Delta M_S/M_S)/\Delta t, \quad \gamma\_S = (\Delta M_B/M_B)/\Delta t$$

where, γ is exchange rate, ΔM is the mass change of dye within estuary, ΔM is total mass of dye at previous step, t is time, subscript S and B represent surface and bottom layer, respectively.

4. Results

4.1. Shipborne observation

Fig. 2 shows the temporal and spatial variability of five water quality variables, including SS, COD, TOC, TN, and TP, collected during 2011 field period in the Yeongsan River Estuary. Along-estuary variability of five variables is shown for each five sampling periods, comprising 25 boxes in Fig. 2. In each box, a vertical red dashed line represents the boundary between the artificial lake and the estuarine section.

Yearly record of rainfall and discharge in the study area during 2011 can also be found in Fig. 2. In general, rainfall and discharge showed similar pattern of increase and decrease (Fig. 2a), which indicated they open the discharge gate of the dam when a rainfall event happens. The discharge, which has more direct impact than rainfall on the hydrography and water quality in the estuary section, showed high peaks during July and August. One can note that our samples were mostly taken during discharge events (e.g., colored bars in Fig. 2a) except September sampling period.

SS ranged a few to 20 mg/L in the estuarine section during most of observation periods (Fig. 2). In the estuarine section, elevated SS were observed during May and August observation period when rainfall and thus discharge at the dam occurred. The spatial variability was not significant in the estuarine section, but SS were little higher in the artificial lake than on all the stations in the estuarine section (Fig. 2), except September sampling period. During September, when light rainfall occurred but no discharge was executed, the very first station in the estuarine section showed dramatic increase in SS at the bottom layer.

The highest COD was observed during March (i.e., spring season) and minimum occurred during December (i.e., winter) in the artificial lake (Fig. 2). In the estuarine section, on the contrary, higher concentrations of COD were observed during May and August when rainfall and large discharge occurred. During those periods, COD was relative higher in the upper estuarine section and then decreased with the distance from the dam. Also, during those high discharge periods, COD was significantly higher in the upper column than the bottom samples on station 2, the closest estuarine sample to the dam.

Higher TOC in the lake was found during the period of freshwater discharge at the dam (March, May, August and December) than the September period of no discharge (Fig. 2). TOC in the lake was two or three times higher in the lake than in the estuarine section for most sampling periods. In the estuarine section, there was no significant seasonal trend in TOC nor spatially in the along-estuarine direction. With respect to the vertical distribution, TOC was slightly higher in the upper layer in most cases, but the difference seemed to be insignificant.

TN and TP showed similar trend of an order of magnitude greater in the lake than in the estuarine section during all observation periods (Fig. 2). It should be noted that, in the estuarine section, elevated concentrations of TN and TP were observed during May (period of high rainfall and discharge) with a clear along-estuary trend of higher concentration in the surface layer of inner estuarine location decreasing toward down-estuary. During other periods, on the other hand, there was no such trend observed.

Another set of shipborne observations were conducted during

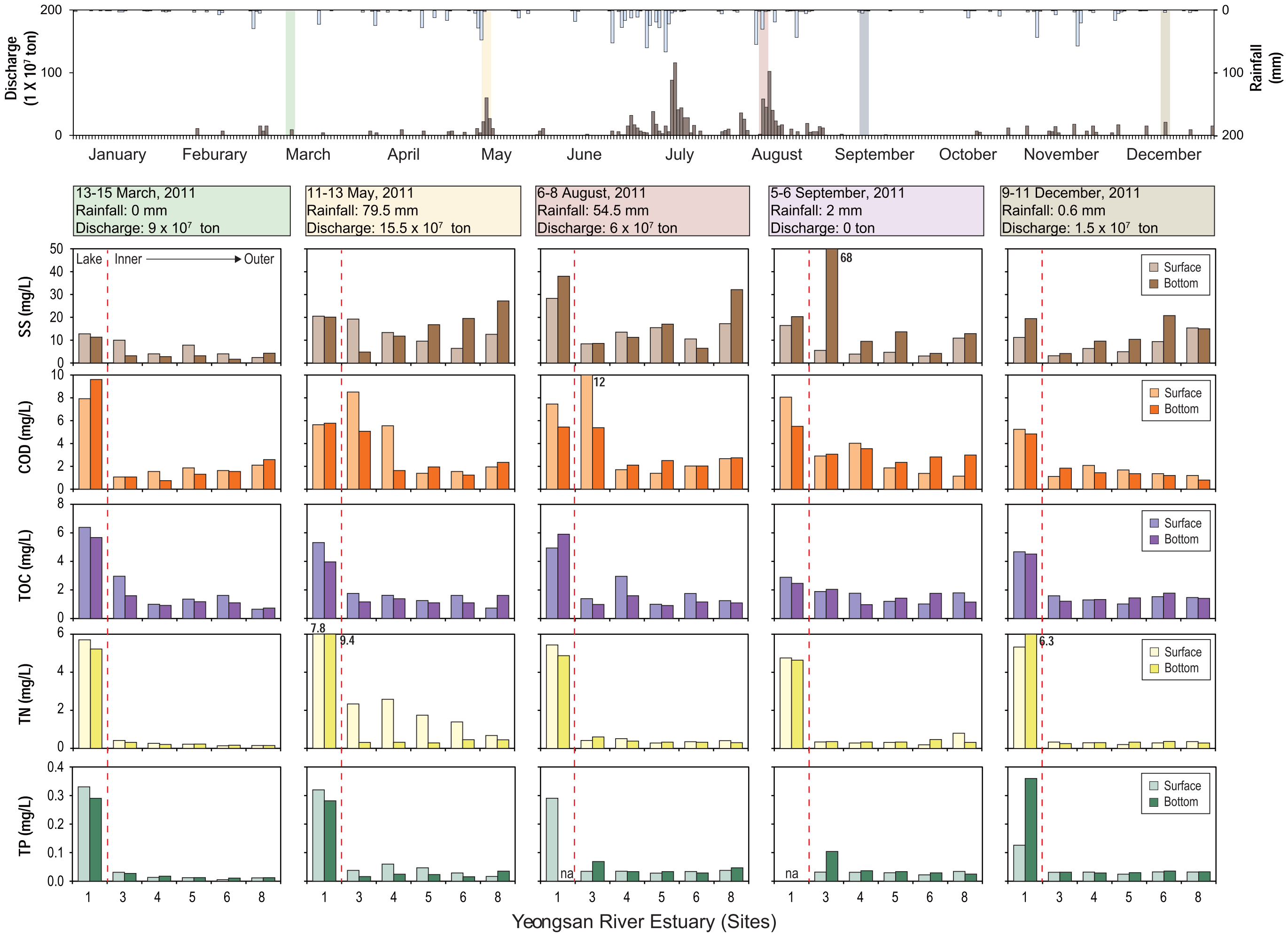


Fig. 2. Temporal and spatial variability of five water quality variables, including suspended solids (SS), chemical oxygen demands (COD), total organic carbon (TOC), total nitrogen (TN), and total phosphorus (TP). Temporal variability of freshwater discharge from Lake Yeongsan in 2011 is presented.

May and June 2011, including intensive 5 observations in 2 weeks. The sampling program was designed to cover the condition of hydrography and water quality variables before and after a significant rain event. The sampling was taken at 4 different depths in this intensive sampling configuration, to better represent more detailed structure in vertical than those found in 2011 sampling scheme. Fig. 3 shows the along-channel variability of several water quality variables including salinity, DO, SS, TN, and TP. Salinity distribution shows well-mixed condition on May 23rd and then a two-layer structure is well established on 29th and later. It should be noted that the observation on May 29th was conducted on 2 days after a significant rainfall (94.7 mm) given in the study area. Correspondingly, all other water quality variables also showed significant change before and after the rainfall. SS was relatively low (~20 mg/L or lower) in most areas before the rainfall, while it increased dramatically at the bottom and outer section of the estuary right after the rainfall event. Then, it took about a week to 10 days to get back to background concentrations of SS. Before the rainfall, DO distribution showed a well-developed along-channel gradient, whereby it was relatively greater in the upper estuary and smaller (below 5 mg/L) in the lower estuary. After the rainfall, however, the DO concentration increased over the entire estuary. In particular, a two-layer structure of higher DO at the surface and lower value at the bottom layer was developed during early June, which is 1–2 weeks after the rainfall event. TN was relatively low (<0.5 mg/L) over the entire estuary before the rainfall. After the rainfall event, it increased up to 5 times more than normal value especially in the surface layer. Then, the value decreased back to normal level after 5–10 days of the event. The distribution pattern of elevated TN was similar to that of lower salinity, indicating this great TN concentration might be related to the water mass with lower salinity. As similar to TN, TP was relatively low before the rainfall and increased in the surface layer after the rain.

4.2. *Long-term monitoring*

Compared to the shipborne measurements, the long-term observation data are somewhat limited since the data were collected only 4 times a year and only at the surface of the water column. However, this 4 sampling data-set represented some seasonal variation of the water quality variables (Fig. 4). First of all, one can note that the data of COD, TN, and TP from the station MP4 (lower estuary; represented by light green dots in Fig. 4) showed relatively higher values than those from MP1 (upper estuary). On the other hand, SS were relatively higher in the upper estuary than that in the lower estuary. COD concentrations showed an interesting seasonal variation of the elevated COD occurrence during summer sampling period. This elevated COD sometimes coincide with the elevated TN and TP concentrations, particularly during 2011 and 2012. On the contrary, the peaks in the SS data were

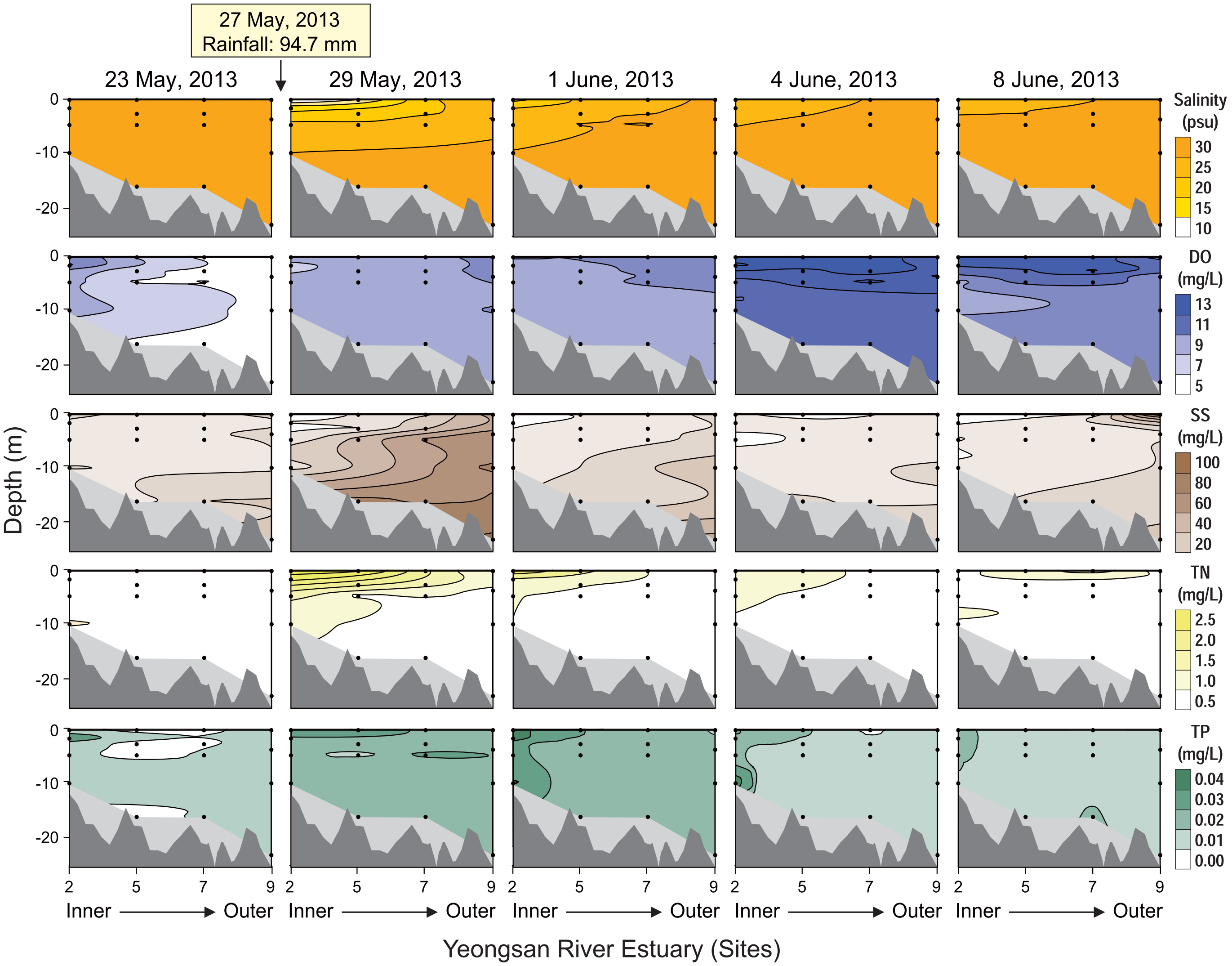


Fig. 3. Vertical profiles of five water quality variables, including salinity, dissolved oxygen (DO), suspended solids (SS), total nitrogen (TN), and total phosphorus (TP), along the estuary (from St. 2 to 9) during the five sampling periods (23rd and 29th May, and 1st, 4th and 8th June of 2011).

observed mostly during winter or spring sampling period.

4.3. Simulation

In order to estimate the flux and fate of water quality properties in the study area, an EFDC model was implemented in the Yeongsan River Estuary. As a first step, the model was calibrated finely to the 2011 observation data with respect to physical matters, for instance, hydrodynamics and hydrography. Then, the water quality model including the mass balance of the 21 state variables was simulated by use of the calibrated hydrodynamic model.

Fig. 5 shows the performance of the calibrated EFDC water quality model for the several water quality variables of interest in the estuarine section. The model data were averaged for the area between the Yeongsan dike and the red dashed line in Fig. 1. As similar, the observation data from the stations 2, 3, and 4. In general, the model seemed to provide a reasonable reproduction of observed data (Fig. 5). In the surface layer, there exist two significant blooming events in Chl-a concentration, one in June and the other during October to November. High concentrations in both total nitrogen and nitrate were recorded during May and July, which seemed to precede the blooming events. The seasonal variability of TOC showed two peaks in May and July, which was similar to that of nitrogen variables. The trend of total phosphorus and phosphate also showed a similar pattern to that of nitrogen nutrients, but the peak during May was relatively smaller. DO was higher during winter and spring and decreased with relatively low concentrations during summer. Seasonal variability of all these variables in the bottom layer were similar to those occurred in the surface layer, but the magnitude of each peak was small.

We examined the monthly net budget of salt, suspended sediments, DIN, and DIP during the simulation period, i.e., entire year 2011 (Fig. 6). Model results of hydrodynamics were combined with each water quality variables to estimate the net flux and flushing rate. Hydrodynamic results from the simulation (not shown in this paper) showed that two-layer estuarine circulation, whereby less saline surface water flows down-stream and more saline bottom water flows upstream, persisted during most of simulation period except January when fresh water was not discharged. Thus, the calculation was summarized into the budgets and fluxes of two layers based on the location of isopycnic boundary, $\sigma\theta = 19\ \mathrm{kg\ m^{-3}}$, to identify the surface and bottom layers. First, the salt flux calculation showed a net balance between the landward input of salt in bottom layer and the seaward outflux in the surface layer (Fig. 6).

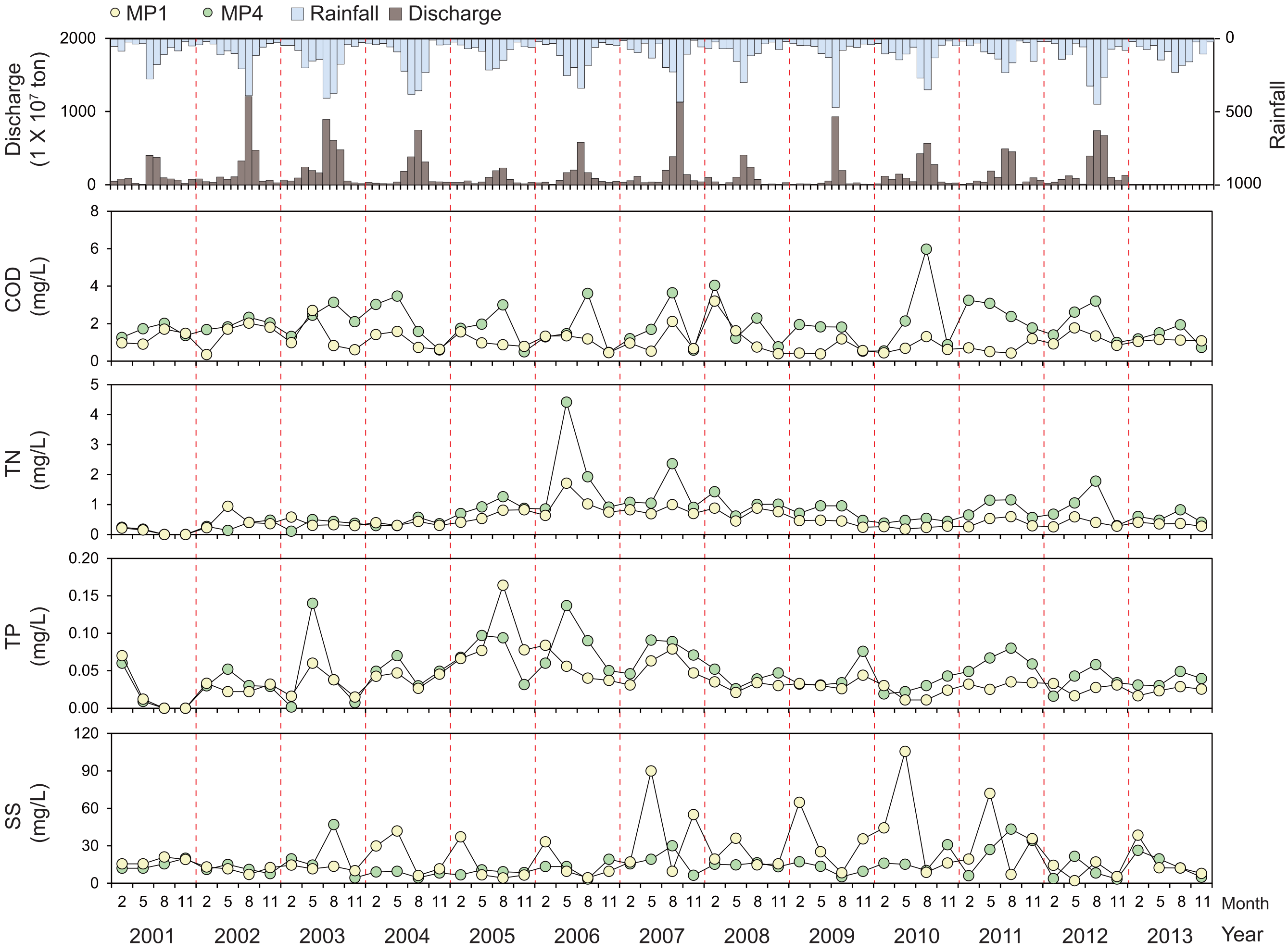


Fig. 4. Thirteen-year (2001–2013) seasonal time series data sets of freshwater discharge, chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and suspended solids (SS) in two sampling stations of the National Marine Environmental Monitoring of Korea.

In case of SS, the amount transported landward through the bottom layer was more than the down-estuarine flux at the surface layer during January to June and September to December, i.e., months other than summer. The dotted line in Fig. 6c, representing the accumulated SS flux over time, showed this net outflux of SS clearly. During summer flooding periods (July and August), the flux of SS increased up to almost 13 × 10^6 kg/month in the surface layer which was more than twice of outflux in the bottom layer, resulting in a net outflux during those two month periods. Since the effect of those two summer data overwhelmed the yearly flux, the integrated flux over a year was estimated as a net outflux of about 9.63 × 10^6 kg/month.

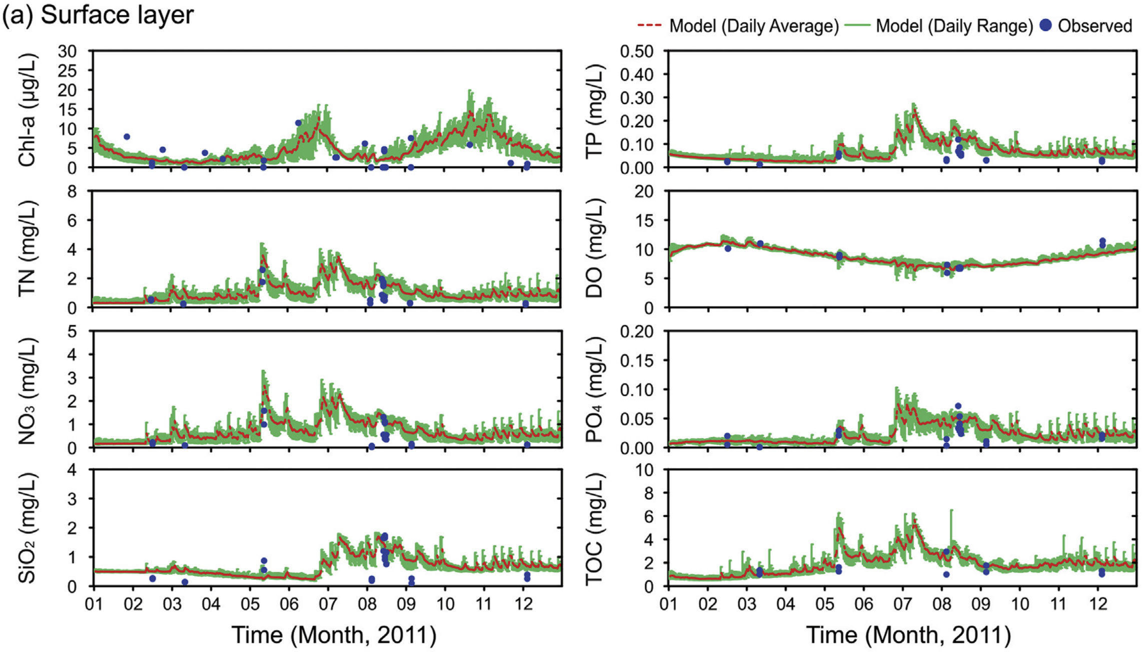
Fate of water quality variables in the study area is represented by the DIN and DIP fluxes (Fig. 6d and e). Similar to the pattern in SS, the fluxes of both DIN and DIP were also dominated by the behavior during summer months, i.e., July and August. DIN and DIP fluxes during those summer months showed strong outfluxes in the surface layer which were an order of magnitude higher than influxes in the bottom layer. Although the magnitudes were smaller during other seasons, the net fluxes of two layers showed consistently seaward over the entire year. The yearly integration of DIN and DIP fluxes reached up to seaward direction of 4.12 × 10^6 and 0.24 × 10^6 kg/month, respectively. A 56% and 75% fraction of DIN and DIP, respectively, was transported downstream during July and August.

In order to evaluate the exchange rate (i.e., flushing rate) of the Yeongsan estuary system, we conducted numerical dye experiments for the five experimental periods matching 2011 data collection. Passive and conservative dye was traced over 2-week period, which were analyzed to estimate the flushing rate and the surface water volume ratio. The results showed that lesser saline surface water, that must be related to the fresh water discharge from the dam, remained within Yeongsan River Estuary for 2–4 days (Fig. S2). The flushing rate was actually slower at higher discharge event probably because two-layer estuarine circulation was enhanced and the dye in bottom layers entrained in the surface layers.

5. Discussion

As shown in Fig. 2, the concentrations of several water quality variables in the artificial lake were significantly higher than those in the estuarine section. In particular, the nutrients levels including TN and TP were several times or sometimes even an order of magnitude greater in the lake than estuary. The most reasonable explanation for such high nutrient levels could be that those elevated nutrient concentrations represent excessive supply via riverine inputs that are trapped within the lake (e.g., Lohrenz et al., 1997; Dai et al., 2008). A stable environment with the enhanced supply of nutrients may then support excessive biological production of organic matters (OM, represented by TOC in our study) in the lake than other normal estuaries. Such high concentrations of

(a) Surface layer



(b) Bottom layer

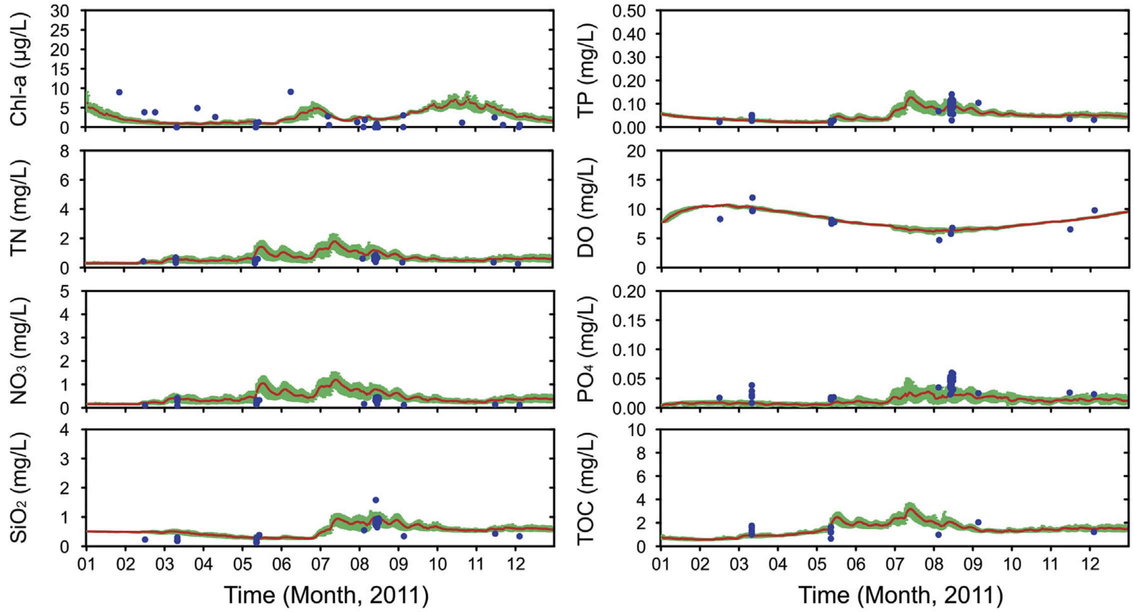


Fig. 5. Performance of the calibrated EFDC water quality model for eight variables, including chlorophyll-a (Chl-a), total nitrogen (TN), nitrate (NO_3), silicate (SiO_2), total phosphorus (TP), dissolved oxygen (DO), phosphate (PO_4), and total organic carbon (TOC) in surface and bottom waters during the entire year of 2011.

nutrient and TOC might be flushed out to the estuarine section when the dam discharge occured. It resulted in episodic events of elevated nutrient and TOC in the surface layer of the estuarine section as seen in our shipborn observation data sets (Figs. 2 and 3).

Our numerical simulation results showed a clear pattern of seasonal trend in the fluxes of several water quality variables. Fig. 6 shows the temporal and spatial variability of five water quality variables, where the peak fluxes occurred during July and August in the upper section of the estuary. The seasonal characteristics were consistent with the previous findings of Bang et al. (2013) and Cho et al. (2014) that the two-layer estuarine circulation is highly active during the summer high precipitation periods. One can note that, during summer, outfluxes of those nutrients and OM in the surface layer is several times greater than influxes of those matters in the bottom layer (Fig. 6), resulting in a net outflux of nutrients and OM in the estuarine section. This outflux pattern during summer dominated the magnitude of fluxes over a year, and thus net fluxes are directed seaward when integrated over the year (Fig. 6). The influx of DIN and DIP from the dyke and outflux of those variables at the estuary mouth were estimated along with the uptake of those nutrients by phytoplankton (Fig. S3). The larger fluxes of those nutrients compared to algal uptake during high-discharge summer period also support the findings. We believe that the net outfluxes of nutrients and OM in our study area is derived from the fact that there exists an artificial lake as part of estuarine system. After the artificial dam was constructed, riverine nutrient loading and eutrophication have been limited within the lake and these excessive nutrients might result in high biological production

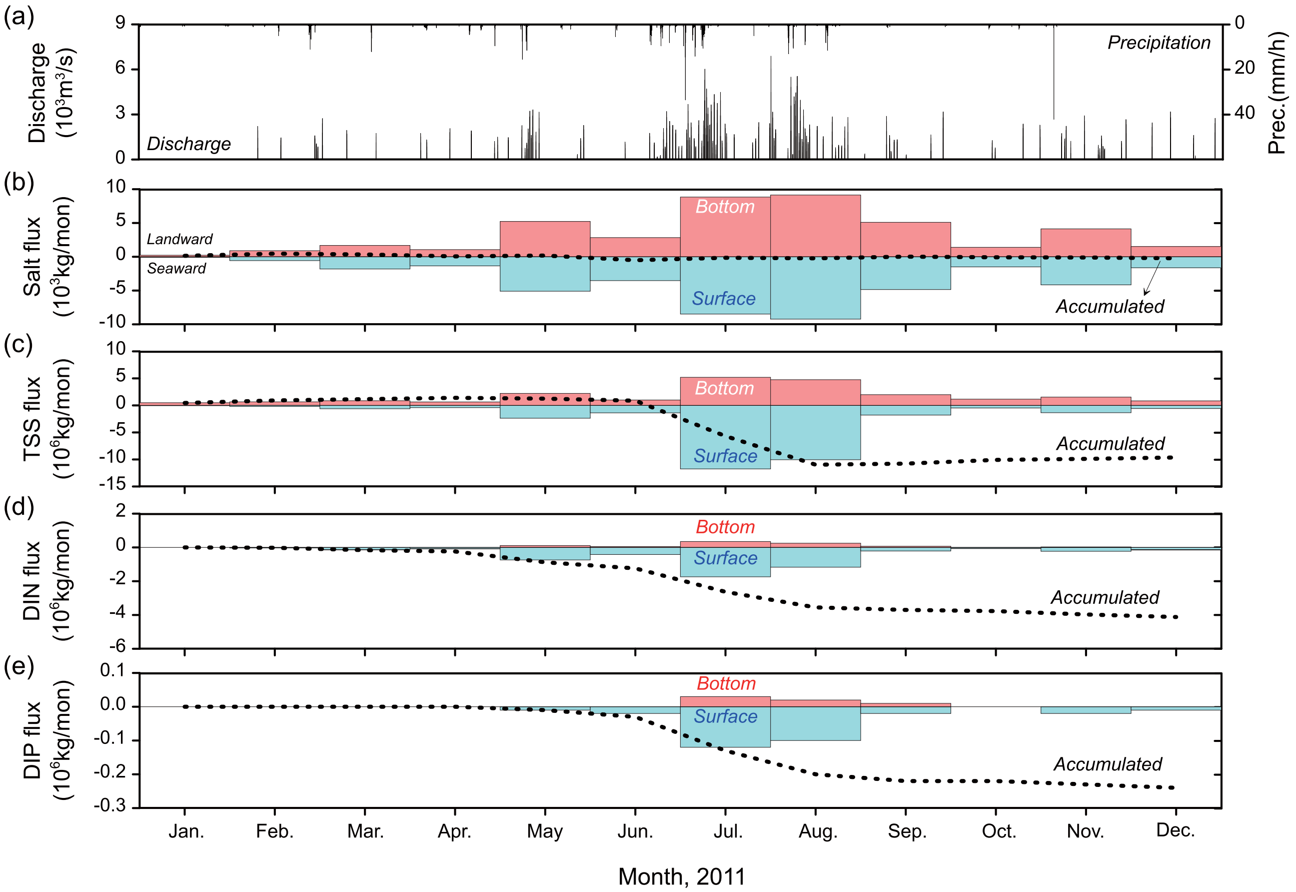


Fig. 6. Monthly net budget of salt, suspended solids (SS), dissolved inorganic nitrogen (DIN), and dissolved inorganic phosphorus (DIP) in the study area (see the location in Fig. 1) during the entire year of 2011. Temporal variation of precipitation and freshwater discharge are also presented.

inside the lake but not outside. These elevated nutrients and OM are flushed out to the estuarine section episodically, but other than those events the estuarine section is usually under lower concentrations of nutrients and OM during normal periods. This contrasts to findings from other natural estuarine systems, in which high sediment and nutrient loadings result in excessive biological production of OM and thus being considered as efficient carbon sink places (e.g., Lohrenz et al., 2008, 2010, 2013; Cai et al., 2011).

We can characterize the Yeongsan River Estuary as a system controlled mainly by two separate processes in the artificial lake and estuarine section. Extremely high loading of nutrients provides the extensive biological production of OM, resulting in elevated concentrations of nutrients and OM only in the lake but not in the estuarine section. Once the dam gate is open, however, this high concentration of nutrients and OM are discharged into the estuarine section, which can only be episodic. Our data from intensive observation program clearly showed this flushing processes right after the dam discharge (Fig. 3). The results in Fig. 3 depict that the water masses discharged from the lake, characterized by lower salinity and high concentration of nutrients, are diluted out quickly and the nutrients level get back to normal concentration within 5–10 days after the discharge event. Our numerical dye experiments provided the results that the water discharged from the dam remained in the estuarine section only during a few days, which also supported the findings of fast flushing rate. The flushing time in the Yeongsan River Estuary is too short to enhance biogeochemical processes including biological production even under the high nutrient loading. As such, an estuarine system combined with an artificial dam and lake, like Yeongsan River Estuary, cannot be act as an efficient carbon sink mainly due to that the relatively slow biogeochemical processes would not keep up with fast flushing rate even under elevated nutrient loading during high discharge events.

Recently, Cho et al. (2014) conducted a numerical dye study to show transport pattern in the Yeongsan River Estuary. They suggested a typical two-layer circulation during and after discharge event derives a strong up-estuary transport of neutrally-buoyant tracers in the bottom layer. Based on their findings, we might hypothesize that this landward transport pattern dominates the transport of water quality variables in the study area, which helps maintenance of higher nutrient concentrations supporting greater biological productivity. However, strong imbalance of nutrient concentration between surface (lower concentration) and bottom layers (higher concentration) seemed to result in opposite pattern of a net outflux of nutrient even during enhanced two-layer circulation periods (Figs. 2 and 3).

Although our numerical experiment results only cover a single year of data, we tried to extend our understanding to longer-term effect. Given the assumption that the circulation pattern in the Yeongsan River Estuary have been generally consistent for the past 10 years or so (at least after the construction of the dam), we can apply similar flushing pattern of nutrients and a proxy of OM (e.g., COD) to long-term monitoring data sets. The analysis of long-term monitoring data showed that a seasonal variability in nutrients and COD levels in the surface layer for the past 13 years was consistent with that found in our observation data (Fig. 4). Thus, our findings of fast flushing rate of nutrients and OM via surface outflow during summer (or high freshwater discharge period) can also be applicable for this long-term data. We can conclude that, at least after the artificial dam was constructed, the Yeongsan River Estuarine system does not support higher biological production nor plays an active role as a carbon sink.

6. Conclusions

We analyzed two different shipborne observation data sets along the Yeongsan River Estuary and in the lake inside an artificial dam and also a 13-year long data set from two monitoring stations in the very estuary. The results showed high concentrations of SS, nutrients, and OM at the station in the artificial lakes and lower concentrations in the estuarine section. When there exists a rainfall event and thus discharge occurs at the dam, water masses characterized by lower salinity and higher SS, nutrients, and OM are observed in the surface layer of the estuarine section. However, such lower salinity and high nutrient concentration only lasts short period of time of 5–10 days. Meantime, the hydrodynamic model results showed that the circulation in the estuarine section was governed by the freshwater discharge from the lake, whereby an enhanced two-layer estuarine circulation was dominant during and after the freshwater discharge, while well-mixed conditions occured during the remaining periods. Such two-layer estuarine circulation combined with the dynamic water quality model resulted in that the magnitude of outfluxes of nutrients in the surface layer outnumbered the influxes in the bottom layer during summer high precipitation periods. Since the fluxes during summer dominated the flux over a year, the yearly-integrated fluxes also showed strong outfluxes of nutrients rather than being remained and utilized in the estuarine system. Numerical dye experiment results also showed that the residence time of the water discharged from the dam in the estuarine section is only a few days, which was consistent with findings in the observation data. Due to this fast flushing rate, excessive nutrient loading from the lake cannot be used entirely to produce biological matters in the estuarine section. This limited biological productivity of the Yeongsan River Estuary, which has environments consisting of the lake and estuarine section divided by an artificial dam, hinders it from an active carbon sink, which was not the case for open estuaries.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.chemosphere.2017.04.085.

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<Supplementary Materials>

Seasonal variability of estuarine dynamics due to freshwater discharge and its influence on biological productivity in Yeongsan Estuary, Korea

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Supplementary Figures

Fig. S1. Changes of tidal flat areas during the last 30 years ((a) 1983, (b) 1988, (c) 1998, (d) 2007, and (e) 2011) in Yeongsan Esuary, Korea mapped using available satellite images (Landsat Archive Imagery).

Fig. S2. Time series of flushing rate (upper), surface layer water volume ratio (mid), and fresh water discharge (lower) in (a) March, (b) May, (c) August, (d) September, and (e) December, 2011 in Yeongsan Estuary, Korea.

Fig. S3. DIN and DIP fluxes at the Yeongsan dike and the estuary mouth, along with algal uptake.

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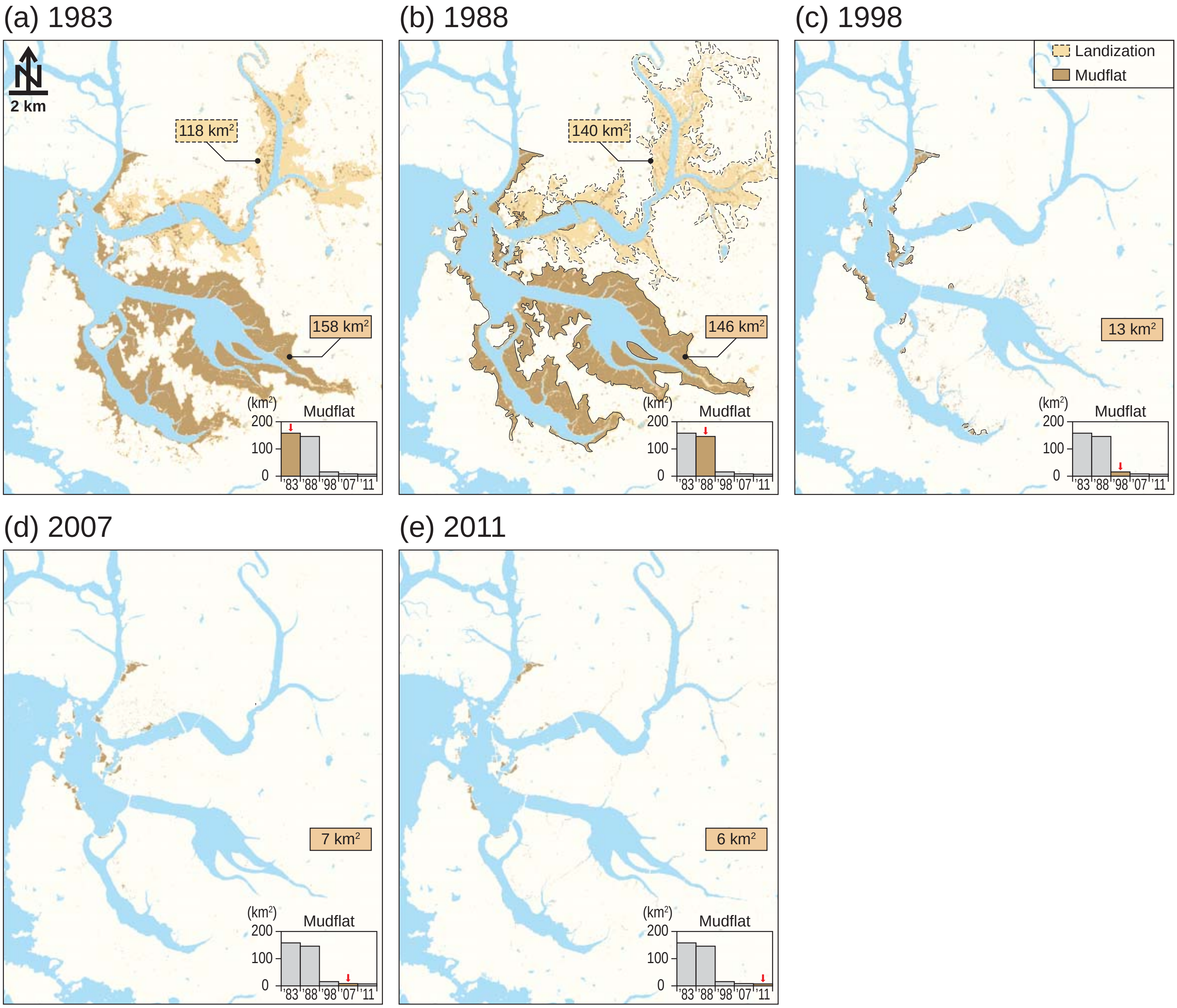
Figure S1.


(a) 1983

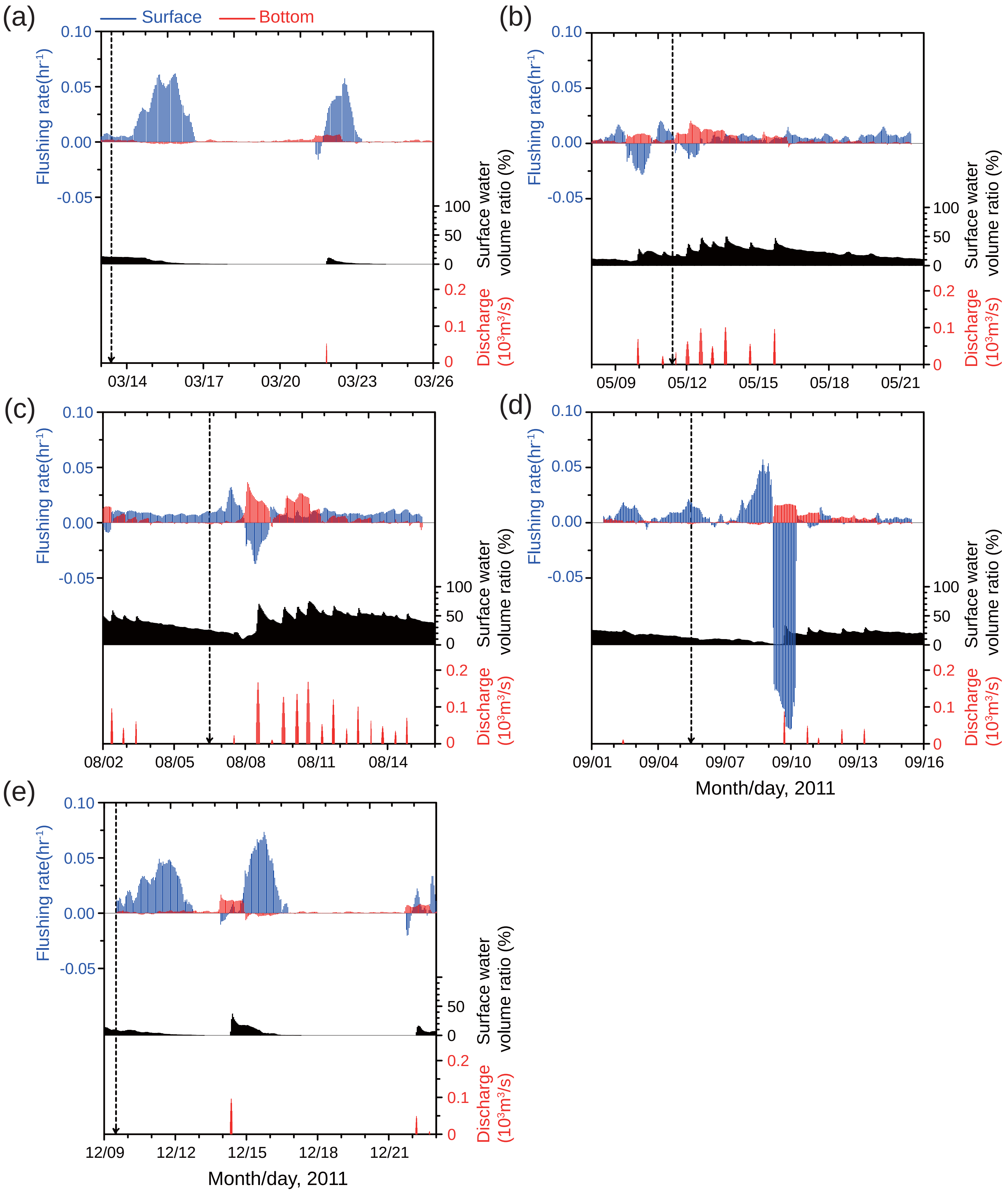
(b) 1988

(c) 1998

(d) 2007

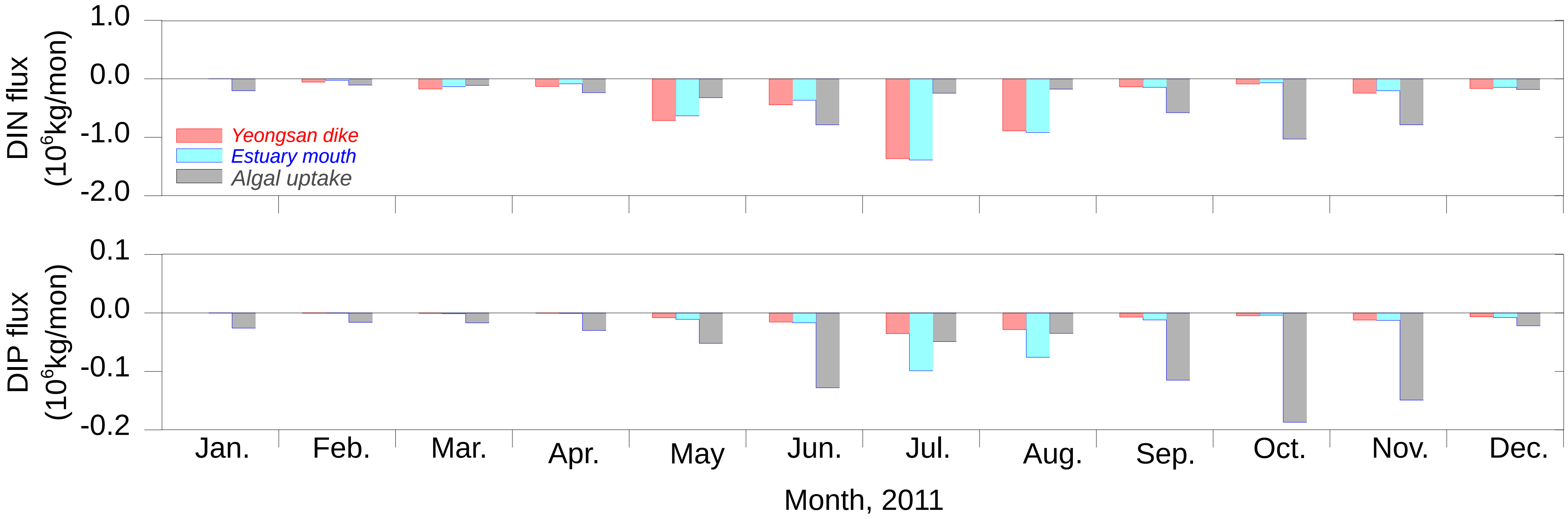
(e) 2011

Figure S2.



(a)
Surface
Bottom
Flushing rate(hr^{-1})
0.10
0.05
0.00
-0.05
Surface water volume ratio (%)
100
50
0
Discharge (10^{3}m^3/s)
0.2
0.1
0
03/14
03/17
03/20
03/23
03/26
(b)
05/09
05/12
05/15
05/18
05/21
(c)
08/02
08/05
08/08
08/11
08/14
(d)
09/01
09/04
09/07
09/10
09/13
09/16
Month/day, 2011
(e)
12/09
12/12
12/15
12/18
12/21
Month/day, 2011

Figure S3.



DIN flux
(10^6kg/mon)
1.0
0.0
-1.0
-2.0
Yeongsan dike
Estuary mouth
Algal uptake
DIP flux
(10^6kg/mon)
0.1
0.0
-0.1
-0.2
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month, 2011