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Phosphorus Mass Balance in a Highly Eutrophic Semi-Enclosed Inlet Near a Big Metropolis: A Small Inlet can Contribute towards Particulate Organic Matter Production

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Abstract

Terrigenous loading into enclosed water bodies has been blamed for eutrophic conditions marked by massive algal growth and subsequent hypoxia due to decomposition of dead algal cells. This study aims to describe the eutrophication and hypoxia processes in a semi-enclosed water body lying near a big metropolis. Phosphorus mass balance in a small inlet, Ohko Inlet, located at the head of Hiroshima Bay, Japan, was quantified using a numerical model. Dissolved inorganic phosphorous inflow from Kaita Bay next to the inlet was five times higher than that from terrigenous load, which may cause an enhancement of primary production. Therefore, it was concluded that not only the reduction of material load from the land and the suppression of benthic flux are needed, but also reducing the inflow of high phosphorus and oxygen depleted water from Kaita Bay will form a collective alternative measure to remediate the environmental condition of the inlet.

Key words

eutrophication, enclosed water body, hypoxia, phosphorus, sediment, sediment oxygen demand

1. Introduction

Eutrophication is one of the most serious environmental problems in enclosed water bodies wherein excessively high nutrient concentrations lead to massive growth of algae. Soon thereafter, dissolved oxygen (DO) levels drop due to the decomposition of dead cells, a process involving rapid DO consumption. The depletion of DO in the bottom layer of the water column badly affects the benthic ecosystem and presents negative impacts on the various aquaculture activities therein. Although terrigenous loading is usually the major cause of eutrophication in estuaries, "estuarine circulation" has been identified as another cause, which may affect the material cycle in estuaries (Yamamoto and Hashimoto, 2007).

Phosphorus and nitrogen are the major elements which enhance the growth of microalgae. Of these, phosphorus has the tendency to accumulate in sediments, behaving quite differently from nitrogen of which some part is released to the air by denitrification. Organic matter released from extensive phytoplankton blooms accumulates in sediments and consumes oxygen while undergoing decomposition processes. In addition to studies on the release rate of phosphate from sediments as affecting DO concentration (Ishikawa and Nishimura, 1989), phosphorus dynamics using numerical models have been studied for various estuaries (Dale and Prego, 2003; Falco et al., 2010; Su and Dong, 1999; Malmaeus et al., 2008; Wong et al., 2007).

The setting of this research is the Ohko Inlet, a small inlet located next to a small estuary, Kaita Bay, and both fringing the northern edges of the main estuary, Hiroshima Bay. Ohko Inlet receives only a small amount of terrigenous load, while Kaita Bay receives river discharge from the Seno River. Both have muddy sediments. Up until today, however, the manner as to how the inlet affects the material cycle in the estuary or vice versa is not known quantitatively. Issues related to material cycles cannot be understood and appreciated without numerical models because of so many processes interacting within the coastal ecosystems.

In this study, we describe the eutrophication and hypoxia processes in Ohko Inlet using a numerical model. In particular, we want to clarify the physico-chemical influence of the small inlet on the estuary next to it or vice versa. There are so many estuaries like Hiroshima Bay which are associated with small inlets lying next to big metropolitan areas around the world that are affected by eutrophication and hypoxia. Remediation measures to control eutrophication and hypoxia in the inlet derived from careful analyses of material budget and environmental relationship to the main estuary will provide information useful for the alleviation of eutrophication and hypoxia in estuaries.

2. Materials and methods

2.1. Study site

Ohko Inlet (34^{o} 21'N, 132^{o} 28' E, 0.047 km^2, 4 m avg. depth; 1.9×10^8 L) is located on the northern headwaters of Hiroshima Bay in the Seto Inland Sea, Japan (Fig. 1). The Seto Inland Sea is the largest enclosed sea in Japan surrounded by the main islands of Honshu, Shikoku and Kyushu. Seawater exchange rate in the Ohko Inlet is very low due to its isolated and peripheral location. Major terrigenous loads into this inlet are rain water and sewage. In times of heavy rain, however, the sewage partially overflows or is pumped out. The sediment of the inlet is highly muddy and anoxic, producing hydrogen sulfide. Blue water, which is the result of oxidation of hydrogen sulfide, is observed more than 50 times per year (Asaoka, 2009). Bottom water of the inlet is, as expected, hypoxic in summer. Kaita Bay

(34°21'N, 132°31'E, 6.4 km^2, 10 m avg. depth) is located next to the Ohko Inlet, receiving river discharge and whose sediment is also highly muddy and becoming hypoxic in the summer. One of the possible sources of nutrients is Kaita Bay located next to the Ohko inlet, since it is surrounded by industrial and residential areas.

2.2. Model framework

A model framework expressing phosphorus budget designed in this study is shown in Fig. 2. Input sources of dissolved inorganic phosphate (DIP) are the terrigenous load passing through the pumping station, those released from the sediment, including some which are regenerated by the decomposition of dissolved organic phosphorus (DOP) and detritus phosphorus (Det-P), and inputs from Kaita Bay as well. The DIP is taken up by planktonic or benthic micro algae (PMA-P or BMA-P).

DOP transported from the same sources as DIP is decomposed into DIP or some parts flow out to Kaita Bay. Particulate phosphorus such as PMA-P and detritus forms (Det-P) is also exchanged between the inlet and Kaita Bay. Solid matter from the pumping station is assumed to directly settle down to the sediment because their sinking rate is much faster than that of suspended particulate matter.

DO concentration is also calculated taking into account inputs to the inlet such as seawater intrusion from Kaita Bay and reaeration at the water surface. DO in the inlet is consumed by the decomposition of the suspended matter from the pumping station and suspended particles such as detritus, PMA, and BMA in the water column and benthic system. Sediment oxygen demand (SOD) is defined as the sum of oxygen demand required for decomposition of organic matter derived from BMA, settled suspended matter from the pumping station, detritus and PMA on the surface of the sediment.

STELLA (ver. 9.0.3; isee systems, inc.) was used for calculation.

2.3 Parameters used in this study

Parameters used in this study are summarized in Table 1. The values not described in the table were calculated or obtained from the data on sewage discharge recorded in the pumping station during the years 2005 to 2006 were obtained from the records of the Hiroshima City government office. Average seawater exchange rate (0.1 d^{-1}) is calculated on the basis of effluent water volume from the pumping station and seawater exchange rate of Kaita Bay located east of Ohko Inlet. Monthly monitoring data on concentrations of phosphorus, DO and water temperature in the Ohko Inlet and Kaita Bay were obtained from the government offices of Hiroshima City and Hiroshima Prefecture (Stn. 19), respectively.

Uptake of DIP by PMA and BMA was expressed with the Michaelis-Menten equation (Eq. 1) according to Dugdale (1967).

$$\rho = \rho_{\max} \times \frac{[DIP]}{Ks + [DIP]} \quad \cdot\cdot\cdot \text{(Eq. 1)}$$

ρ is nutrient uptake rate (pmol $cell^{-1}$ h^{-1}). ρ_{max} is the maximum uptake rate (pmol $cell^{-1}$ h^{-1}). $[DIP]$ is the DIP concentration in the ambient seawater water (μmol L^{-1}). K_s is the half-saturation constant (μmol L^{-1}) for DIP uptake.

Decomposition rate of DOP was expressed with Eq. 2 depending on water temperature (Suzuki, 2008).

$$DCt[DOPdecmp] = DC0[DOPdecomp] \times \exp(te \times T) \quad \cdot\cdot\cdot \text{(Eq. 2)}$$

DCt[*DOPdecomp*] is the decomposition rate of DOP to DIP at temperature t °C (day^{-1}) under aerobic or anaerobic condition. *DC0*[*DOPdecomp*] is decomposition rate of DOP to DIP at 0 °C (day^{-1}) under aerobic or anaerobic condition. *T* and *te* are water temperature (°C) and temperature coefficient, respectively. A similar equation to Eq. 2 was used for the decomposition process of particulate matter.

DO flux by reaeration was calculated following Fox equation (Eq. 3; Matsunashi et al., 1993).

$$D_r = \frac{k_a \cdot ([DO]_s - [DO])}{h_s} \quad \cdot\cdot\cdot \text{(Eq. 3)}$$

D_r is DO flux by reaeration. $[DO]_s$ is the saturated concentration of DO under the ambient seawater condition (mg m^{-3}). [DO] is the DO concentration (mg m^{-3}). k_a and h_s are the reaeration coefficient (-) and the depth of surface seawater affected by reaeration (m), respectively.

BMA-P and PMA-P are calculated on the basis of chlorophyll a (Chl*a*)/ carbon ratio and the Redfield ratio (Andersen, 1997). Observed Chl*a* concentrations in the Ohko Inlet and Kaita Bay were obtained from Suzuki (2008) and Hiroshima Prefecture (Stn. 19), respectively.

3. Results and discussion

3.1 Simulation of phosphate concentration and budget

The simulated DIP and dissolved total phosphorus (DTP; DIP+DOP) values corresponded well with observed values (Fig. 3). Estimated phosphorus budget of the Ohko Inlet was shown in Fig. 4. DIP inflow from Kaita Bay via seawater exchange was 5 times higher than the discharge from the pumping station. Although the discharge was initially believed to be a major source which has made the inlet eutrophic, however, it was clarified from the present calculation that the major source of DIP comes from seawater inflow from Kaita Bay located next to the inlet. About 90% of the DIP input into the inlet is transformed to PMA-P, and they outflow as particulate phosphorus. The amount of PMA-P outflow is twice higher than that of inflow from Kaita Bay. This can be the cause of eutrophication in Kaita Bay.

On the other hand, major DOP inflow was from the sediment, followed by discharge from the pumping station and internal loading from decomposition. As shown in Fig. 4, DIP input from Kaita Bay with seawater exchange is mainly used for primary production. Produced PMA-P is sedimented and transformed to DOP. Thus, the sediment in this inlet is significantly affected by organic phosphorus sedimentation, and consequently, the release flux of DOP from the sediment is higher than that of inflow from Kaita Bay.

The phosphorus release flux obtained in this model was 131 μmol m^{-2} d^{-1}. The high release flux of phosphorus from the sediment is attributed to the vigorous decomposition of BMA-P, evidenced by extreme negative values of ORP (-280 to -395 mV; Asaoka and Yamamoto, 2010). The value of phosphorus release flux from the sediment estimated in this study is consistent with the values reported for other eutrophic areas in the Seto Inland Sea, Japan (19 to 291 μmol m^{-2} d^{-1}; Ministry of Environment., 2003) and Tolo Harbour, Hong Kong (84 to 113 μmol m^{-2} d^{-1}; Chau, 2002).

3.2 Simulation of DO concentration and consumption

Simulated and observed DO concentrations are shown in Fig. 5. The simulated DO concentrations corresponded well with the observed values, decreasing during the summer stratified season. Percent contribution of each decomposition process towards DO consumption is shown in Fig. 6. Almost all the DO (more than 97 to 99%) were those from the decomposition of PMA dead cells occurring throughout the year. Calculated SOD is shown with observed Chl*a* concentration (Suzuki, 2008) in Fig. 7. The DO depletion in summer is likely to be caused by decomposition of PMA which bloomed in the spring. The SOD (5.8 to 270 mg O_2-m^{-2} d^{-1}) obtained in this study agreed well with those reported for the SOD in Hiroshima Bay (100 to 610 mg O_2-m^{-2} d^{-1}; Seiki et al., 1994) to which the Ohko Inlet is facing.

3.3 Controlling eutrophication and hypoxia

In order to propose measures for the alleviation of eutrophication in the Ohko Inlet, sensitivity analysis was conducted at various cut down levels of TP from terrigenous, benthic flux and inflow from Kaita Bay (Fig. 8). Cutting down of inflow from Kaita Bay, regulating benthic load and terrigenous load show effectiveness (in order of decreasing magnitude) in controlling TP concentrations in the inlet. The calculations from the sensitivity analyses showed that the complete suppression of each point source, namely terrigenous, benthic, and Kaita Bay will effectively alleviate TP concentrations. This will translate into total phosphorus (TP) concentration decreasing by 21, 24 and 29% corresponding to 1.41, 1.37 and 1.28 μmol L^{-1}, respectively. Cutting down DTP inflow from Kaita Bay to decrease the concentration of TP in the inlet would be comparable to cutting down the terrigenous load. However, the TP concentration at this stage still exceeds the defined level of eutrophication (0.02 mg P L^{-1}).

The response of the DO concentration in the bottom water of the inlet was also calculated as a result of reductions of terrigenous load, benthic flux and inflow from Kaita Bay (Fig. 9). The lowest DO concentration in the summer season did not increase more than 2.9 mg L^{-1} with no significance among all cut down parameters.

The other possible reason as to why the DO concentration in the Ohko Inlet did not recover is the inflow of oxygen depleted water from Kaita Bay. According to data from the Fisheries Agency, DO concentration in the bottom waters of Kaita Bay in the summer of 2006 was 2.4 mg L^{-1}. In the case of inflow reduction from Kaita Bay calculated above, the value might underestimate DO recovery in the inlet because some remediation measures working in the Kaita Bay environment would accelerate the DO concentration recovery in Kaita Bay waters and this will subsequently work better towards the recovery of DO concentration in the Ohko Inlet.

From the sensitivity analyses conducted above, it is clearly understood that alleviation of hypoxia in the Ohko Inlet cannot be accomplished alone by the reduction of terrigenous load and the improvement of the sediment quality in the inlet. It is also necessary to improve environmental conditions in Kaita Bay whose water inflows into the Ohko Inlet.

4. Conclusion and suggestion

In the present study, the major path of phosphorus into the Ohko Inlet has been established as starting with DIP input from Kaita Bay and its transformation to PMA-P and its subsequent deposition to the bottom. Thus, the sediment also supplies a ready source of DIP and DOP to the water column. The decomposition of the PMA-P from dead algal cells is the major contributor to SOD. Furthermore, the combined outputs of DOP and PMA-P were higher than the inputs from Kaita Bay. Thus, the Ohko Inlet serves as a phosphorus source to Kaita Bay and Hiroshima Bay as well. DO depletion in the inlet is mainly caused by PMA decomposition. However, recovery of DO level will not be accomplished by 100% reduction of terrigenous load and the suppression of the benthic flux by covering of the sediment surface with sand because the inflow from Kaita Bay is also oxygen depleted. Therefore, to alleviate hypoxia in the Ohko Inlet, it would be necessary not only to reduce terrigenous load and implement remediation measures on the sediments in the inlet but also to restore the clean environmental condition of Kaita Bay, because it is also the material source to the inlet in addition to its supply of DO depleted water. For example, remediation of the organically enriched sediment in Kaita Bay would be an alternative and indirect restoration measure of the environmental condition of the Ohko Inlet.

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Fig. 1 Map showing the Ohko Inlet. The study site is indicated with a box.

Fig. 2 Model framework presenting phosphorus budget of the Ohko Inlet.

Fig. 3 Simulated seasonal variation in DTP and DIP with the observed values in Ohko Inlet.

Fig. 4 Phosphorus budget of the Ohko Inlet calculated using the present model..

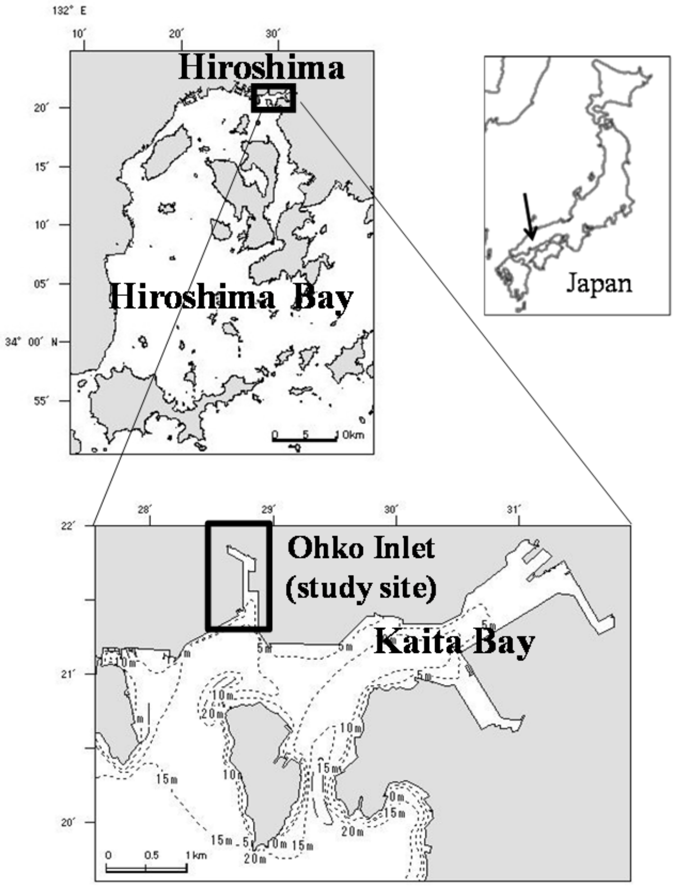
Fig. 5 Seasonal variation in DO concentration calculated with the present model with the observed DO concentrations in the Ohko Inlet

Fig.6 %-contribution of each decomposition process towards DO consumption.

Fig. 7 Simulated sediment oxygen demand (SOD) and observed chlorophyll *a* concentrations.

Fig.8 Estimated TP concentrations of the Ohko Inlet water responding to cut down of each TP source (terrigenous load, benthic flux, and inflow from Kaita Bay

Fig.9 Estimated lowest DO concentrations of the Ohko Inlet responding to cut down of each TP source (terrigenous load, benthic flux, and inflow from Kaita Bay



Hiroshima
Hiroshima Bay
Japan
Ohko Inlet
(study site)
Kaita Bay

Fig. 1

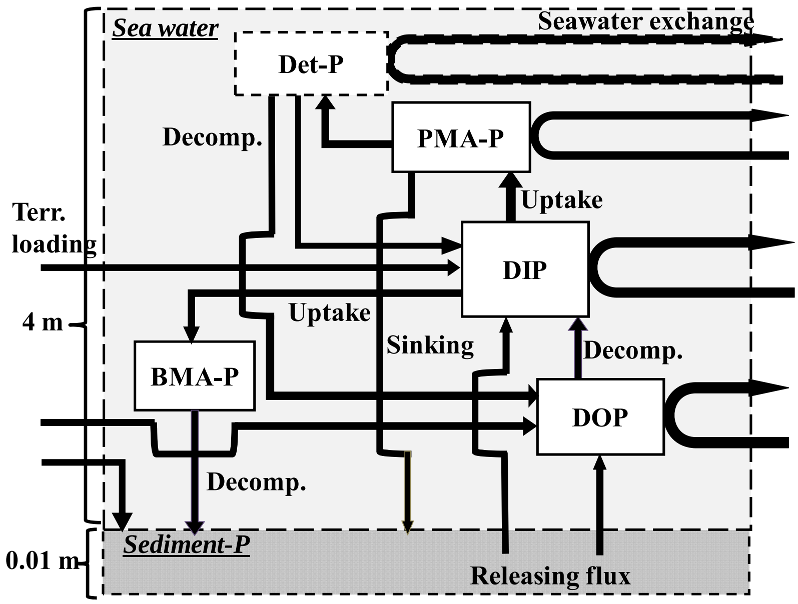
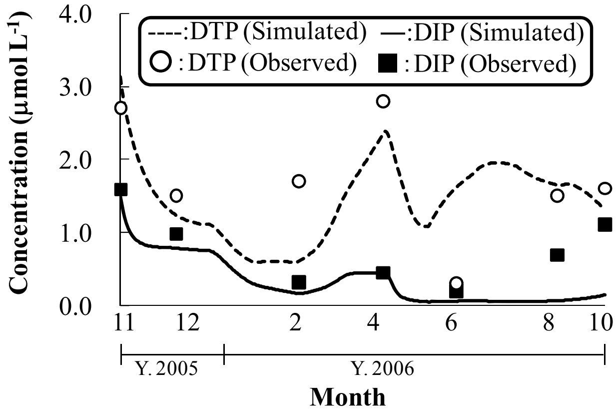
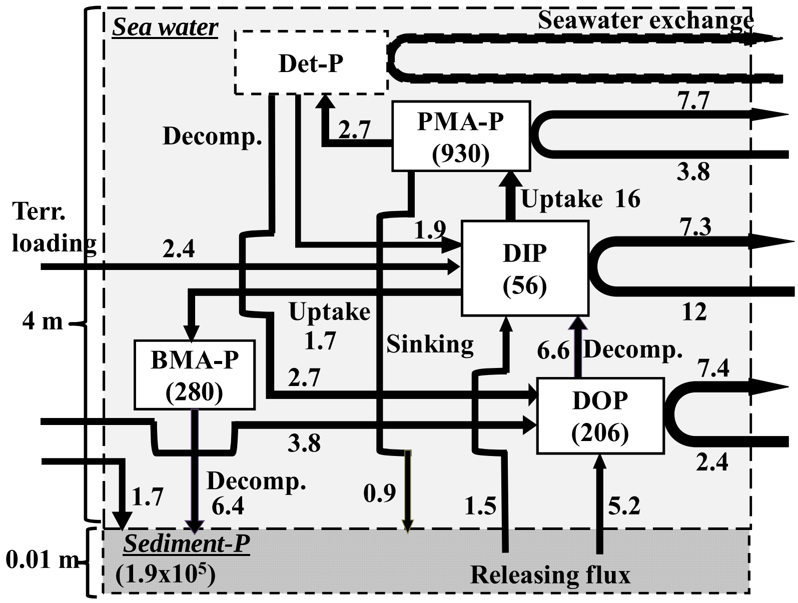

Sea water
Seawater exchange
Det-P
Decomp.
PMA-P
Uptake
Terr. loading
DIP
Uptake
4 m
Sinking
Decomp.
BMA-P
DOP
Decomp.
Sediment-P
0.01 m
Releasing flux

Fig. 2



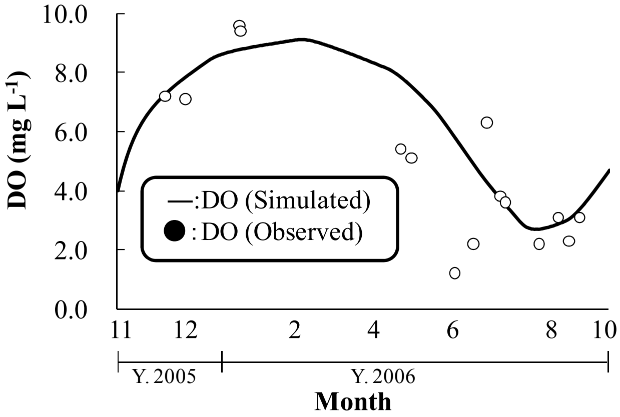
Concentration (μmol L-1)
4.0
3.0
2.0
1.0
0.0
----:DTP (Simulated)
—:DIP (Simulated)
○ : DTP (Observed)
■ : DIP (Observed)
11
12
2
4
6
8
10
Y. 2005
Y. 2006
Month

Fig. 3



Stock: mol inlet^{-1}; Flow : mol d^{-1} inlet^{-1}

Fig. 4



DO (mg L-1)
10.0
8.0
6.0
4.0
2.0
0.0
—:DO (Simulated)
●:DO (Observed)
11
12
2
4
6
8
10
Y. 2005
Y. 2006
Month

Fig. 5

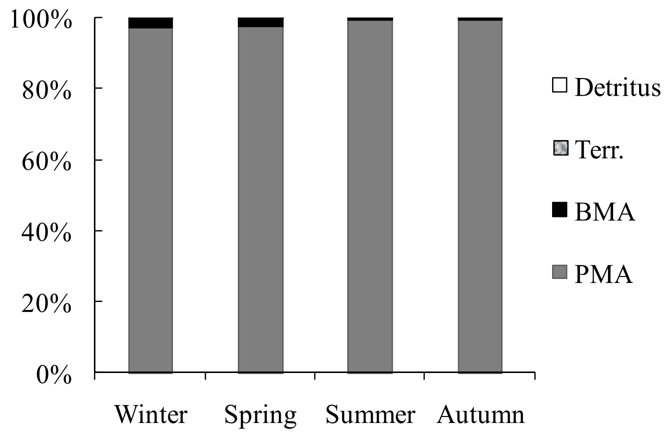
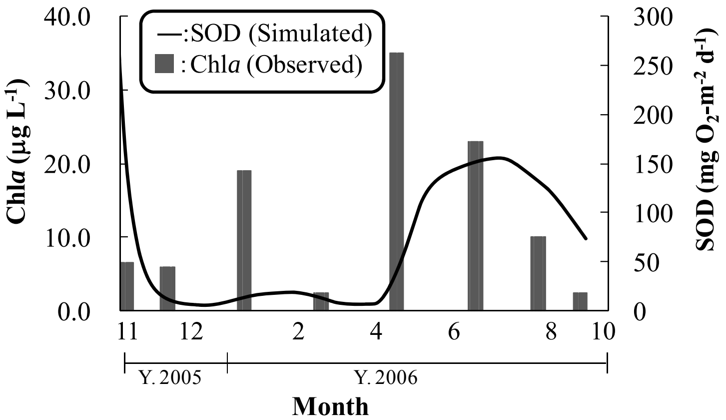
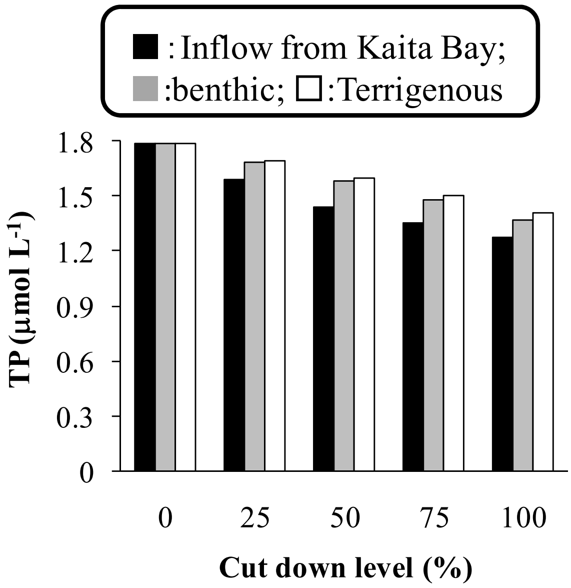

100%
80%
60%
40%
20%
0%
Winter
Spring
Summer
Autumn
Detritus
Terr.
BMA
PMA

Fig.6



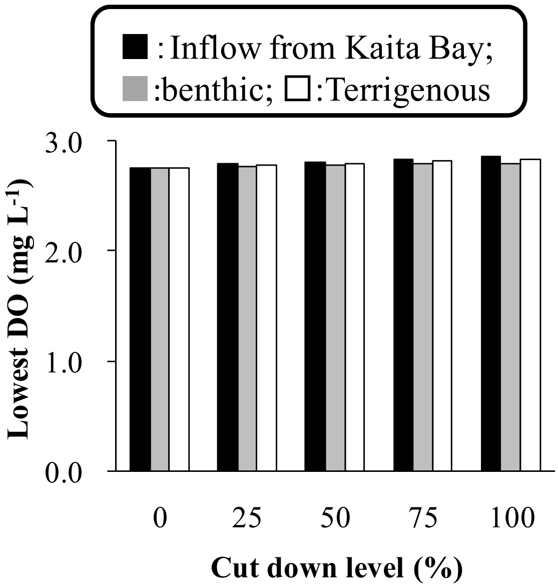
40.0
30.0
20.0
10.0
0.0
Chla (μg L-1)
—:SOD (Simulated)
: Chla (Observed)
300
250
200
150
100
50
0
SOD (mg O2-m-2 d-1)
11
12
2
4
6
8
10
Y. 2005
Y. 2006
Month

Fig. 7



: Inflow from Kaita Bay;
:benthic; :Terrigenous
1.8
1.5
1.2
0.9
0.6
0.3
0
TP (µmol L-1)
0
25
50
75
100
Cut down level (%)

Fig.8



: Inflow from Kaita Bay;
:benthic; :Terrigenous
3.0
2.0
1.0
0.0
Lowest DO (mg L-1)
0
25
50
75
100
Cut down level (%)

Fig.9

Table 1 The parameters used in this model

Decomposition rate of PP to DOP at 0℃ at aerobic condition	0.006 d^{-1}	Wang et al. (2003)
Decomposition rate of PP to DOP at 0℃ at anaerobic condition	0.0008 d^{-1}	Wang et al. (2003)
Decomposition rate of PP to DIP at 0℃ at aerobic condition	0.005 d^{-1}	Wang et al. (2003)
Decomp. rate of DetP to DOP at 0℃ under the aerobic condition	0.006 d^{-1}	Wang et al. (2003)
Decomp. rate of DetP to DOP at 0℃ under the anaerobic condition	0.0008 d^{-1}	Wang et al. (2003)
Decomp. rate of DetP to DIP at 0℃ under the aerobic condition	0.005 d^{-1}	Wang et al. (2003)
Decomp. rate of DetP to DIP at 0℃ under the anaerobic condition	0.0005 d^{-1}	Wang et al. (2003)
Decomp. rate of DOP to DIP at 0℃ under the aerobic condition	0.005 d^{-1}	Wang et al. (2003)
Decomp. rate of DOP to DIP at 0℃ under the anaerobic condition	0.0005 d^{-1}	Wang et al. (2003)
Harf-saturation constatnt for DIP uptake of BMA	61.2 µM	Suzuki (2008)
Harf-saturation constatnt for DIP uptake of PMA	0.68 µM	Tarutani et al. (1994)
Sinking rate of PMA-P	0.25 d^{-1}	Sugihara et al. (2004)
SS-P flux from the oumping station	36 mmol m^{-2} d^{-1}	Paramater fitting
DOP benthic flux from sediment	110 µmol m^{-2} d^{-1}	Paramater fitting
DIP benthic flux from sediment	31 µmol m^{-2} d^{-1}	Yamamoto et al. (1998)
Reaeration coefficient	0.15	Matsunashi et al. (1993)
Water depth	4 m	Suzuki (2008)