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Development and Application of the Ecosystem Model in Brackish Lake Obuchi, Japan

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In order to evaluate the water quality (N, P and C) and the biological mass balance of semi-enclosed brackish Lake Obuchi, Japan, an ecosystem model was developed and applied to the lake, using the flow field calculated by a hydrodynamic model. The time series data of the observed tide level, river discharge and meteorological parameters from January 2001 to December 2002 were incorporated as the parameters of the hydrodynamic model. Water quality and biomass balance were estimated by the ecosystem model, and simulated fluctuations in water quality agreed with our observations. The carbon contents of POC, phytoplankton and zooplankton in the lake were calculated by the model at an average 7200, 1500 and 22 kg, respectively, which somewhat agreed with our observations of POC (5900 kg), phytoplankton (3800 kg), and zooplankton (150 kg).

Key words : brackish Lake Obuchi, ecosystem model, water quality, butrient, material flux

INTRODUCTION

Brackish Lake Obuchi, located in Aomori Prefecture in northern Japan, has an area of 3.7 km^2, a mean depth of 2.5 m, and a maximum depth of 4.5 m. The Obuchi River connects the lake to the Pacific Ocean. Water quality of the lake is of the mesotrophic type. At the center of the lake, the salinity is 10-15 psu in the surface layer and 20-30 psu in the bottom layer, with the halocline at a depth of 1-3 m throughout the year (Ueda *et al.*, 2002). Since there are fluctuations of salinity and water currents due to tide levels fluctuating continually in the brackish area, the behavior of the substances appeared to be complex. The authors (Ueda *et al.*, 2004a) developed a 3D-hydrodynamic model for Lake Obuchi, which allowed us to simulate salinity and water currents, making it possible to obtain a good correspondence with the observation data.

The ecosystem model in Lake Obuchi constructed for this study provided a comparative verification between our calculations and our observation results, while also simulating the material balance of phosphorus, nitrogen and carbon.

MATERIALS AND METHODS

General description of model

The numerical model (Fig. 1) employed in this study is essentially the same as the one described by Taguchi *et al.* (1999). The model was deve-

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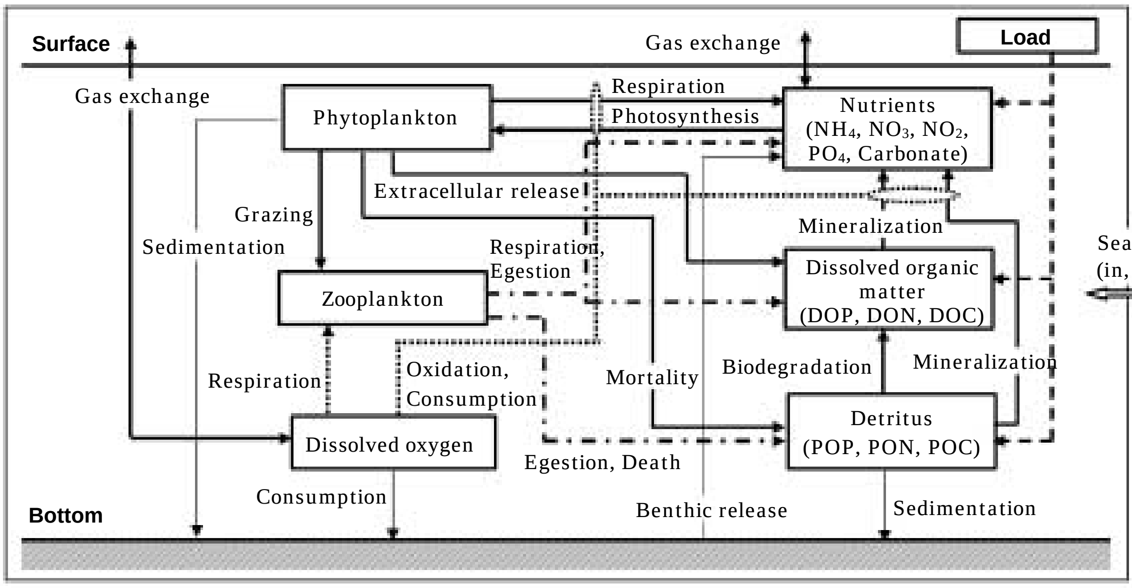

Fig. 1. Schematic view of the ecosystem model.

Table 1. Condition of twenty boxes for the ecosystem model in Lake Obuchi.

	Number of vertical layer													
	L1 (0−1 m)		L2 (1−1.5 m)		L3 (1.5−2 m)		L4 (2−2.5 m)		L5 (2.5−3 m)		L6 (3−4 m)		L7 (>4 m)	
	volum	area	volum	area	volum	area	volum	area	volum	area	volum	area	volum	area
Box−1	321	413	102	255	67	143	38	110	18	43	5	25	−	−
Box−2	314	375	120	283	93	203	49	150	18	45	4	20	−	−
Box−3	396	440	149	385	97	203	80	180	67	140	39	128	−	−
Box−4	289	330	123	273	103	213	91	195	79	168	33	130	−	−
Box−5	517	690	171	385	148	300	132	280	117	250	114	210	9	38
Box−6	550	630	245	500	236	478	229	463	220	450	306	415	53	180
Box−7	366	648	71	190	47	103	29	80	12	35	3	13	−	−
Box−8	54	85	13	35	2	8	−	−	−	−	−	−	−	−
Box−9	46	75	8	25	−	−	−	−	−	−	−	−	−	−
Box−10	85	168	19	63	3	8	1	5	−	−	−	−	−	−
Box−11	211	243	101	203	101	203	100	203	99	198	190	198	144	188
Box−12	540	568	266	533	266	533	266	533	266	533	533	533	1,872	533
Total	3,688	4,663	1,386	3,128	1,163	2,390	1,014	2,198	896	1,860	1,225	1,670	2,078	938

* Units of volum and area are $\times 10^3\,m^3$ and $\times 10^3\,m^2$, respectively.

loped to evaluate the physical−biological interactions in an estuarine lower−trophic ecosystem in terms of its phosphorus, nitrogen and carbon cycles. The ecosystem model was of the box type (Fig. 2), being divided horizontally into 12 boxes and vertically into 7 layers (Table 1). The flow fields for the ecosystem model were calculated by a hydrodynamic model. The time series data of the observed tide level, river discharge and meteorological parameters from April 2001 to December 2002 were incorporated as the parameters of the hydrodynamic model.

The basic formula of the physical processes of diffusion, outflow and inflow in our ecosystem model is:

$$\frac{\partial}{\partial t} h \cdot S \cdot C = J_{in}\, C_{in} - J_{out} C + \mathrm{L} + H_{diff} + W_{adv} + W_{diff}$$

where h = thickness of each layer, S = surface area of each box, C = concentration of water qua-

Table 2. Parameterization of the biochemical process.

Biochemical process — Formulation

[Phytoplankton (Chlorophyll−*a*)]

$$\frac{\partial}{\partial t} Chla \cdot V = (Photosynthesis)-(Extracellular\ release)-(Respiration)-(Natural\ mortality)-(Sedimentation)-(Grazing)$$

1. *Photosynthesis*

$$v_{\max}\frac{PO_4{-}P}{PO_4{-}P+K_{IP}}\ \frac{TIN}{TIN+K_{IN}}\left(\frac{T}{T_{opt}}\right)\left(\exp\left(1-\frac{T}{T_{opt}}\right)\right)^n\left(\frac{I}{I_{opt}}\right)\left(\exp\left(1-\frac{I}{I_{opt}}\right)\right)ChlaV$$

2. *Extracellular release*
   $\delta(Photosynthesis)$
3. *Respiration*
   $R_0 \exp(R_t\ T)\ ChlaV$
4. *Natural mortality*
   $M_0 \exp(M_t\ T)\ ChlaV$
5. *Sedimentation*
   $Schla\ Chla\ S$
6. *Grazing*
   $g_{max}(1-\exp\lambda(C_{cr}-C_{chla}))Zoo$

[Zooplankton]

$$\frac{\partial}{\partial t} Zoo\quad V=(Grazing)-(Egestion)-(Natural\ mortality)$$

1. *Grazing*
   $g_{max}(1-\exp\lambda(C_{cr}-C_{chla}))Zoo$
2. *Egestion*
   $(Grazing)\ (1-\beta_0)$
3. *Natural mortality*
   $D_0 \exp(D_t\ T)\ ChlaV$

[TP, total phosphorus]

$$\frac{\partial}{\partial t} POP \cdot V=(Mortality\ of\ phytopla.)\ \gamma_{CChla}/\gamma_{CN}/\gamma_{NP}+(Egestion\ of\ zoopla.+Mortality\ of\ zoopla.)/\delta_{CN}\cdot\delta_{NP}-(Decomposition)-(Sedimentation)+(Load)$$

$$\frac{\partial}{\partial t} DOP \cdot V=(Extracellular\ release)\cdot\gamma_{CChla}/\gamma_{CN}/\gamma_{NP}+(Decomposition\ of\ POP)-(Mineralization)+(Load)$$

$$\frac{\partial}{\partial t} PO_4{-}P \cdot V=-(Photosynthesis-Respiration\ of\ phytopla.)\ \gamma_{CChla}/\gamma_{CN}/\gamma_{NP}+(Egestion\ of\ zoopla.)/\delta_{CN}\cdot\delta_{NP}+(Decomposition\ of\ POP)+(Mineralization)+(Benthic\ release)+(Load)$$

[TN, total nitrogen]

$$\frac{\partial}{\partial t} PON \cdot V=(Mortality\ of\ phytopla.)\cdot\gamma_{CChla}/\gamma_{CN}+(Egestion\ of\ zoopla.+Mortality\ of\ zoopla.)/\delta_{CN}-(Decomposition)-(Sedimentation)+(Load)$$

$$\frac{\partial}{\partial t} DON \cdot V=(Extracellular\ release)\gamma_{CChla}/\gamma_{CN}+(Decomposition\ of\ PON)-(Mineralization)+(Load)$$

$$\frac{\partial}{\partial t} TIN \cdot V=-(Photosynthesis-Respiration\ of\ phytopla.)\cdot\gamma_{CChla}/\gamma_{CN}+(Egestion\ of\ zoopla.)/\delta_{CN}+(Decomposition\ of\ PON)+(Mineralization)+(Benthic\ release)+(Load)$$

Parameters		Unit
$PO_4{-}P$	: phosphate	mg L^{-1}
POP	: particulate organic phosphorus	mg L^{-1}
DOP	: dissolved organic phosphorus	mg L^{-1}
PON	: particulate organic nitrogen	mg L^{-1}
DON	: dissolved organic nitrogen	mg L^{-1}
TIN	: total inorganic nitrogen	mg L^{-1}
OM	: concentration of organic matter	mg L^{-1}
POM	: particulate organic matter	mg L^{-1}
POC	: particulate organic carbon	mg L^{-1}
DOC	: dissolved organic carbon	mg L^{-1}
C_{hla}	: chlorophyll−*a*	mg L^{-1}
v_{max}	: maximum growth rate	1.2 d^{-1}
K_{IP}	: half saturation constant of phosphorus	0.003 mg L^{-1}
K_{IN}	: half saturation constant of nitrogen	0.006 mg L^{-1}
n	: 1−3	
T	: water temperature	°C
T_{opt}	: optimum water temperature	20°C
I	: Irradiance	MJ $m^{-2}\ d^{-1}$
I_{opt}	: optimum irradiance	8MJ $m^{-2}\ d^{-1}$
V	: volum of box	m^3
V_t	: total volume	$9.04\times10^6\ m^3$
S	: area of box	m^2
S_t	: total area	$3.5\times10^6\ m^2$
δ	: ratio for the photosynthesis	
R_0	: respiration rate at 0°C of phytoplankton	0.005 d^{-1}
R_t	: water temperature dependence coefficient of respiration rate of phytoplankton	0.0693°C^{-1}
M_0	: mortality rate at 0°C of phytoplankton	0.05 d^{-1}
M_t	: water temperature dependence coefficient motality rate of phytoplankton	0.0693°C^{-1}
$Schla$	: sedimentation rate of phytoplankton	0.1 m d^{-1}
g_{max}	: maximum grazing rate	0.3 exp (0.0693t)d^{-1}
[1] λ	: Ivlev's coefficient	7
C_{cr}	: threshold value of grazing	0.07 mgC L^{-1}
β_0	: gross growth efficiency	0.3
D_0	: mortality rate at 0°C zooplankton	0.05
D_t	: water temperature dependence coefficien of motality rate of zooplankton	0.0693°C^{-1}
γ_{CChla}	: ratio of Carbon/Chla in phytoplankton	38
γ_{CN}	: ratio of Carbon/nitrogen in phytoplankton	2.8
γ_{NP}	: ratio of nitrogen/phosphorus in phytoplankton	11
δ_{CChla}	: ratio of Carbon/Chla in zooplankton	
δ_{CN}	: ratio of Carbon/nitrogen in zooplankton	2.8
δ_{NP}	: ratio of nitrogen/phosphorus in zooplankton	11
α	: ratio of photosynthesis/(oxygen production) in phytoplankton	4.3
β	: ratio of (decomposition of C)/(oxygen consumption)	4.3
λ_0	: decomposition rate at 0°C	N : 0.006 d^{-1} P : 0.008 d^{-1} C : 0.001 d^{-1}

Table 2. Continued.

Biochemical process	Formulation	Parameters	Unit
[TOC, total nitrogen]			
$\frac{\partial}{\partial t} POC \cdot V =$	$(Mortality\ of\ phytopla.) \cdot \gamma_{CChla} + (Egestion\ of\ zoopla. + Mortality\ of\ zoopla.) - (Decomposition) - (Sedimentation) + (Load)$	λ_t : water temperature dependence coefficient of decomposition rate	0.0693°C^{-1}
		Sv : sedimentation rate of particulate	N : 0.1, P : 0.1, m d^{-1} C : 0.1
$\frac{\partial}{\partial t} DOC \cdot V =$	$(Extracellular\ release) \cdot \gamma_{CChla} + (Decomposition\ of\ POC) - (Mineralization) + (Load)$	dos_0 : rate of oxygen consumption at 0°C	0.2 g m^{-2} d^{-1}
[DO, dissolved oxygen]		dos_t : water temperature dependence coefficient of oxygen consumption releas at °C	0.0693°C
$\frac{\partial}{\partial t} DO \cdot V =$	$(Photosynthesis - Respiration) \cdot \alpha + (Egestion\ of\ zoopla.)\beta - (Decomposition\ of\ particulate + Mineralization)\beta + (Oxygen\ consumption) + (Gas\ exchange)$	rel_0 : rate of oxygen release at 0°C	0.2 g m^{-2} d^{-1}
		rel_t : water temperature dependence coefficient of oxygen release rate	0.0693°C^{-1}
	1. *Decomposition of particulate* (*Mineralization*) $\lambda_0\ exp\ (\lambda_t\ T)\ OM \cdot V$		
	2. *Sedimentation of particulate* $Sv \cdot POM \cdot S$		
	3. *Oxygen consumption* $dos_0\ exp\ (dos_t\ (T - T_0))\ S$		
	4. *Benthic release* $rel_0\ exp\ (rel_t(T - T_0))\ S$		

[1)]Ivlev (1945)

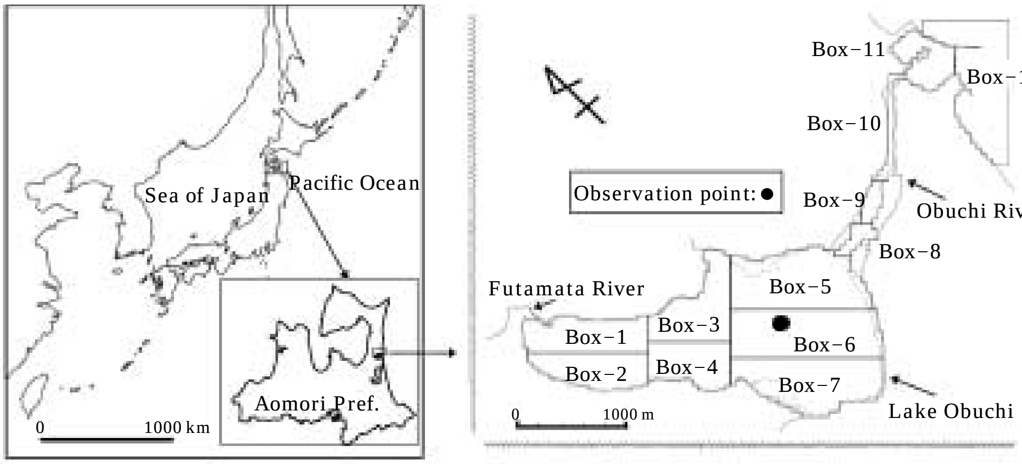

Fig. 2. Calculated boxes and partition grids in Lake Obuchi.

lity, C_{in} = concentration of water quality in inflow, J_{in} = volume of inflow, J_{out} = volume of outflow, L = inflow load, H_{diff} = horizontal diffusion quantity, W_{adv} = vertical advection quantity, and W_{diff} = vertical diffusion quantity.

Table 2 shows the basic formula for the chemical−biological process. The nutrient load was determined by the emission (load) factor method based on a report (Rokkasho Village, 2002) on land usage in the watershed of Lake Obuchi. The ecosystem model was used for comparative verification between our calculations and observation results in Box−6 (Fig. 2), while also simulating the material balance of phosphorus, nitrogen and carbon.

RESULTS AND DISCUSSION

Reproducibility of the model

Figure 3 shows the numerical results and observation data of TP (total phosphorus), TN (total nitrogen), TOC (total organic carbon), and DO (dissolved oxygen) in the upper (L1; depth of 0–1 m) and lower layers (L6; depth of 3–4 m) of the lake, respectively. The numerical results of TP, TN, TOC and DO in the upper layer corresponded well to the concentration fluctuations in the observation data as did the calculation results of TP, TN, TOC and DO in the lower layer, but the high concentrations of TP and TN in summer did not reappear. This appears to be a major factor underlying the absence of the phenomenon by which NH_4^+ and PO_4^{3-} are released from the bottom sediments when the dissolved oxygen content in the lower layer declines in summer (UEDA *et al.*, 2000). The parameters of the benthic release rate of P and N and the oxygen consumption rate were set considering a time–series fluctuation of the calculation results. However, in order to improve the accuracy of the model, it is necessary to obtain these parameters by an experiment using lake sediments.

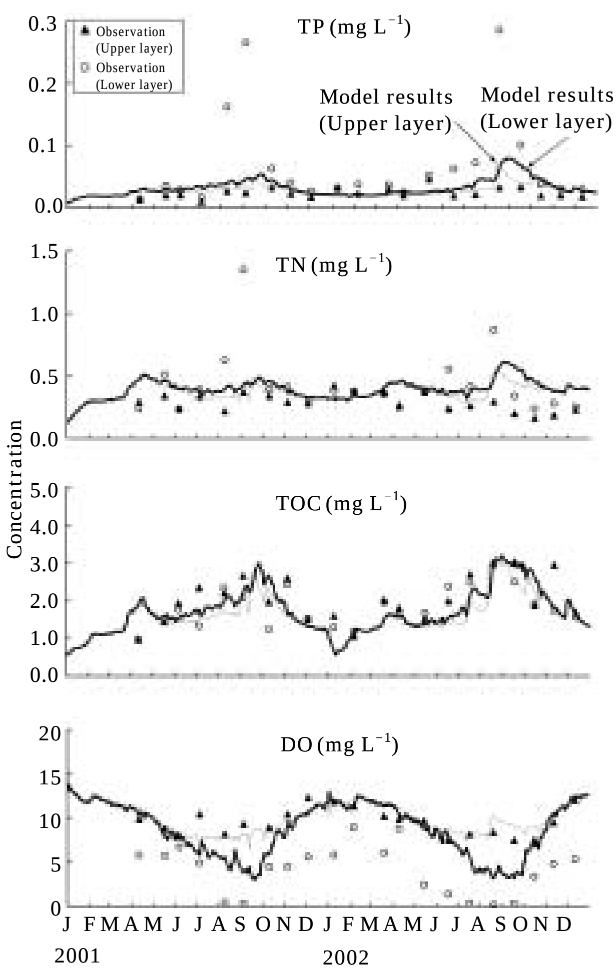

Fig. 3. Relationships between the model results (lines) and observations (circles) of TP (total phosphorus) and TN (total nitrogen) in upper and lower layers in Lake Obuchi.

Estimate of biomass and material balance

Figure 4 shows the fluctuations in the carbon mass balance of Lake Obuchi calculated by the ecosystem model. The mean carbon contents of DOC (dissolved organic carbon), POC, phytoplankton and zooplankton were calculated as 10500, 7200, 1500 and 22 kg–C, respectively, while the equivalent DOC, POC, phytoplankton and zooplankton observation data were 16500, 5900, 3800 and 150 kg–C, respectively, it seems more like congruence. However, the zooplankton results showed a seven–fold difference between the numerical and observation results, and the two peaks of spring and autumn in the observations showed no correspondence with the model.

Figure 5 shows the mass fluxes of phosphorus, nitrogen and carbon estimated by the ecosystem model. The load of phosphorus in the lake was formed by discharges from the land (3.7 kgP d^{-1}), the ocean (8.9 kgP d^{-1}), and elution (4.1 kgP d^{-1}) from bottom sediment. Among those sources

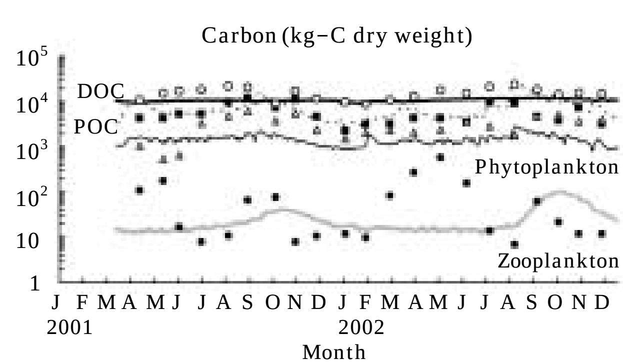

Fig. 4. Relationships between the model results (lines) and observations of the mass balance of carbon. The observation data of DOC (dissolved organic carbon), POC (particle organic carbon), phytoplankton and zooplankton are shown by ●, ×, △ and ○, respectively.

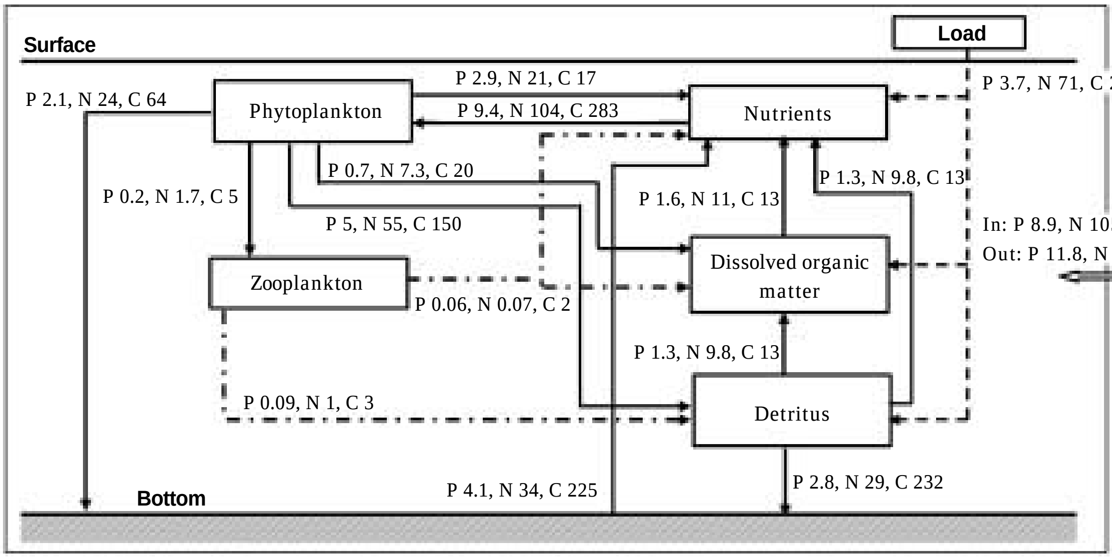

Fig. 5. Phosphorus, nitrogen and carbon mass fluxes computed by the ecological model in Lake Obuchi. The flow fluxes are daily integrated values in units of kg day^{-1}.

most of the phosphorus (11.8 kgP d^{-1}) was discharged from the lake into the Pacific Ocean, 30% (4.9 kgP d^{-1}) of which settled to the bottom. The nitrogen load amounted to 210 kgN d^{-1}, 75% of which was discharged into the ocean, while 25% (52 kgN d^{-1}) settled to the bottom of the lake. The carbon load was 743 kgC d^{-1}, over 90% of which was discharged into the ocean. The model's numerical results for sedimentation rates were then compared to those from the observations (UEDA *et al*., 2004b), and the calculation results of N and C agreed with observation results in 95 ±5% and 87±8%, respectively, and showed a good correspondence. However, the calculation result of P sedimentation rate showed considerable underestimation (approxemately 50%) in comparison with observation results.

Finally, the ecosystem model constructed for brackish Lake Obuchi verified that the mass fluxes of phosphorus, nitrogen and carbon corresponded closely to the field observations. However, it is still necessary to improve the model in order to measure the correspondence between elutions of phosphorus and nitrogen from the lake bottom in summer.

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<국문적요>

일본 기수호(Lake Obuchi)에서 생태계 모델의 개발과 적용

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반폐쇄성 기수호인 Obuchi호에서 수질과 생물학적 mass balance를 평가하기 위해 생태계 모델을 개발하고 적용하였다. 2001년 1월부터 2002년 12월까지 관찰된 조석의 차이, 강으로부터의 유입수 및 기상 변수들에 대한 시계열 자료들을 hydrodynamic 모델의 변수들로 접목시켰다. 수질과 생물 생체량 balance는 생태계 모델에 의해 평가되었으며, 모의된 수질 값은 관찰 값과 일치하였다. 호수에서 모델에 의해 계산된 POC와 식물플랑크톤, 동물플랑크톤의 carbon 함량은 각각 7,200 kg, 1,500 kg, 22 kg으로 나타났으며, 이는 관찰 값 POC (5,900 kg), 식물플랑크톤(3,800 kg), 동물플랑크톤(150 kg)과 어느 정도 비교할 수 있었다.