The Depletion of Dissolved Oxygen in the Hypolimnion of Lake Kizaki from April to July in 1975

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Abstract

The oxygen uptake by biological reaction in the hypolimnetic water and the oxygen flux into the sediment were studied quantitatively in order to make clear the development of the oxygen depletion in the hypolimnion observed in Lake Kizaki by applying of a one-dimensional diffusion model.

The biological O_2 consumption rate constant (k) and eddy diffusion coefficient (D) were found to be $5 \times 10^{-8} s^{-1}$ and $5 \times 10^{-2} cm^2 \cdot s^{-1}$ respectively, by applying the fixed initial and boundary conditions to the one-dimensional diffusion model.

The total depletion of oxygen in the hypolimnion and oxygen flux into the sediment tended to increase with time to become maximum on June 25, 1975, and these values decreased rapidly thereafter, while the oxygen uptake by biological reaction decreased gradually with time throughout the whole period of observation.

The oxygen uptake in the hypolimnetic water and oxygen flux into the sediment in May, June and July of 1975, were found to be 25, 20 and 13 $mmol \cdot m^{-2} \cdot d^{-1}$ and 11, 22 and 18 $mmol \cdot m^{-2} \cdot d^{-1}$ respectively.

1. Introduction

A thermocline disturbs the exchange of dissolved substances and heat between epilimnion and hypolimnion, because a eddy diffusion coefficient at the thermocline occasionally approximates the order of magnitude of a molecular diffusion coefficient (SWEERS, 1971; HESSLEIN and QUAY, 1973; JASSBY and POWELL, 1975). Decomposition of organic matter causes the depletion of dissolved oxygen as well as the accumulation of inorganic nutrients in the hypolimnetic water of a stratified lake. The high biological productivity associated with eutrophication causes vertical transport of organic matter, with the hypolimnion of the lake consuming large amounts of oxygen.

It has been observed that the hypolimnetic oxygen depletion is affected by the primary productivity occurring in the euphotic layer of the lake (LASENBY, 1975; CORNETT and RIGLER, 1979, 1980). However, the quantitative relationship between the hypolimnetic oxygen depletion and primary productivity remains to be investigated.

The present study aims to clarify the development of the oxygen depletion in the hypolimnion during the stratified periods of Lake Kizaki. A one-dimensional mathematical model was employed to solve this problem.

2. Theory

The local time rate of change in the concentration of non-conservative chemical materials can be described by the terms diffusion, advection, and chemical and/or biological reactions (SVERDRUP *et al.*, 1961).

The horizontal gradient of the concentration of dissolved oxygen is assumed to be negligible in the hypolimnion of Lake Kizaki as observed in many lakes in the temperate zone (BURNS, 1976). The advective process is also neglected because of no evidence of the intrusion of ground water into the profoundal area of this lake (HORIUCHI *et al.*, 1963). Thus, only the vertical gradient of dissolved oxygen need be considered for a quantitative understanding of the development of the oxygen depletion in the hypolimnion of this lake.

The degradation of phytoplanktonic organic matter proceeds with the con-

sumption of dissolved oxygen, which obeys first-order kinetics (EDWARDS and ROLLEY, 1965; McDONELL and HALL, 1969; EDBERG and HOFSTEN, 1973; MATSUNAGA, 1981).

Considering the above, the local time rate of the change in the concentration of dissolved oxygen can be described as follows.

$$\frac{\partial \phi}{\partial t} = D \frac{\partial^2 \phi}{\partial z^2} - k\phi \quad (1)$$

where, ϕ = concentration of dissolved oxygen ($\mu\text{mol} \cdot \text{l}^{-1}$)

t = time (s^{-1})

D = eddy diffusion coefficient ($\text{cm}^2 \cdot \text{s}^{-1}$)

z = depth in the water layer measured positively upward from the sediment-water interface (cm)

k = reaction rate constant for biological oxygen uptake (s^{-1}).

This equation can be solved with the initial and boundary conditions described below.

The initial conditions and the boundary conditions are

$$\text{at } t=0, z \geq 0: \phi = \phi_0, \quad (2)$$

$$\text{at } 0 \leq t \leq T, z=0: \phi = \phi_0 - \alpha t$$

$$t > T, z=0: \phi = 0, \quad (3)$$

where, ϕ_0 = constant with respect to depth ($\mu\text{mol} \cdot \text{l}^{-1}$)

α = depletion rate of dissolved oxygen at the sediment-water interface ($\mu\text{mol} \cdot \text{l}^{-1} \cdot \text{s}^{-1}$)

T = time when the concentration of dissolved oxygen goes to zero at the sediment-water interface ($=\phi_0/\alpha$)

The solution of equation 1 is given in equation 4 of Table 1.

3. Materials and Methods

The field observation was conducted from March to July in 1975 at the pro-foundal area of Lake Kizaki, Nagano Prefecture. The water samples were col-

lected by a pumping system. A special device was used for the collection of water samples near the sediment-water interface (Fig. 1).

Duplicate determination of dissolved oxygen was conducted by the Winkler method within a tolerance of $\pm 2\%$. Water temperature was measured by reversal thermometers with an accuracy of $\pm 0.02^\circ\text{C}$. The thermal eddy diffusivity was calculated from the change in vertical profile of water temperature with time by the application of the method described by HUTCHINSON (1957).

4. Results

4-1. Estimations of the Initial and Boundary Conditions

The vertical profile of water temperature indicated that the stratification of lake water in Lake Kizaki began in late April, when dissolved oxygen was found to distribute with vertical uniformity in the hypolimnion and its average concentration was calculated to be $348 \pm 7 \mu\text{mol} \cdot \text{l}^{-1}$ on April 22, 1975. Thus, the initial time ($t=0$) and initial concentration of dissolved oxygen (ϕ_0) were fixed on April 22, 1975 and $348 \mu\text{mol} \cdot \text{l}^{-1}$ respectively.

Dissolved oxygen in the water samples 7 cm above the sediment-water interface was determined to estimate the boundary condition, reflecting the change in the concentration of dissolved oxygen in the sediment-water interface (Fig. 2). The concentration of dissolved oxygen in this layer decreased linearly with time, when water was aerobic. $6.3 \times 10^{-5} \mu\text{mol} \cdot \text{l}^{-1} \cdot \text{s}^{-1}$ were obtained for the depletion rate of dissolved oxygen at the sediment-water interface (α) from a slope of the regression line with a relation to the concentration of dissolved oxygen in the overlying water above the sediment, and time. The concentration of dissolved oxygen in this water layer on June 25, 1975 was zero, as calculated from the values of ϕ_0 and α ($T = \phi_0/\alpha = 5.25 \times 10^5 \text{s}$).

4-2. Estimation of Thermal Eddy Diffusivity

Thermal eddy diffusion coefficient was calculated on the basis of the change in

Table 1. Equations 4 and 5. See text for discussion.

$$\begin{aligned}
\phi = & \phi_0 \exp(-kt) \operatorname{erf}\left(\frac{z}{2\sqrt{Dt}}\right) \\
& + \frac{1}{2} [\phi_0 - (t - \frac{z}{2\sqrt{Dk}})\alpha] \exp\left(-z\sqrt{k/D}\right) \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}} - \sqrt{kt}\right) \\
& + \frac{1}{2} [\phi_0 - (t + \frac{z}{2\sqrt{Dk}})\alpha] \exp\left(z\sqrt{k/D}\right) \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}} + \sqrt{kt}\right) \\
& + \frac{\alpha}{2} \left[\left(t' - \frac{z}{2\sqrt{Dk}} \right) \exp\left(-z\sqrt{k/D}\right) \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt'}} - \sqrt{kt'}\right) \right. \\
& \left. + \left(t' + \frac{z}{2\sqrt{Dk}} \right) \exp\left(z\sqrt{k/D}\right) \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt'}} + \sqrt{kt'}\right) \right] 1(t')
\end{aligned} \tag{4}$$

where, $t' = t - T$

$$\begin{cases} 1(t') = 0 & \text{at } t' \leq 0 \\ 1(t') = 1 & \text{at } t' > 0. \end{cases}$$

$$\begin{aligned}
\phi = & \phi_0 \exp(-kt) \operatorname{erf}\left(\frac{z}{2\sqrt{Dt}}\right) \\
& - a \exp[-bz - (k - Db^2)t] \\
& + \frac{a}{2} \exp(-k + Db^2)t \left[\exp(-bz) \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}} - b\sqrt{Dt}\right) + \exp(bz) \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}} + b\sqrt{Dt}\right) \right] \\
& + \frac{1}{2} [\phi_0 - a - (t - \frac{z}{2\sqrt{Dk}})\alpha] \exp\left(-z\sqrt{k/D}\right) \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}} - \sqrt{kt}\right) \\
& + \frac{1}{2} [\phi_0 - a - (t + \frac{z}{2\sqrt{Dk}})\alpha] \exp\left(z\sqrt{k/D}\right) \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}} + \sqrt{kt}\right) \\
& + \frac{\alpha}{2} \left[\left(t' - \frac{z}{2\sqrt{Dk}} \right) \exp\left(-z\sqrt{k/D}\right) \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt'}} - \sqrt{kt'}\right) \right. \\
& \left. + \left(t' + \frac{z}{2\sqrt{Dk}} \right) \exp\left(z\sqrt{k/D}\right) \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt'}} + \sqrt{kt'}\right) \right] 1(t')
\end{aligned} \tag{5}$$

where, $t' = t - T$

$$\begin{cases} 1(t') = 0 & \text{at } t' \leq 0 \\ 1(t') = 1 & \text{at } t' > 0 \end{cases}$$

the vertical profile of water temperature with time from April 22 to July 21, 1975 (Fig. 3) to predict the eddy diffusion coefficient. The thermal eddy diffusion coefficient ranged from $5.0-8.0 \times 10^{-2} \text{cm}^2 \cdot \text{s}^{-1}$ in May, to $3.0-9.1 \times 10^{-2} \text{cm}^2 \cdot \text{s}^{-1}$ in June and $2.5-6.6 \times 10^{-2} \text{cm}^2 \cdot \text{s}^{-1}$ in July, respectively (Table 2). The average value was calculated to be $5.6 \times 10^{-2} \text{cm}^2 \cdot \text{s}^{-1}$ in the hypolimnion from April 22 to July 21, 1975.

4-3. Estimation of Reaction Rate Constant (k) and Eddy Diffusion Coefficient (D)

The reaction rate constant (k) and eddy diffusion coefficient (D) are estimated by the trial and error method for the calcu-

lated values using equation 4, with the initial and boundary conditions (equations 2 and 3) described above to fit the changes in the concentration of dissolved oxygen with time in the hypolimnion (Fig. 4). It was estimated finally to be $k = 5 \times 10^{-8} \text{s}^{-1}$ and $D = 5 \times 10^{-2} \text{cm}^2 \cdot \text{s}^{-1}$, respectively. In this case, the sum of squares of the residuals was calculated to be $5,097 \mu\text{mol}^2 \cdot l^{-2}$ with numbers of the samples ($n=60$).

5. Discussion

5-1. Application of Mathematical Model for Oxygen Depletion in the Hypolimnion

For a quantitative understanding of oxygen depletion in the hypolimnion of Lake

Fig. 1. An apparatus for sampling water overlying bottom sediment.
1; water pump, 2; cubical shape pipe frame (side length=1.8 m)
3; inlet parts, 4; lead

Fig. 2. Change in the concentration of dissolved oxygen in overlying water (7 cm above the bottom surface) at the profundal area of Lake Kizaki.

Kizaki, a one-dimensional diffusion model was employed for the change in concen-

tration of dissolved oxygen with time from April to July, 1975. In this application, the significance of the term for the physical process of diffusion becomes more important near the sediment-water interface, whereas the term for the process of biological reaction becomes more significant as the distance from the interface increases. Then, the initial and boundary conditions are also important in applying the model for this purpose. From equation 4, k and D had been obtained using the initial ($\phi = \phi_0$ at $t=0$) and boundary ($\phi = \phi_0 - \alpha t$; $0 < t \leq T$, and $\phi = 0$; $t > T$ at $z=0$) conditions, where ϕ_0 , α and T were $348 \mu\text{mol}\cdot\text{l}^{-1}$, $6.3 \times 10^{-5} \mu\text{mol}\cdot\text{l}^{-1}\cdot\text{s}^{-1}$ and $5.52 \times 10^6 \text{ s}$, respectively.

Then k and D were used to estimate

Fig. 3. Changes in water temperature from April to July in 1975 at the profundal area of Lake Kizaki.

Table 2. Changes in the thermal eddy diffusivity from April to July in 1975 at the profundal area of Lake Kizaki.

Depth from bottom	22 April	22 May	19 June	24 July
m	$10^{-2}\text{cm}^2\cdot\text{s}^{-1}$			
21	6.0	—	—	—
20	6.0	2.2	—	—
19	5.6	2.2	1.0	—
18	5.6	3.0	1.4	—
17	6.5	4.5	2.5	—
16	7.6	6.2	3.8	—
15	8.0	8.1	5.2	—
14	7.7	9.0	6.6	—
13	7.1	8.9	6.2	—
12	6.9	8.8	5.8	—
11	6.3	8.3	4.7	—
10	5.5	7.4	4.1	—
9	5.3	6.9	3.4	—
8	5.4	7.1	3.0	—
7	5.3	7.5	2.8	—
6	5.1	7.6	2.9	—
5	5.0	8.8	3.1	—
4	5.5	9.1	3.0	—
3	5.5	7.6	2.8	—
2	5.7	7.0	2.6	—
1	—	—	—	—

from equation 1 with variable initial and boundary conditions because of the extreme difficulty of maintaining the values of the initial and boundary conditions throughout the field observation.

The initial and boundary conditions were represented as $\phi = \phi_0 - a \exp(-bz)$ at $t=0$, and $\phi = \phi_0 - a - \alpha t$; $0 < t \leq T$ and $\phi = 0$; $t > T$ at $z=0$, respectively, where a ($\mu\text{mol}\cdot\text{l}^{-1}$), b (cm^{-1}) and α ($\mu\text{mol}\cdot\text{l}^{-1}\cdot\text{s}^{-1}$) were constant, respectively. The solution of equation 1 is given in equation 5 by using these conditions and each of the parameters (ϕ_0 , α , a , b , k , D) were estimated when the calculated values of dissolved oxygen fitted best with the observed values of dissolved oxygen (Fig. 4). Then, $\phi_0 = 360 \mu\text{mol}\cdot\text{l}^{-1}$, $\alpha = 6.3 \times 10^{-5} \mu\text{mol}\cdot\text{l}^{-1}\cdot\text{s}^{-1}$, $a = 26.38 \mu\text{mol}\cdot\text{l}^{-1}$, $b = 1.278 \times 10^{-3} \text{cm}^{-1}$, $k = 5 \times 10^{-8} \text{s}^{-1}$, and $D = 5 \times 10^{-2} \text{cm}^2\cdot\text{s}^{-1}$, respectively, were obtained and $3,701 \mu\text{mol}^2\cdot\text{l}^{-2}$ was calculated for the sum of squares of the residuals with numbers of the samples ($n=60$). Moreover, $5,097 \mu\text{mol}^2\cdot\text{l}^{-2}$ was obtained calculating the fixed initial and boundary conditions. There was no significant difference for k and D with fixed and variable initial and boundary conditions,

Fig. 4. Changes in the concentration of dissolved oxygen from April to July in 1975 at the profundal area of Lake Kizaki. Solid-line concentration profiles computed using equation 4 and the values of parameters given in the text. Dashed-line concentration profiles computed using equation 5 and the values of parameters given in the text.

because the calculated F value did not exceed the tabulated value with the 10% level of significance ($F=5,097/3,701=1.37 < F(10; 53, 55)$). Thus, $5 \times 10^{-8} \text{s}^{-1}$ and $5 \times 10^{-2} \text{cm}^2 \cdot \text{s}^{-1}$ were obtained values for k and D .

The thermal eddy diffusion coefficients were calculated from the changes in the vertical profile of water temperature with time. The coefficient was found to range from 3 to $9 \times 10^{-2} \text{cm}^2 \cdot \text{s}^{-1}$ with the average of $5.6 \times 10^{-2} \text{cm}^2 \cdot \text{s}^{-1}$. Almost comparable values in the range of 5 – $10 \times 10^{-2} \text{cm}^2 \cdot \text{s}^{-1}$ were obtained in the same season in this lake (HORIUCHI, 1959). As cited above, the thermal eddy diffusion coefficient values closely approached the eddy diffusion coefficient.

The reaction rate constant on the degradation of phytoplanktonic organic matter in vitro (19°C) was determined to be 9.0

$\times 10^{-7} \text{s}^{-1}$ (MATSUNAGA, 1981), while the value of the reaction rate constant obtained in this lake was one order of magnitude lower than that obtained in vitro. Water temperature, and organic composition of particulate matter and its concentration must be the determinative factors controlling the figure of k . According to EDWARDS and ROLLEY (1965), McDONNELL and HALL (1969) and EDBERG and HOFSTEN (1973), the oxygen consumption rate doubles for every 10°C elevation of the ambient water temperature in the decompositive processes of sedimentary organic matter. Each cellular organic constituent has a different k value (HANDA, 1972; MATSUNAGA, 1981), and phytoplankton grown in the laboratory consists of biologically labile organic compounds to a great extent comparable to those of particulate matter in natural waters (HANDA, 1972).

In addition, the concentration of particulate organic carbon in Lake Kizaki ranged from 0.2 to 0.4 mgC·l⁻¹ in the hypolimnion, against 1.8–3.5 mgC·l⁻¹ in vitro (MATSUMURA, 1981). Thus, it is most likely that *k* of the hypolimnion of Lake Kizaki (7°C) is lower than that obtained in the laboratory at 19°C, because 7°C water temperature was observed in the hypolimnion of Lake Kizaki in April to July, 1975. Nevertheless, it is difficult to obtain a quantitative explanation of the difference of *k* values obtained in the laboratory work and in the hypolimnion of Lake Kizaki. This is a problem to be investigated in future.

5-2. Estimations of Oxygen Uptake in Lake Water and Oxygen Flux into the Sediment

The depletion rate of oxygen in the hypolimnion is governed by the upward flux of oxygen through the thermocline, the rate of oxygen uptake by the biological reaction in the hypolimnetic water and the oxygen flux into the sediment through its surface.

The euphotic layer was overlaid with the thermocline. The latter occurred in the water layer between 5 and 10 m depth in April through July, 1975 as shown in Fig. 3. The diffusion coefficient in the thermocline was much smaller than the thermal molecular diffusion coefficient ($1 \times 10^{-3} \text{ cm}^2 \cdot \text{s}^{-1}$, SWEERS, 1971; JASSBY and POWELL, 1975) and almost the same order of magnitude as the molecular diffusion coefficient of chemical substances such as Rn and Fluorescent dye ($1 \times 10^{-5} \text{ cm}^2 \cdot \text{s}^{-1}$, HESSLEIN and QUAY, 1973). These findings indicate that the upward flux of oxygen through the thermocline is insignificant from April through July in Lake Kizaki because of the very low upward flux of oxygen ($0.002 \text{ mmol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), even when applying the maximum gradient of dissolved oxygen in this layer ($20 \mu\text{mol} \cdot \text{l}^{-1} \cdot \text{m}^{-1}$). Thus, this agent was not considered to clarify the process of oxygen depletion in the hypolimnion of Lake Kizaki.

The oxygen depletion in the water column at 0 to 18 m from the surface of

the sediment (equivalent to 10 to 28 m from the lake water surface) may be attributed to the oxygen uptake by the biological reaction in the hypolimnetic water and oxygen flux into the sediment through its surface. The depletion of oxygen in the hypolimnion (A) and the oxygen flux into the sediment (C) were calculated as follows.

$$A = - \int_0^z \frac{\partial \phi}{\partial t} dz, \quad z=1800(\text{cm}) \quad (6)$$

$$C = D \frac{\partial \phi}{\partial z}, \quad z=0 \quad (7)$$

The depletion of oxygen as well as the oxygen flux into the sediment is positive. Thus, the oxygen uptake in the hypolimnetic water by the biological reaction (B) can be calculated as follows.

$$B = A - C \quad (8)$$

Changes in these calculated values with time are shown in Fig. 5.

Fig. 5. Changes in the total oxygen depletion in the hypolimnion (A), the biological oxygen uptake in hypolimnetic water (B), and the oxygen flux into the sediment (C) from April to July in 1975 at the profundal area of Lake Kizaki. The rates were computed using equations 4, 6, 7 and 8, and the values of parameters given in the text.

The depletion of oxygen in the hypolimnion and oxygen flux into the sediment tended to increase with time and reached the maximum values of 43 and 27 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ respectively on June 25, 1975. However, these values decreased very rapidly thereafter with the development of the anaerobic layer in the overlying water of the sediment.

The monthly mean oxygen flux into the sediment was estimated to be 11, 22 and 18 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ in May, June and July, respectively accounting for 30, 53 and 57% of the total oxygen depletion in the hypolimnion in May, June and July, respectively. These oxygen flux values were almost the same as those obtained by the in situ bell jar method system used in Puget Sound (4.3-43 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, PAMATMAT and BANSE, 1969). In view of these facts, it can be concluded that the oxygen flux into the sediment is one of the determinative processes in the oxygen depletion within the hypolimnion.

The oxygen uptake by the biological reaction in the hypolimnetic water tended to decrease gradually with time from 27 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ on April 22, 1975 to 13 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ on July 21, 1975. However, the oxygen uptake rate was found not to change dramatically as observed in the total depletion of oxygen in the hypolimnion (A) and oxygen flux into the sediment (C). These values accounted for 100% and 50% of the total oxygen depletion in the hypolimnion. This indicates that oxygen uptake in the hypolimnetic water also play an important role in the ongoing oxygen depletion in the hypolimnion.

EDBERG (1976) reported that oxygen consumption of sediment was 32-44% of the total oxygen depletion in several Swedish lakes in summer. WOOD and VERDUIN (1971) and LASENBY (1975) found that oxygen consumption in the sediment and hypolimnetic waters of Lake Erie and Dickey Lake accounted for 11 and 89, and 27 and 73% of the total depletion of oxygen, respectively. In view of the data from Lake Kizaki as well as those of the lakes

in various continents, the oxygen uptake by biological reaction in the hypolimnetic waters may be considered to affect considerably the depletion of oxygen in the hypolimnion as well as the oxygen flux into the sediment through its surface, throughout the whole period of observation.

Acknowledgments

The author would like to express his thanks to Prof. T. KOYAMA, Prof. Emeritus Nagoya University, for his encouragement during the course of this study. Thanks are also given to Messrs. T. SUGIURA and N. TANAKA for their assistance in the field work. The author also is indebted to Dr. N. HANDA, Nagoya University, for his critical reading of the manuscript.

摘 要

湖の深層で観察される酸素欠乏の発達過程を解明するために、木崎湖の深層を対象にして、深層水中での生物活動による、酸素消費量と底泥への酸素のフラックスを、一次元拡散モデルを用いて定量的に検討した。

一次元拡散モデルに、別に定められた初期条件と境界条件とを適用した。この場合に得られた生物による酸素消費の速度定数 (k) と渦拡散係数 (D) は、それぞれ $5\times 10^{-3}\text{s}^{-1}$ および $5\times 10^{-2}\text{cm}^2\cdot\text{s}^{-1}$ であった。

深層における、酸素欠乏量と底泥への酸素のフラックスは、1975年6月25日の最大値に達するまではともに増加し、その後はともに急激に減少した。ところが、生物活動による酸素消費量は、観測された期間を通して徐々にではあるが一方向的に減少する傾向を示した。

生物活動による酸素消費量は、1975年5月、6月および7月において、それぞれ25、20および13 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ であった。また底泥への酸素のフラックスは同様にそれぞれ11、22および18 $\text{mmol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ であった。

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Accepted: 27 April 1982