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Numerical Calculation of DO Distribution in Yashima Bay, Japan

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ABSTRACT

A mathematical model was developed to predict the spread of oxygen. This model was considered in well mixed water on the basis of mass balance equation. The effects of source and sink of dissolved oxygen such as advection, diffusion, reaeration and consumption of biomass were applied into the mathematical model. Since the experiments were done in the night time, the effect of primary production could be neglected. The solution of the model which was developed by Horiguchi (1969) had been considered by the scheme of implicit method. Successive over relaxation method (S.O.R) was selected for use. In the DO dispersion model, the velocity data were obtained from the results of Monton, A. and Sasaki, T.(1995)'s studies. These terms were applied to all quality constituents of sea water. The local addition and removal of the DO terms obtained from the results of Inoue's biological experiments (1983-1987). Each term was introduced into the suitable investigation area. The results of the prediction are nearly the same as the observation. Similar to its spread, the pattern of DO dispersion from the prediction at low tide is also similar to the pattern of DO dispersion from observation at low tide.
Key words: advective, dispersion, diffusive

INTRODUCTION

Adequate oxygen is necessary for the life of fish and other aquatic organisms. Dissolved oxygen (DO) levels in nature are dependent on the physical, chemical and biochemical activities prevailing in the water body. The analysis for DO is a key test in water pollution control activities. The oxygen is often a limiting factor in aquatic systems because nearly all aquatic organism, with the exception of some bacteria, have to consume oxygen to survive.

The solution models were formulated and solved numerically to approximate the distribution pattern of dissolved oxygen content within the Yashima bay. The results of Inoue(1983-1987)'s biochemical experiments on the rate of respiration of yellow-tail in restricted activity, the rate of reaeration of oxygen from air, the uptake rate of benthal and the rate of oxygen consumption by sea water were applied.

Site of study, Yashima bay, is the shallow and small bay which is located at the eastern part of the Seto Inland sea, Takamatsu Prefecture, Japan as shown in Figure 1. The average depth of the bay over its total area is about 6.2 m. Maximum depth in the north part is about 14 m. The total area is about 6 km^2. In the Yashima bay, there are many fish farms in which many floating net cages are used for the yellow tail culture. The area of fish farms are about 30% of the total area.

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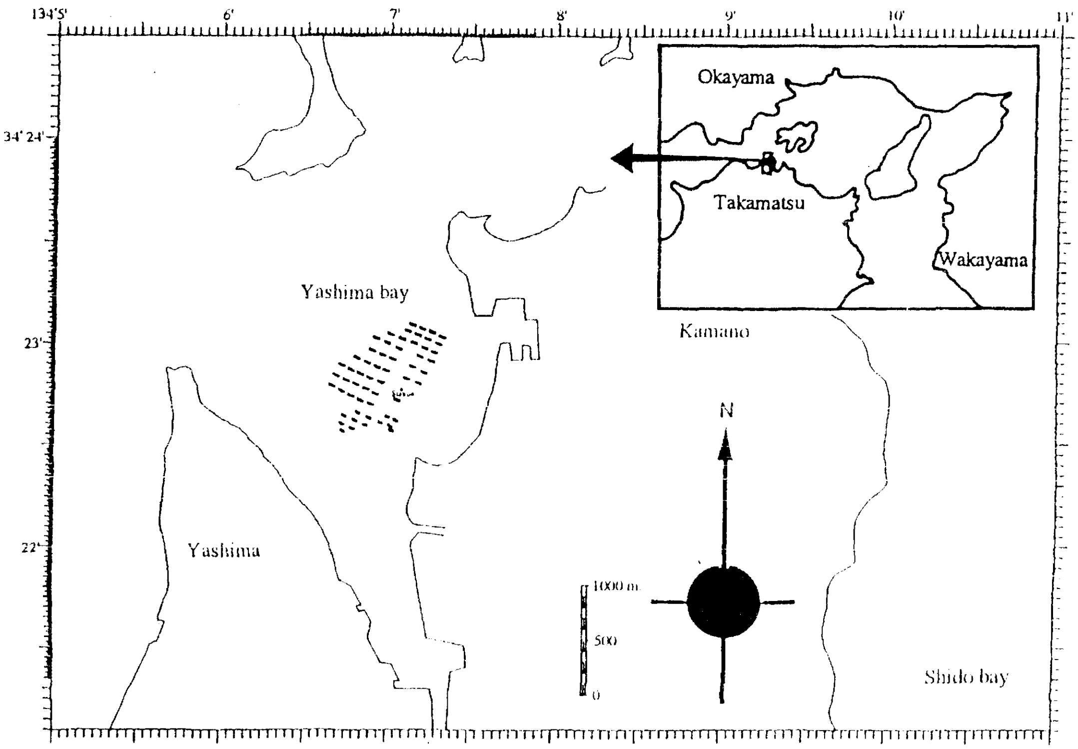


Figure 1 Surveying station in Yashima bay and at Kamano, Kagawa Prefecture (1994).

METHODS

The sources and sinks of dissolved oxygen

The major source and sink of oxygen in the bay are:

1. The reaeration of oxygen from air

There is a continual exchange of oxygen between a water surface and the air. This process yields specific meaning to the distribution of dissolved oxygen in sea water. In order to predict the distribution of dissolved oxygen in the bay, it is necessary to know the rate of oxygen transfer from the air.

From the study of Thames Survey Committee (1964), the transfer of oxygen from air to water is caused by molecular diffusion. This process is sufficiently rapid to maintain the concentration oxygen in the water at the interface equilibrium. When the water is moving, the rate of absorption is higher, since fresh surfaces are formed more rapidly, and since turbulence causes well mixing of oxygen. The solutions could be rewriten as:

$$R_1 = \frac{K_1}{H} \cdot (S_s - S) \tag{1}$$

where R_1 = rate of mass transfer of oxygen from air per unit volume (mg/l/sec)

K_l = exchange coefficient (cm/sec)

S_s = oxygen concentration at saturation (mg/l)

S = oxygen concentration at time t (sec)

H = aeration depth (cm)

2. Effect of benthal oxygen uptake

The effect of benthal oxygen uptake is one of the important factors for DO budget. Since aquatic systems are located in shallow sea, the effect of oxygen consumption by associated plants and aquatic organisms become increasingly importance.

Several investigators agreed with the conclusion that the oxygen uptake rate of the benthal systems were dependent on oxygen concentration. Inoue (1987), researching on the benthal oxygen uptake rate in the aquatic system, expressed the formula as:

$$R_2 = \frac{1}{H}\sqrt{2 \cdot K_m \cdot D \cdot S} \qquad \text{(mg/l/sec)} \qquad (2)$$

where R_2 = rate of oxygen uptake by bacteria activity per unit volume (mg/l/sec)

$2\,K_m\,D$ = diffusion coefficient in sediment (mg/(hr^2.m))

H = aeration depth (cm)

3. Oxygen consumption by sea water in area of fish farms

Dissolved oxygen of sea water in area of fish farms is continuously consumed by their constituents of biochemical processes. Some need in respiration of plankton, some need in decomposition of organic matter, and some loss in chemical oxidation processes of inorganic substances.

Inoue (1986.) had considered that oxygen consumption by sea water consists as:

3.1 oxygen demand of respiration of phytoplankton

3.2 oxygen demand of decomposition of detritus by bacteria

3.3 oxygen demand of decomposition of dissolved organic matter by bacteria

3.4 oxygen demand of chemical oxidation of inorganic substances.

Since the oxygen demand for chemical oxidation was negligible, Inoue (1986.), proposed the empirical equation as:

$$R_3 = = \alpha_1 \cdot \frac{N}{\Delta s^2} + OUW \qquad \text{(mg/l/sec)} \qquad (3)$$

where R_3 = rate of oxygen consumption by sea water in area of fish culture per unit volume (mg/l/sec)

OUW = oxygen consumption by sea water (mg/l/sec)

α_1 = proportional coefficient (mg.cm^2 /(sec.l.indiv.))

N = number of fish per cage (indiv.)

Δs^2 = area of fish farm per cage (cm^2)

4. Respiration of yellow tail.

From the works of Inoue, H., in 1986 it was proposed that rate of respiration of 2 years old of yellow tail may be related as a function of fresh body weight and water temperature. The validity of this respiration relation is reliable within the range 16°C - 28 °C. The total of respiration rate of 2 years old of yellow tail per unit volume at each grid point may be expressed as:

$$R_4 = \frac{N}{\Delta s^2 \cdot H} \cdot \alpha_{20^\circ} \cdot Q_{01}^{(T-20^\circ)} \cdot W^{\gamma} \qquad \text{(mg/l/sec)} \qquad (4)$$

where R_4 = rate of respiration of fish per unit volume (mg/l/sec)

α_{20° = level of metabolism coefficient at 20°C.

Q_{01} = temperature coefficient

W = mean fresh body weight of yellow tail in kg.

γ = weight exponent

N = number of fish per cage (indiv.)

Δs^2 = area of fish farm per cage (cm^2)

H = sea water depth. (cm)

5. Advection and diffusion of sea water

Since DO content is propagated with the flow. The pattern DO dispersion also relates to advection and diffusion of sea water which may be shown in terms of velocity. In these model, velocity data were obtained from Monton and Sasaki (1995).

Dissolved oxygen dispersion simulation

A possible way of analyzing the spreading of pollutants in the frame work used the equation of conservation of dissolved substances. This study was limited to well mixed water.

1. Conservation of dissolved substance

The mass conservation law of dissolved substance was selected to be the mathematical model. The average mass conservation equation for substance in vertical direction can be written as:

$$\frac{\partial S}{\partial t} + U\frac{\partial S}{\partial x} + V\frac{\partial S}{\partial y} = \frac{1}{H}\cdot\frac{\partial}{\partial x}[K_x \cdot H\frac{\partial S}{\partial x}] + \frac{1}{H}\cdot\frac{\partial}{\partial y}[K_y \cdot H\frac{\partial S}{\partial y}] + R \qquad (5)$$

where $\frac{\partial S}{\partial t}$ is unsteady term

$U\frac{\partial S}{\partial x} + V\frac{\partial S}{\partial y}$ are advective terms

$$\frac{1}{H}\cdot\frac{\partial}{\partial x}[K_x\cdot H\frac{\partial S}{\partial x}]+\frac{1}{H}\cdot\frac{\partial}{\partial y}[K_y\cdot H\frac{\partial S}{\partial y}]$$ are diffusive terms

R are the terms of the local addition and removal of the substance that consist of the

a) rate of mass transfer of oxygen from air per unit volume (R_1)

b) rate of oxygen uptake by bacteria activity per unit volume (R_2)

c) rate of oxygen consumption by sea water in area of fish culture per unit volume (R_3)

d) rate of respiration of fish per unit volume (R_4).

2. Boundary conditions

In this study, DO dispersion model is controlled by three boundary conditions:

2.1 Advection boundary conditions at sea surface and bottom

2.2 Diffusion boundary conditions at sea surface and bottom

2.3 Geometrical boundary conditions

2.1 Advection boundary conditions at sea surface and bottom

Advection boundary conditions at the bottom $z = h(x,y)$ and at the sea surface $z = -\zeta(x,y,t)$ are expressed as:

$$(w\cdot s)_h = (u\cdot s)_h\frac{\partial h}{\partial x} + (v\cdot s)_h\frac{\partial h}{\partial y}$$

$$-(w\cdot s)_{-\zeta} = s_{-\zeta}\cdot\frac{\partial\zeta}{\partial t} + (u\cdot s)_{-\zeta}\frac{\partial\zeta}{\partial x} + (v\cdot s)_{-\zeta}\frac{\partial\zeta}{\partial y}. \tag{6}$$

Then

$$(w\cdot s)_h - (w\cdot s)_{-\zeta} = (u\cdot s)_h\frac{\partial h}{\partial x} + (v\cdot s)_h\frac{\partial h}{\partial y} + s_{-\zeta}\cdot\frac{\partial\zeta}{\partial t} + (u\cdot s)_{-\zeta}\frac{\partial\zeta}{\partial x} + (v\cdot s)_{-\zeta}\frac{\partial\zeta}{\partial y} \tag{7}$$

2.2 Diffusion boundary condition at sea surface and bottom

Diffusivity boundary conditions at the bottom and sea surface are expressed as:

$$K_z\frac{\partial s}{\partial z}\bigg|_h = K_x\frac{\partial s}{\partial x}\bigg|_h\frac{\partial h}{\partial x} + K_y\frac{\partial s}{\partial y}\bigg|_h\frac{\partial h}{\partial y}$$

$$K_z\frac{\partial s}{\partial z}\bigg|_{-\zeta} = K_x\frac{\partial s}{\partial x}\bigg|_{-\zeta}\frac{\partial(-\zeta)}{\partial x} + K_y\frac{\partial s}{\partial y}\bigg|_{-\zeta}\frac{\partial(-\zeta)}{\partial y}. \tag{8}$$

The equation will be as follows:

$$K_z \frac{\partial s}{\partial z}\bigg|_h + K_z \frac{\partial s}{\partial z}\bigg|_{-\zeta} = K_x \frac{\partial s}{\partial x}\bigg|_h \frac{\partial h}{\partial x} + K_y \frac{\partial s}{\partial y}\bigg|_h \frac{\partial h}{\partial y} + K_x \frac{\partial s}{\partial x}\bigg|_{-\zeta} \frac{\partial(-\zeta)}{\partial x} + K_y \frac{\partial s}{\partial y}\bigg|_{-\zeta} \frac{\partial(-\zeta)}{\partial y} \quad (9)$$

2.3 Geometrical boundary conditions

Geometrical boundary conditions were expressed by determining the ambient points. There is no velocity flux across the boundary. Hence nine patterns of geometrical boundary were classified as shown in Table 1. The patterns of geometrical boundary were automatically made up by input data as different code.

3. The vertically averaged equation of mass conservation in finite differential form

According to the Horiguchi(1969)' study, he applied the finite differential method into Eq.(5) by using implicit method. This study obtain

$$U\frac{\partial S}{\partial x} = U_{i,j}^{t+1}\frac{S_{i,j+1}^{t+1} - S_{i,j-1}^{t+1}}{2\Delta s}$$

$$V\frac{\partial S}{\partial y} = V_{i,j}^{t+1}\frac{S_{i-1,j}^{t+1} - S_{i+1,j}^{t+1}}{2\Delta s}$$

$$\frac{1}{H}\frac{\partial}{\partial x}(K \cdot H\frac{\partial S}{\partial x}) = \frac{1}{H_{i,j}}\frac{1}{\Delta s}(\frac{K_{i,j+1} + K_{i,j}}{2} \cdot \frac{H_{i,j+1}^{t+1} + H_{i,j}^{t+1}}{2} \cdot \frac{S_{i,j+1}^{t+1} + S_{i,j}^{t+1}}{\Delta s}$$

$$- \frac{K_{i,j} + K_{i,j-1}}{2} \cdot \frac{H_{i,j}^{t+1} + H_{i,j-1}^{t+1}}{2} \cdot \frac{S_{i,j}^{t+1} + S_{i,j-1}^{t+1}}{\Delta s})$$

$$\frac{1}{H}\frac{\partial}{\partial y}(K \cdot H\frac{\partial S}{\partial y}) = \frac{1}{H_{i,j}}\frac{1}{\Delta s}(\frac{K_{i-1,j} + K_{i,j}}{2} \cdot \frac{H_{i-1,j}^{t+1} + H_{i,j}^{t+1}}{2} \cdot \frac{S_{i-1,j}^{t+1} + S_{i,j}^{t+1}}{\Delta s}$$

$$- \frac{K_{i,j} + K_{i+1,j}}{2} \cdot \frac{H_{i,j}^{t+1} + H_{i+1,j}^{t+1}}{2} \cdot \frac{S_{i,j}^{t+1} + S_{i+1,j}^{t+1}}{\Delta s}) \quad (10)$$

where $K_x = K_y = K$.

Substituting Eqs.(10) into Eq.(5) the equation is as follows:

$$S_{i,j}^{t} = A_{i,j}^{t+1} \cdot S_{i,j}^{t+1} + B_{i,j}^{t+1} \cdot S_{i,j+1}^{t+1} + C_{i,j}^{t+1} \cdot S_{i,j-1}^{t+1} + D_{i,j}^{t+1} \cdot S_{i-1,j}^{t+1} + E_{i,j}^{t+1} \cdot S_{i+1,j}^{t+1} + RR \quad (11)$$

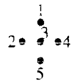
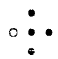
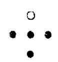
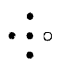
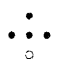
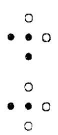
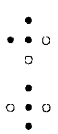
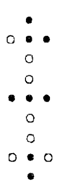
where

$$A_{i,j}^{t+1} = 1 + \frac{1}{H_{i,j}^{t+1}}\frac{1}{4}(K_{i,j+1} + K_{i,j})(H_{i,j+1}^{t+1} + H_{i,j}^{t+1})\frac{\Delta t}{\Delta s^2}$$

$$+\frac{1}{H_{i,j}^{t+1}}\frac{1}{4}(K_{i,j}+K_{i,j-1})(H_{i,j}^{t+1}+H_{i,j-1}^{t+1})\frac{\Delta t}{\Delta s^2}$$

$$+\frac{1}{H_{i,j}^{t+1}}\frac{1}{4}(K_{i-1,j}+K_{i,j})(H_{i-1,j}^{t+1}+H_{i,j}^{t+1})\frac{\Delta t}{\Delta s^2}$$

Table 1 Geometrical boundary conditions for implicit method.

	Type	Condition
	1	—
	2	K2=K4,H2=H4,S2=S4
	3	K1=K5,H1=H5,S1=S5
	4	K2=K4,H2=H4,S2=S4
	5	K1=K5,H1=H5,S1=S5
	6	K1=K5,H1=H5,S1=S5 and K2=K4,H2=H4,S2=S4 K1=K2=K4=K5,H1=H2=H4=H5,S1=S2=S4=S5
	7	K1=K5,H1=H5,S1=S2 and K2=K4,H2=H4,S2=S4 K1=K2=K4=K5,H1=H2=H4=H5,S1=S2=S4=S5
	8	K1=K5,H1=H5,S1=S5 and K2=K4,H2=H4,S2=S4 K1=K4,H1=H4,S1=S4 and K2=K5,H2=H5,S2=S5
	9	K1=K5,H1=H5,S1=S5 and K2=K4,H2=H4,S2=S4 K1=K4,H1=H4,S1=S4 and K2=K5,H2=H5,S2=S5 K1=K2=K4=K5,H1=H2=H4=H5,S1=S2=S4=S5

○ land

• sea

$$+\frac{1}{H_{i,j}^{t+1}}\frac{1}{4}(K_{i,j}+K_{i+1,j})(H_{i,j}^{t+1}+H_{i+1,j}^{t+1})\frac{\Delta t}{\Delta s^2}$$

$$B_{i,j}^{t+1}=\frac{\Delta t}{2\Delta s}U_{i,j}^{t+1}-\frac{1}{4\cdot H_{i,j}^{t+1}}(K_{i,j+1}+K_{i,j})(H_{i,j+1}^{t+1}+H_{i,j}^{t+1})\frac{\Delta t}{\Delta s^2}$$

$$C_{i,j}^{t+1}=-\frac{\Delta t}{2\Delta s}U_{i,j}^{t+1}-\frac{1}{4\cdot H_{i,j}^{t+1}}(K_{i,j}+K_{i,j-1})(H_{i,j}^{t+1}+H_{i,j-1}^{t+1})\frac{\Delta t}{\Delta s^2}$$

$$D_{i,j}^{t+1}=\frac{\Delta t}{2\Delta s}V_{i,j}^{t+1}-\frac{1}{4\cdot H_{i,j}^{t+1}}(K_{i-1,j}+K_{i,j})(H_{i-1,j}^{t+1}+H_{i,j}^{t+1})\frac{\Delta t}{\Delta s^2}$$

$$E_{i,j}^{t+1}=-\frac{\Delta t}{2\Delta s}V_{i,j}^{t+1}-\frac{1}{4\cdot H_{i,j}^{t+1}}(K_{i,j}+K_{i+1,j})(H_{i,j}^{t+1}+H_{i+1,j}^{t+1})\frac{\Delta t}{\Delta s^2} \quad (12)$$

$$RR = R_1 - R_2 - R_3 - R_4.$$

4. Successive over relaxation method (S.O.R)

For solving large linear system of finite differential equations(11), it requires iterative method for convergent predicted values. The iterative procedure is close to be convergent when the difference between the exact solution and the successive approximations tend to zero as the number of iterations increase.

Successive Over Relaxation method(S.O.R) is selected since it converges very fast. The equation of S.O.R is expressed as:

$$^{n+1}S_{i,j}^{t+1}={}^{n}S_{i,j}^{t+1}+\alpha_2\cdot{}^{n}R_{i,j}^{t+1} \quad (13)$$

where α_2 = acceleration parameter ($1 < \alpha_2 < 2$)

$^{n}S_{i,j}^{t+1}$ = n th iterated value of oxygen concentration

$^{n}R_{i,j}^{t+1}$ = displacement or specified accuracy.

RESULTS AND DISCUSSION

The model of DO dispersion is introduced to predict pattern of DO spreading in Yashima bay at low tide. This model combined the effects of source and sink which had been investigated by Inoue (1983-1987). The results of prediction were checked by the observed data which performed on October 6-7, 1994.

1. Data from the observations

On October 6-7, 1994 the quality of sea water such as dissolved oxygen content, temperature, salinity, depth, turbidity and current were observed about two tide cycles. On October 6, 1994 low tide was about 18:00 PM. and high tide was 23:00 PM. On October 7, 1994 low tide was about 6:00 AM. and high tide was 11:00 AM.

The instruments, dissolved oxygen meter YSI Model 57, Alec Electronics Co., LTD. STD Model AST-1000 S, Iio Electric Co., LTD. Model STA-487 turbidity meter 25 cm, current meter Model 201 Portable water and recorder type 3057 Yokogawa Electric Work Co, had been continuously recorded for 21 hours.

Dissolved oxygen meter and turbidity meter were measured at 2 m below the sea surface and current meter was measured at 4 m above the bottom. And every hour, water sample was collected at 2 m below water surface and was analyzed for suspended solid (SS) and chlorophyll a. These data were presented in Table 2. Comparison of water quality between DO content and water depth was shown in Figure 2, between

Table 2 Quality of sea water at Yashima bay station on October 6-7,1994.

Time	DO* (mg/l)	SS* (mg/l)	Velocity1/ East flow (cm/sec)	North flow (cm/sec)	Chl-a1/ (μg/l)	Water2/ temperature (°C)	Salinity2/ (g/1000g)	Depth (m)
15:00	5.7	8.1	4.2	-1.1	1.8	25.7	32.6	5.4
	5.5	7.6	7.6	3.5	1.9	25.6	32.5	5.4
	5.5	7.6	4.5	3.8	2.5	25.4	32.5	5.2
	5.3	8.4	2.9	2.2	2.2	25.4	32.5	5.2
	5.4	8.3	-1.1	3.8	2.2	25.3	32.5	5.2
20:00	5.4	8.9	-7.3	0.9	2.2	25.4	32.5	5.6
	5.4	8.9	-12.1	-5.7	1.7	25.4	32.6	6.2
	5.5	9.6	-12.7	-6.9	1.6	25.3	32.6	6.6
	5.8	8.6	-13.4	-7.7	1.6	25.4	32.6	6.6
1:00	5.5	8.1	2.6	0.2	1.6	25.4	32.6	6.4
	5.5	8.5	4.3	-3.1	1.4	25.3	32.5	6.0
	5.6	8.9	5.8	-3.0	1.4	25.3	32.6	5.4
	5.6	9.3	7.1	0.4	1.4	25.1	32.5	5.0
	5.7	11.7	3.8	0.8	1.5	25.1	32.5	4.8
6:00	5.4	12.4	3.7	8.6	1.8	25.2	32.5	4.6
	5.4	11.2	-0.2	5.5	2.0	25.1	32.5	4.8
	5.6	11.3	-5.3	1.6	2.4	25.1	32.5	5.2
	6.1	9.9	-5.3	-6.1	2.2	25.3	32.6	5.8
	6.3	7.9	0.0	-3.9	1.9	25.4	32.6	6.2
11:00	6.3	6.7	0.0	-6.8	2.1	25.4	32.6	6.6
	6.3	7.4	0.0	-0.4	2.2	25.5	32.6	6.6

1/ Observed data were taken at 2 m below sea water surface.

2/ Observed data were taken at 4 m above the bed.

temperature and salinity was shown in Figure 3, between DO content and Chlorophyll a (Chl-a) was shown in Figure 4 and between DO content and SS was shown in Figure 5. At night time the maximum and minimum of DO content were about 5.8, 5.4 mg/l, respectively.

From Figure 2, it was found that during night time the dissolved oxygen content were controlled by advective and diffusion. During maximum stream of flood and ebb tide, the flow was very fast, the DO change rate rapidly increased. In the opposite way, the flow was very slow during high tide or low tide, the DO change rate decreased.

From Figure 4, it showed that at night time effect of primary production was stable. Since whenever the DO content was changed, the quantity of Chl-a was nearly constant.

From results of turbidity measurement, the relation between SS and attenuation coefficient (C) of turbidity meter was found as:

$$SS = 2.11C + 2.29$$

where C= attenuation coefficient at time t (m^{-1}).

This relation had correlation coefficient about 0.83 which were shown in Figure 6. By this relation, prediction of the continuous data of SS could be done as shown in Figure 7. (denote that during 6:00-9:00 AM was feeding time).

2. Comparisons of result

The programs of dissolved oxygen dispersion had been written in FORTRAN language which were modified by the works of Horiguchi (1969). They consisted of computing program and graphic program. The computing program used to calculate the DO content at all area of model. Graphic program obtained many graphical and digital results. The parameters related to the computer simulation of DO dispersion were shown in Table 3.

On October 6-7, the DO content at low tide (18:00 PM. and 6:00 AM.) were measured in and around area of fish farms. DO dispersion pattern were shown in Figure 8 and Figure 9. On October 6,1994 before dark, minimum of DO content was 5.9 mg/l which located at the south part of fish farms. And on October 7, 1994 at the same place before light, these was minimum of DO content about 4.7 mg/l.

From the hypothetical of principle of respiratory dependence of fish the fish is stress when the DO content is less than 4 mg/l. So it seemed that these conditions indicated security for fish life.

The results of prediction, the patterns of DO dispersion at low tide before dark and before light at low tide, were shown in Figure 10 to Figure 11, respectively. Since the patterns of DO dispersion related to patterns of flow. The patterns of DO distribution were changed when the patterns of flow changed. During ebb tide, the center of DO distribution pattern was on the southern part of the fish culture. The minimum DO content during neap tide were about 4.7 mg/l.

For checking the results of this model, predicted DO content at grid point (100,108) were compared to observed DO content at Yashima station as shown in Figure 12. The result showed that the data from prediction agree with data from of observation. At night time, maximum and minimum of DO content were about 5.8 and 5.4 mg/l respectively. Since the souces and sinks of oxygen were used as average values, so there were some errors as shown in this figure. But the maximum and minimum of predicted DO content and observed DO content were nearly the same.

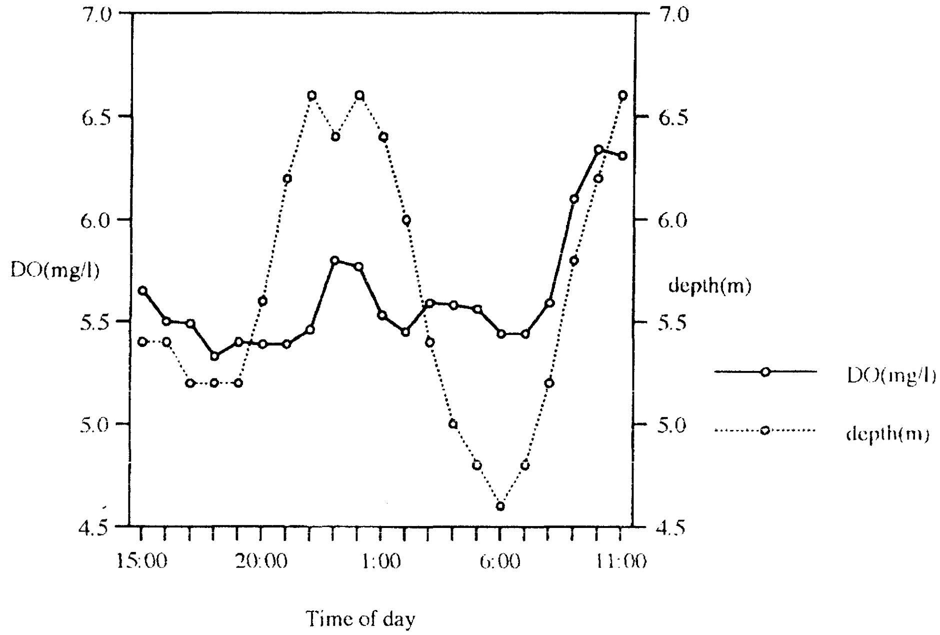


Figure 2 Comparison of DO with depth variation curve at Yashima station on 6-7 October, 1994.

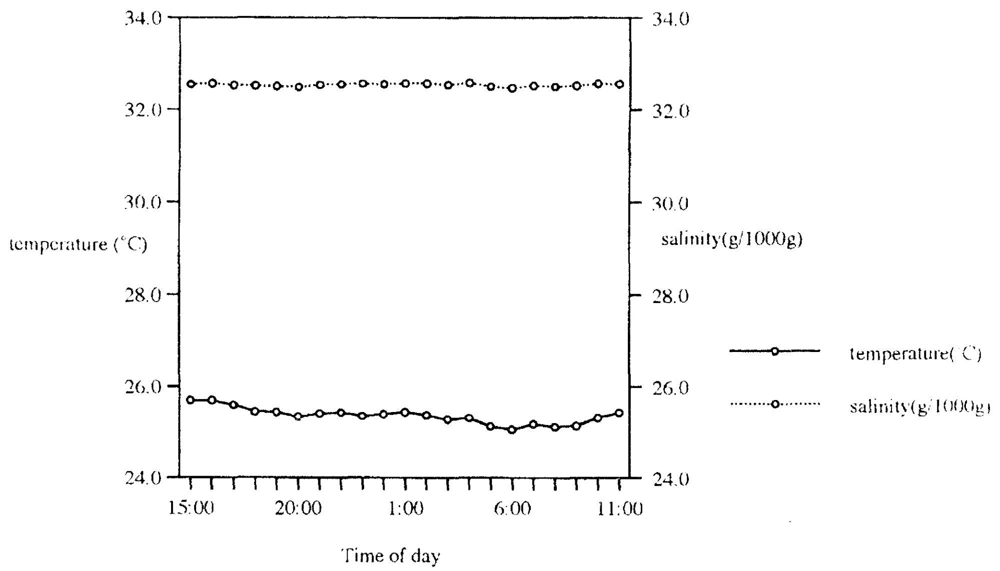


Figure 3 Comparison of temperature with salinity variation curve at Yashima station on 6-7 October, 1994.

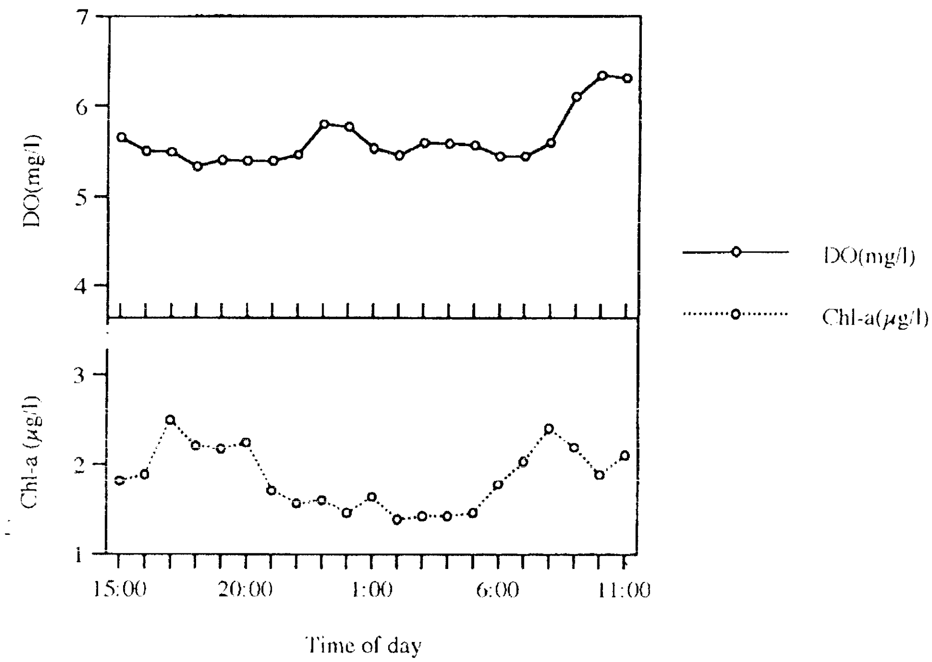


Figure 4 Comparison of DO with Chl-a variation curve at Yashima station on 6-7 October, 1994.

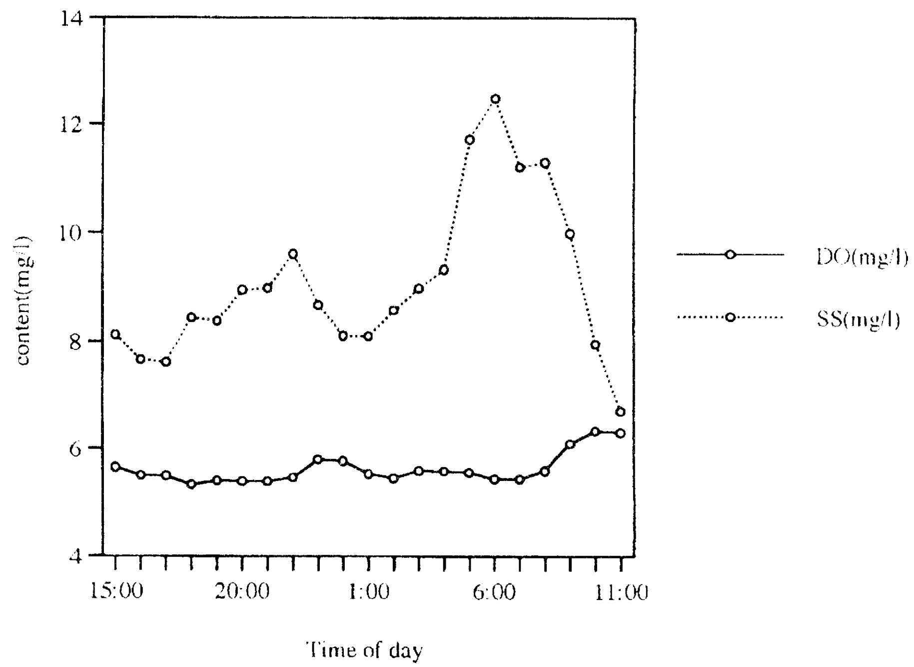


Figure 5 Comparison of DO with SS variation curve at Yashima station on 6-7 October, 1994.

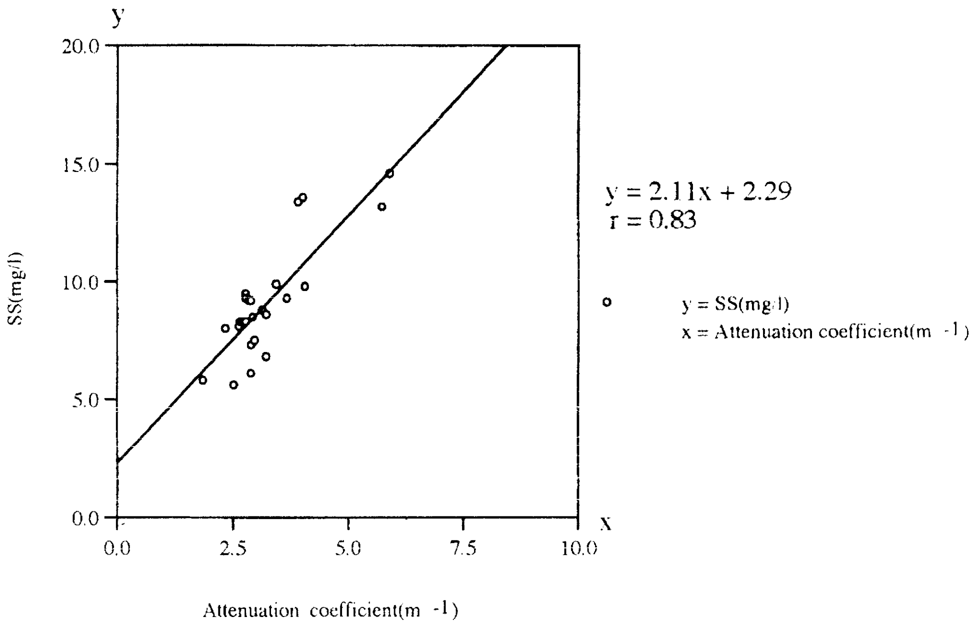


Figure 6 Relation between attenuation coefficient per meter and concentration of suspended solid in Yashima station on 6 October 1994.

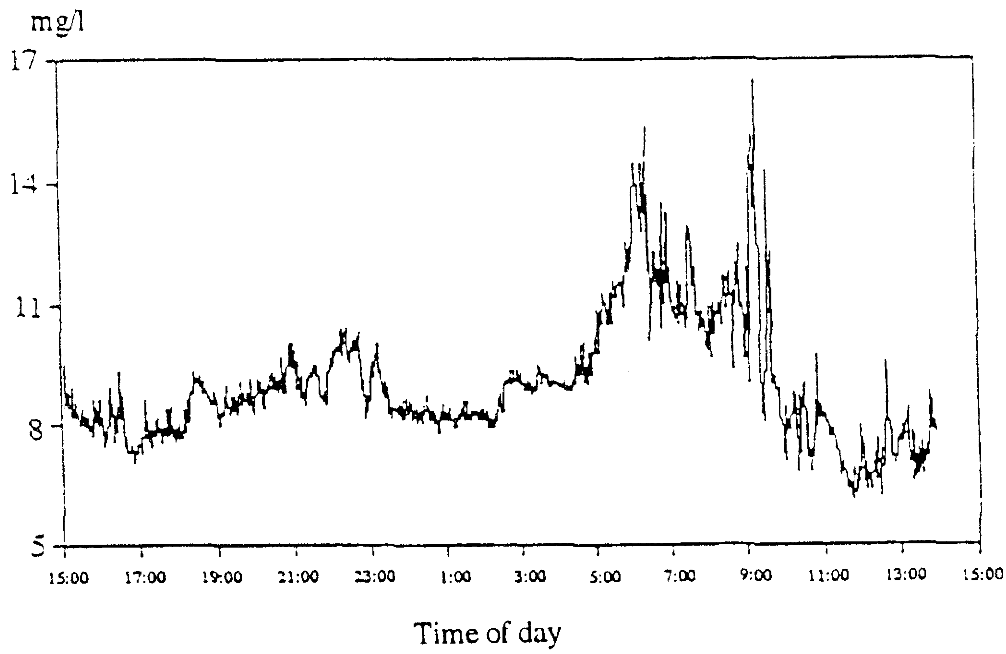


Figure 7 Variation of SS from prediction on October 6-7, 1994.

Table 3 The parameters related to the computer simulation of dispersion of DO.

Description	Unit	Symbol	Value
Time step	sec	Δt	300
Eddy diffusion cefficient	cm^2/sec	K	10^5
Reaeration rate of oxygen from air			
Exchange coefficient	cm/sec	K_l	0.0011
Oxygen concentration at saturation	mg/l	S_s	6.76
Mean sea water depth	cm	H	400
Benthal oxygen uptake rate.			
Term of oxygen uptake by bacteria activity	$mg/(hr^2.m)$	$2 \cdot K_m \cdot D$	138
Mean sea water depth	cm	H	400
DO consumption by sea water			
Proportion coefficient	$\frac{mg \cdot cm^2}{sec \cdot l \cdot indiv.}$	α_1	$3.0x10^{-5}$
Grid interval	cm	Δs	2000
Average number of fish per one cage	indiv./cage	N	$1.9x10^3$
Oxygen consumption rate by sea water at 25.5°C	mg/(sec.l)	OUW	$7.9x10^{-6}$
Respiration rate of Yellow tail			
Average number of fish per one cage	indiv./cage	N	$1.9x10^3$
Mean sea water depth	cm	H	400
Grid interval	cm	Δs	2000
The level of metabolism at 20°C	-	$\alpha_{20°}$	550
Temperature coefficient	-	Q_{01}	1.078
Averaged body weight of fish in October	kg	W	2.3
Temperature	°C	T	25.5
Weight exponent	-	γ	0.78

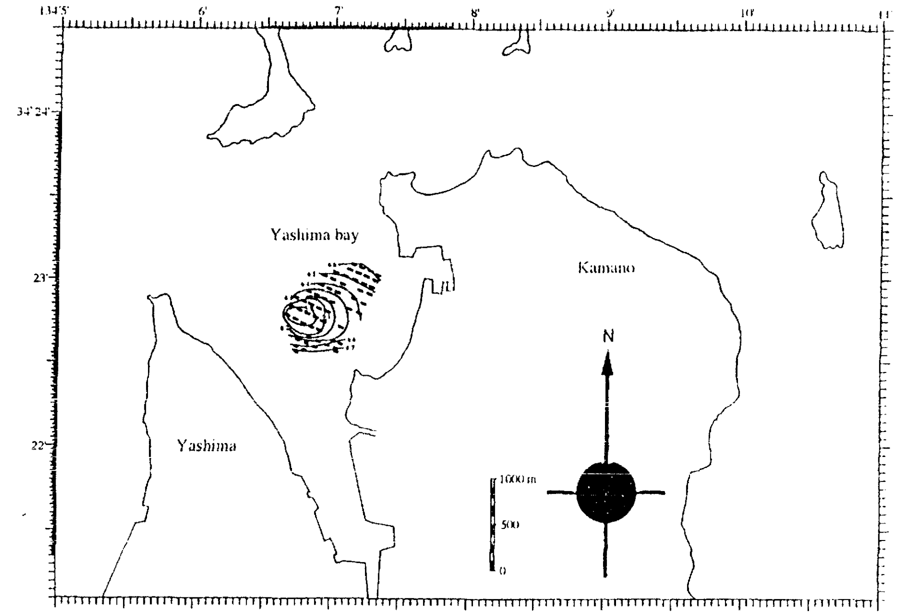


Figure 8 Horizontal distribution of DO content around Yellow tail fish culture in Yashima bay at low tide On 6 October, 1994

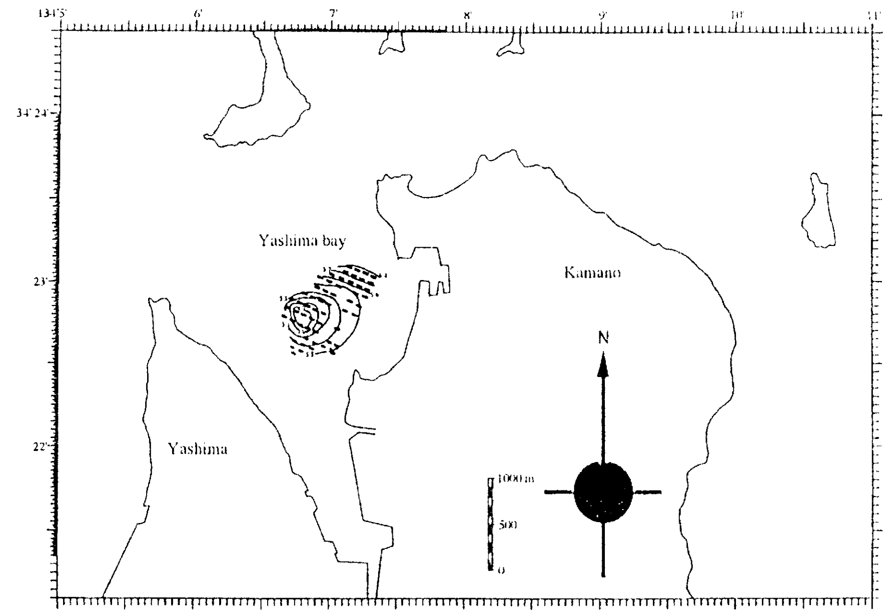


Figure 9 Horizontal distribution of DO content around Yellow tail fish culture in Yashima bay at low tide On 7 October, 1994

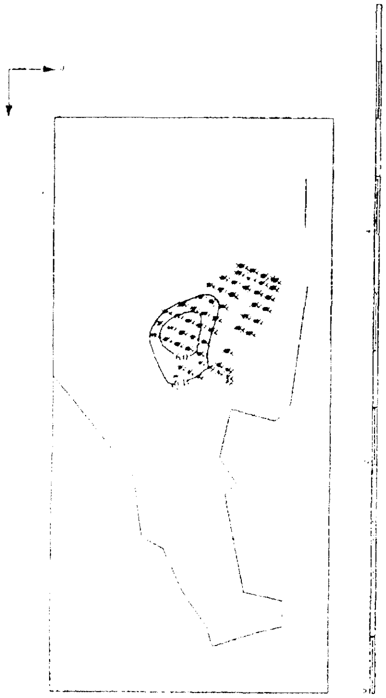


Figure 10 Predicted DO distribution pattern at low tide in site of study before dark

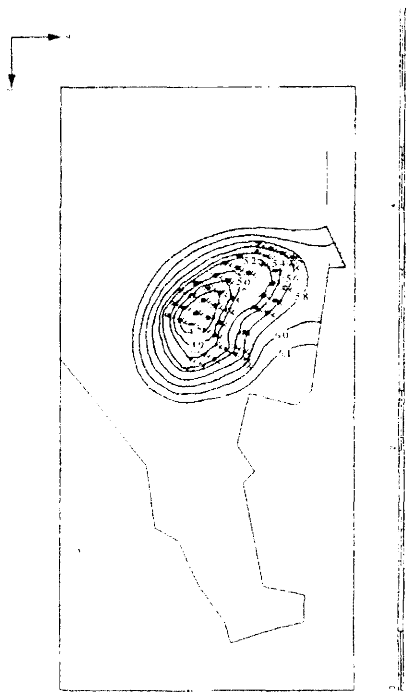


Figure 11 Predicted DO distribution pattern at low tide in site of study before light

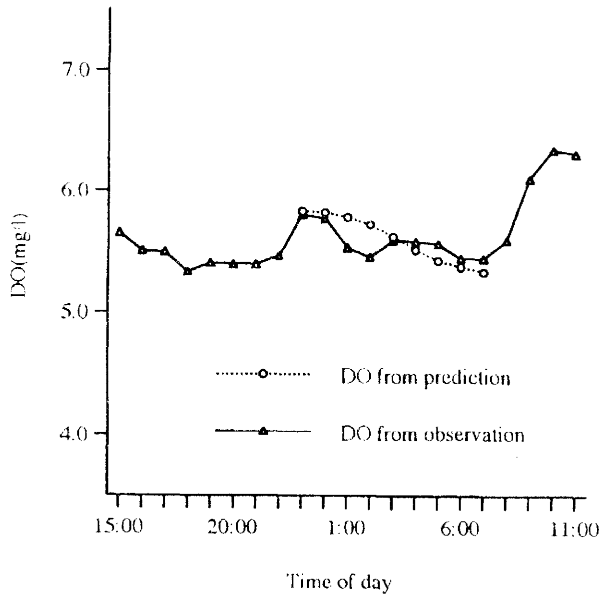


Figure 12 Comparison of DO during spring tide between prediction value at grid point (100,108) and observed value on 6-7 October, 1994. at Yashima station.

LETERATURE CITED

Horiguchi, H. 1969. Numerical Solution of Matter Diffusion, 16th Coast Association Meeting, Japan. 162 p. (in Japan)

Inoue, H. 1983. Experiments of Red Tide Countermeasure Technique. Marine Laboratory of Nagasaki Prefecture, Japan. 77 p. (in Japan)

Inoue, H. 1984. Experiments of Red Tide Countermeasure Technique. Marine Laboratory of Nagasaki Prefecture, Japan. 62 p. (in Japan)

Inoue, H. 1985. Experiments of Red Tide Countermeasure Technique. Marine Laboratory of Kagawa Prefecture, Japan. 74 p. (in Japan)

Inoue, H. 1986. Experiments of Red Tide Countermeasure Technique. Marine Laboratory of Kagawa Prefecture, Japan. 64 p. (in Japan)

Inoue, H. 1987. Experiments of Red Tide Countermeasure Technique. Marine Laboratory of Kagawa Prefecture, Japan. 55p. (in Japan)

Monton, A. and T. Sasaki. 1995. Studies on Numerical Simulation of DO dispersion in the Marine Culture Farm, Kagawa University, Japan. 169 p.

Sasaki, T. and H. Inoue. 1984. Eddy diffusivity for material transport intheBisan-Seto area. Technical Bulletin of Faculty of Agriculture, Kagawa University. 36: 31-38.

Sasaki, T. and H. Inoue. 1985. Studies on the assessment of the allowable stocking capacity of yellowtail cultured in the Fukaura fishfarm . Technical Bulletin of Faculty of Agriculture, Kagawa University. 37: 41-53.

Sasaki, T., T. Potapirom, and H. Inoue. 1986a. Studies on the assessment of the allowable stocking capacity of yellowtail cultured in the Fukaura fishfarm. Technical Bulletin of Faculty of Agriculture, Kagawa University. 37: 131-148.

Sasaki, T., T. Potapirom. and H. Inoue. 1986b. Studies on the assessment of the allowable stocking capacity of yellowtail cultured in the Fukaura fishfarm. Technical Bulletin of Faculty of Agriculture, Kagawa University. 38: 25-36.

Thames Survey Committee, 1964. Absorption of atmospheric oxygen.Effects of polluting discharges on the Thames estuary. London. 1054 p.