Memoirs of the School of Engineering, Okayama University, Vol. 21, No.2, February 1987

Influence of Sewage Treatment System on Water Quality in Kojima Lake

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(Received January 16, 1987)

SYNOPSIS

This study dealt with the characteristics of hydrodynamics of Kojima Lake and the influence of a regional sewage treatment system in construction on the lake.

Clockwise and anticlockwise circulations are caused by seasonal winds in summer and winter, respectively. The distribution of a conservative material continuously discharged off the shore of the sewage treatment plant is scarcely affected by seasonal winds and river discharges. The sewage treatment system improves the water quality of the lake except T-N.

1. INTRODUCTION

Kojima Lake is a artificial lake separated from Kojima Bay. Since the separation the water quality of the lake have deteriorated and the water pollution of the lake is a serious problem. In order to improve the water quality a regional sewage treatment system is in construction and the treated waste water will be discharged into the lake from 1987.

The objectives of this study are to clarify the characteristics of hydrodynamics of the lake and to investigate the influence of the

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sewage treatment system on the water quality of the lake.

2. STUDY AREA

Fig.1 shows Kojima Lake and the locations of observation and a treatment plant in construction. The area of the lake is about 8km². However maximum depth of the lake is about 9m, the depth of most part of the lake is less than 2m, and then the mean depth is 1.6m. Saline water, which inflows through a bank and a lock gate, exists near the bottom in the deeper region.

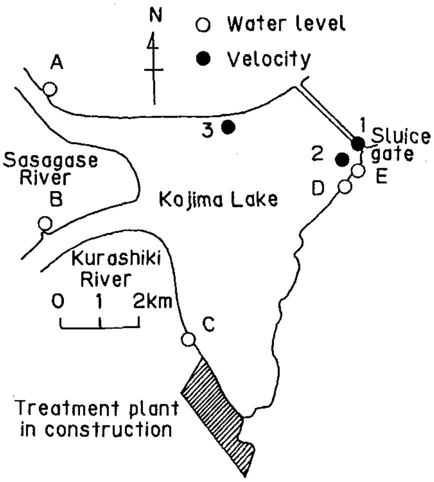


Fig.1 Study area

The Kurashiki River and Sasagase River flow into the lake and about 90% of the total contributory area of the lake is occupied by these river basins. The total flow rate of them is about 20m³/s. The yearly averaged retention period in the lake is about 10 days.

3. COMPUTATIONAL MODEL

3.1 Computational Models for Hydrodynamics and Dispersion of Conservative Material

The characteristics of hydrodynamics and dispersion were investigated using the following three dimensional equations of motion, continuity, dispersion and state.

Equations of motion

$$\frac{\partial u}{\partial t}+\frac{\partial(uu)}{\partial x}+\frac{\partial(uv)}{\partial y}+\frac{\partial(uw)}{\partial z}=fv-\frac{1}{\rho}\frac{\partial P}{\partial x}+\frac{1}{\rho}\left(\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{zx}}{\partial z}\right) \quad ---(1)$$

$$\frac{\partial v}{\partial t}+\frac{\partial(uv)}{\partial x}+\frac{\partial(vv)}{\partial y}+\frac{\partial(vw)}{\partial z}=-fu-\frac{1}{\rho}\frac{\partial P}{\partial y}+\frac{1}{\rho}\left(\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{zy}}{\partial z}\right) \quad ---(2)$$

$$-\rho g-\frac{\partial P}{\partial z}=0 \quad ---(3)$$

Equation of continuity

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad \text{---(4)}$$

Advective dispersion equation of conservative material

$$\frac{\partial c}{\partial t}+\frac{\partial (cu)}{\partial x}+\frac{\partial (cv)}{\partial y}+\frac{\partial (cw)}{\partial z}=\frac{\partial}{\partial x}(D_x\frac{\partial c}{\partial x})+\frac{\partial}{\partial y}(D_y\frac{\partial c}{\partial y})+\frac{\partial}{\partial z}(D_z\frac{\partial c}{\partial z}) \qquad \text{---(5)}$$

Equation of state

$$\rho=\frac{P_0}{\lambda+\alpha_0 P_0} \qquad \text{---(6)}$$

$$\lambda = 1779.5 + 11.25T - 0.0745T^2 - (3.80 + 0.1T)S$$

$$\alpha_0 = 0.6980$$

$$P_0 = 5890 + 38T - 0.375T^2 + 3S$$

where, ρ=fluid density; u,v and w=fluid velocity; P=pressure; τ=shear stress; g=acceleration of gravity; c=concentration of a conservative material; f= Coriolis parameter; S=salinity; T=temperature(°c); and D_x,D_y and D_z= dispersion coefficient.

A space-staggered grid shown in Fig.2 was selected for the finite-difference approximation of Eqs.(1) through (6)[1,2]. A computational grid(Δx=Δy=200m) adopted in Kojima lake is shown in Fig.3. The grid is vertically divided into three layers. The thickness of the top layer is 3m and those of the middle and bottom layer are 2m.

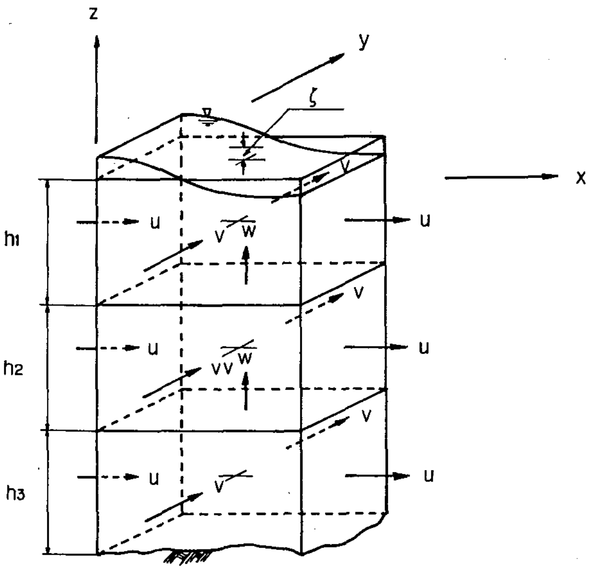


Fig.2 Space-staggered grid

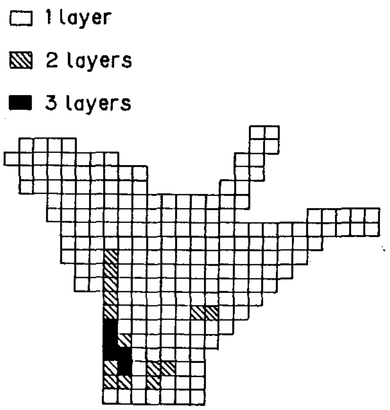


Fig.3 Computational grid

The boundary conditions applicable to the numerical simulation are as follows. At the sluice gate the discharge through the gate is applied. At the mouths of the rivers the water levels or flow rates are applied. The shear stresses at the surface, the bottom and the interlayer are given as follows.

$$\begin{pmatrix}\tau_{sx}\\ \tau_{sy}\end{pmatrix} = \gamma_a^2\,\rho_a\begin{pmatrix}W_x\\ W_y\end{pmatrix}\sqrt{W_x^2 + W_y^2} \qquad ---(7)$$

$$\begin{pmatrix}\tau_{bx}\\ \tau_{by}\end{pmatrix} = \gamma_b^2\,\varphi\begin{pmatrix}u\\ v\end{pmatrix}\sqrt{u^2 + v^2} \qquad ---(8)$$

$$\begin{pmatrix}\tau_{ix}\\ \tau_{iy}\end{pmatrix} = \gamma_i^2\,\rho\begin{pmatrix}\Delta u\\ \Delta v\end{pmatrix}\sqrt{\Delta u^2 + \Delta v^2} \qquad ---(9)$$

where, τ_s, τ_b and τ_i=shear stresses at the surface, the bottom and the interlayer, respectively; W=wind velocity; u and v=flow velocity; Δu and Δv=velocity difference between vertically adjacent layers; ρ_a and ρ=density of air and the lake water, respectively; γ_a^2 and $\gamma_b^2 = 0.0026$; $\gamma_i^2 = 0.0001$.

The horizontal dispersion coefficients of momentum and mass selected are $10m^2/s$. As the stability of a water column reduces the intensity of turbulent mixing, the vertical dispersion coefficient of mass can be taken to be a function of Richardson number [2]. This study adopts following function.

$$D_z = D_0 \exp(-3R_i) \qquad ---(10)$$

where, D_0 is the vertical dispersion coefficient of mass for neutral stability.

3.2 Computational Model for Lake Ecosystem

The computational model for hydrodynamics and dispersion is inappropriate for the long period simulation of lake ecosystem. Therefore, a compartment model is adopted for it. Based on the simulation results of the hydrodynamics and the dispersion of a conservative material, Kojima lake is divided into 5 blocks as shown in Fig.4. The retention period in each block is nearly equal.

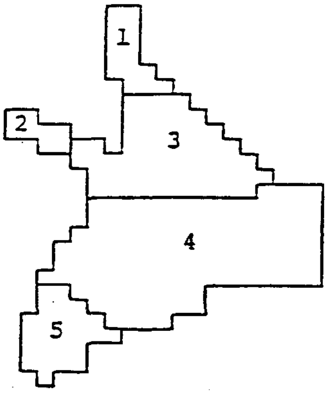


Fig.4 Block system

The differential equations used in this study are shown in Table 1. In the derivation of these equations, the change of phytoplankton and balances of nutrients and COD are taken into account.

Table 1 Equations of lake ecosystem

$$d(ch)/dt=Q_i \cdot ch/V+G_p \cdot ch-k_d \cdot T \cdot ch-Q_o \cdot ch/V$$

$$G_p=\mu_{max}(N_d/(K_N+N_d))(P_d/(K_P+P_d))(E/(K_E+E))K$$

$$COD_t=COD_{ch}+COD_p+COD_d$$

$$COD_{ch}=\xi_{COD} \cdot ch$$

$$d(COD_p)/dt=Q_i \cdot COD_p/V+\xi_{COD} \cdot k_d \cdot T \cdot ch-f_c \cdot COD_p -k_s \cdot A \cdot COD_p/V-Q_o \cdot COD_p/V$$

$$d(COD_d)/dt=Q_i \cdot COD_d/V+k_{COD} \cdot \xi_{COD} \cdot G_p \cdot ch-f'_c \cdot COD_d +A \cdot D_{COD}/V-Q_o \cdot COD_d/V$$

$$N_t=N_{ch}+N_p+N_d$$

$$N_{ch}=\xi_N \cdot ch$$

$$d(N_p)/dt=Q_i \cdot N_p/V+\xi_N \cdot k_d \cdot T \cdot ch-f_c \cdot N_p-k_s \cdot A \cdot N_p/V -Q_o \cdot N_d/V$$

$$d(N_d)/dt=Q_i \cdot N_d/V-\xi_N \cdot G_p \cdot ch+f_c \cdot N_p+A \cdot D_N/V -k_{dN} \cdot N_d \cdot \theta^{T-20}-Q_o \cdot N_d/V$$

$$P_t=P_{ch}+P_p+P_d$$

$$P_{ch}=\xi_P \cdot ch$$

$$d(P_p)/dt=Q_i \cdot P_p/V+\xi_P \cdot k_d \cdot T \cdot ch-f_c \cdot P_p-k_s \cdot A \cdot P_p/V -Q_o \cdot P_p/V$$

$$d(P_d)/dt=Q_i \cdot P_d/V-\xi_P \cdot G_p \cdot ch+f_c \cdot P_p+A \cdot D_P/V -Q_o \cdot P_d/V$$

In this compartment model not only transport by advection but also by dispersion take the form of the product of concentration and volume transport of fluid. The volume transport of fluid which represents dispersion is called exchange flow rate [3]. The flow rate shown in Table 2 includes the exchange flow rate, which is

Table 2 Variables and parameters in ecosystem equations

Symbol	Definition	Value
A	bottom area	
COD	chemical oxygen demand	
ch	chlorophyll-a	
D_{COD}	release rate of COD from sediments	0.13mg/m^2/d
D_N	release rate of nitrogen from sediments	14mg/m^2/d
D_P	release rate of phosphorus from sediments	2.0mg/m^2/d
E	light intensity	
f_c	inorganization rate for detritus	0.01/d
f_c	inorganization rate for dissolved organics	0.01/d
K	correction factor of growth rate for water temperature	$0<K\leq 1$
K_E	Michaelis constant for light intensity	100cal/cm^2/d
K_N	Michaelis constant for nitrogen	0.3mg/l
K_P	Michaelis constant for phosphorus	0.02mg/l
k_{COD}	coefficient of COD increase by metabolism of phytoplankton	0.05g/g
k_d	death rate of phytoplankton	0.0015/°c/d
k_{dN}	denitrification rate	0.03/d
k_s	sedimentation rate	0.03m/d
N	nitrogen	
P	phosphorus	
Q_i	inflow rate	
Q_o	outflow rate	
T	water temperature	
V	water volume	
θ	temperature coefficient	1.06
μ_{max}	maximum growth rate of phytoplankton	0.1/d
ξ_{COD}	ratio of COD/chlorophyll-a in phytoplankton	0.06mg/μg
ξ_N	ratio of N/chlorophyll-a in phytoplankton	0.01mg/μg
ξ_P	ratio of P/chlorophyll-a in phytoplankton	0.001mg/μg

Meaning of subscript

ch	phytoplankton	d	dissolved
p	paticulate	t	total

estimated based on the simulation results for the dispersion of a conservative material.

4. RESULTS AND DISCUSSIONS

4.1 Hydrodynamics in Kojima Lake

The water levels obtained by the numerical simulation at Location D and E are shown in Fig.5 in comparison with the observed values. Here, the lake water was discharged through the sluice gate from 12:15 to 14:50. The simulation results show good agreement with the observed values.

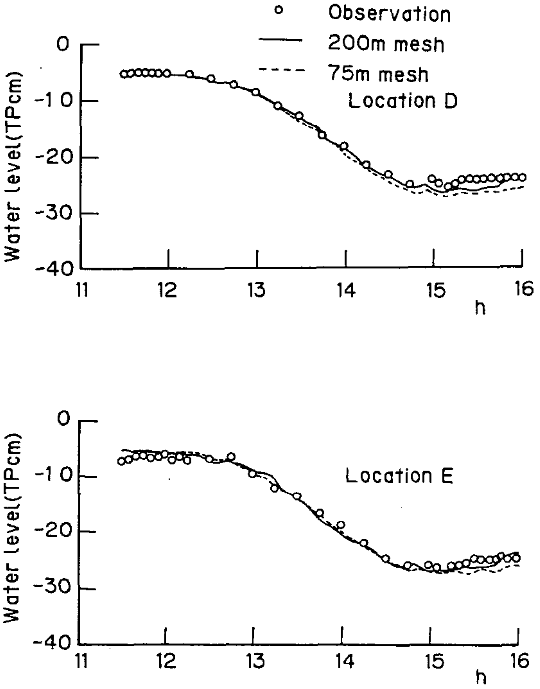


Fig.5 Comparison of numerical simulation with observation

Fig.6 shows the distributions of velocity components during opening the gate and just after closing it. The vertical components of the velocity vectors are multiplied by 100. Before the gate is open, the velocity in the lake is negligible. When the gate is open, all lake currents flow toward the gate. When the gate is closed, the velocity becomes slow again. Just after closing the gate, the velocity components in the middle layer and bottom layer flow in the opposite direction to the gate however those in the surface layer continue to flow toward the gate.

Fig.7 and Fig.8 show the typical wind-driven currents in summer and winter, respectively. These flow patterns are under the condition that the same wind continue to blow for one hour. The clockwise and anticlockwise circulation are found in summer and winter,respectively. The stratification by saline water causes vertical circulations in both cases.

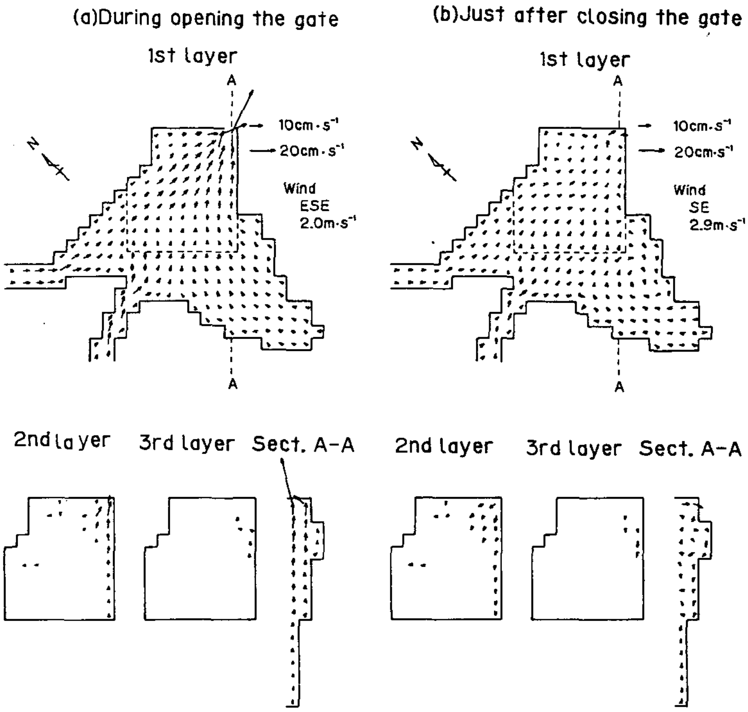


Fig.6 Velocity components during opening the gate and just after closing it

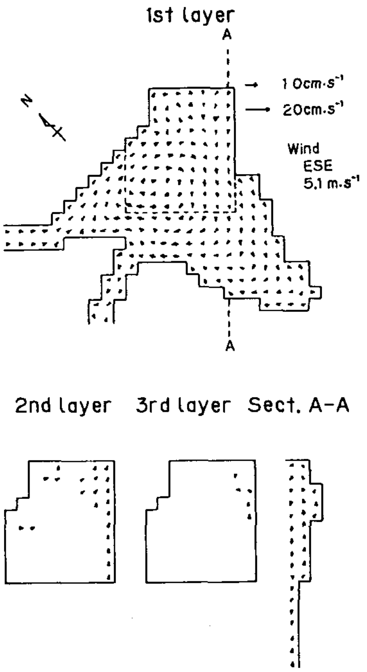


Fig.7 Typical wind-driven currents in summer

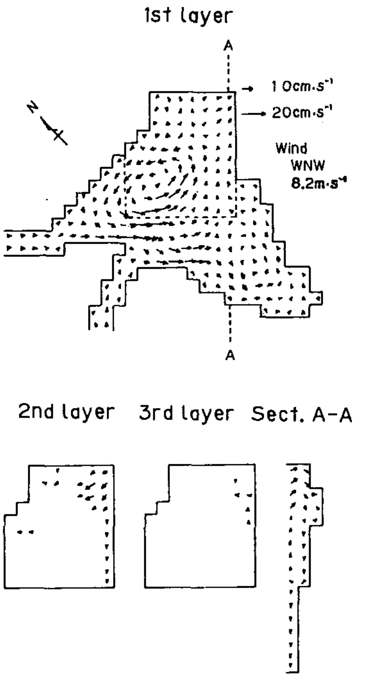


Fig.8 Typical wind-driven currents in winter

4.2 Dispersion of Conservative Material

Assuming that the sewage effluent of $6m^3/s$ containing a conservative material of 10mg/ℓ is discharged off the shore of the treatment plant, the dispersion of the conservative material is investigated by using numerical simulations under the conditions shown in Table 3. The simulation results are shown from Fig.9 to Fig.12. As it is assumed that the sewage effluent only contains the material, the ratio of the effluent to the lake water can be seen from the concentration of the conservative material in the lake.

As may be seen from these figures, the concentration decreases from the offshore of the sewage treatment plant toward the mouths of the rivers. The isolines more than 3mg/ℓ remain around the shore of the plant regardless of seasonal winds and river discharges. The concentration in the middle part of the lake is about 2mg/ℓ in all cases. The seasonal winds and river discharges mainly affect on the isolines of 2mg/ℓ. The influence of the gate operation on the distribution is small.

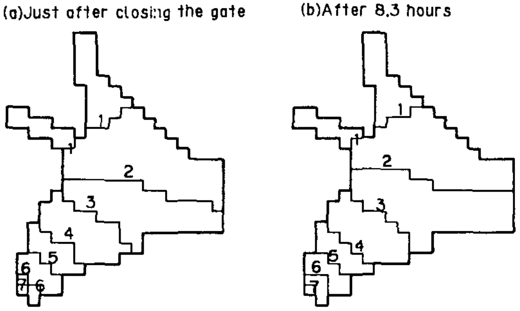
Table 3 Conditions of calculation

Case No.	River discharge	Wind
1	Yearly average Sasagase River;$12.3m^3 \cdot s^{-1}$ Kurashiki River;$4.5m^3 \cdot s^{-1}$	Summer wind*
2	Same as case 1	Winter wind*
3	Average during irrigation period Sasagase River;$15.8m^3 \cdot s^{-1}$ Kurashiki River;$7.9m^3 \cdot s^{-1}$	Summer wind*
4	Average during non-irrigation period Sasagase River;$8.0m^3 \cdot s^{-1}$ Kurashiki River;$3.9m^3 \cdot s^{-1}$	Winter wind*

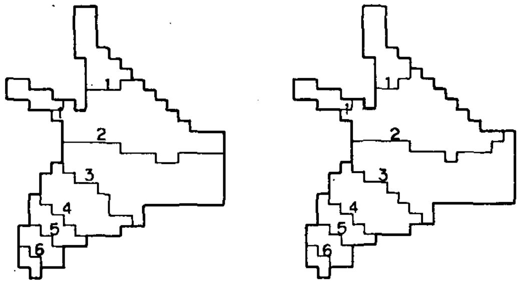
*Summer wind and winter wind data were obtained at Enami near Kojima Lake in August,1984 and January ,1984.

4.3 Change of Water Quality before and after the construction of the Sewage Treatment System.

Water quality data were obtained in 1980, and are compared with simulation results in Fig.13. The simulation results show relatively good agreement with the tendency observed in spite of the insufficiency of the necessary input data. It should be noted that the water quality in the summer of 1980 was better than a ordinary summer be-

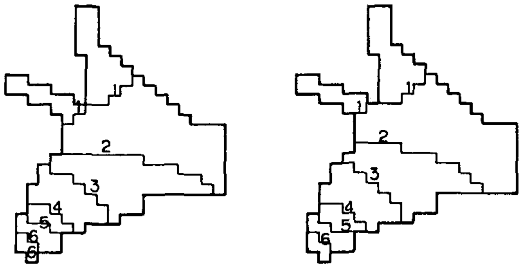

(a)Just after closing the gate

(b)After 8.3 hours

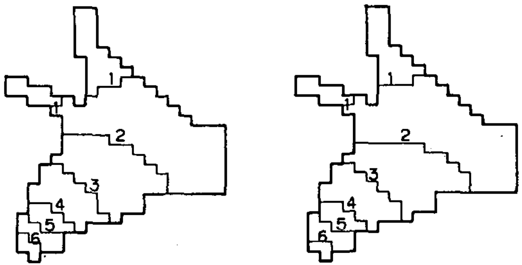

(c)After 20.3 hours

(d)Just before opening the gate (after 28.7 hours)

Fig.9 Concentration distribution for Case 1

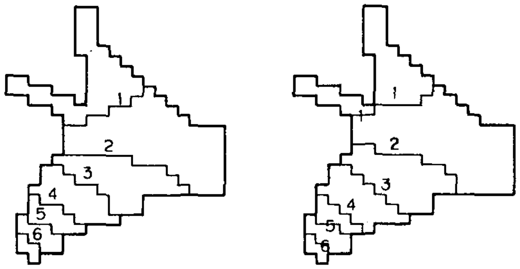

(a)Just after closing the gate

(b)After 8.4 hours

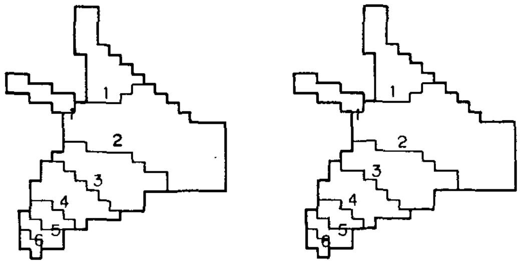

(c)After 20.4 hours.

(d)Just before opening the gate (after 28.7 hours)

Fig.10 Concentration distribution for Case 2

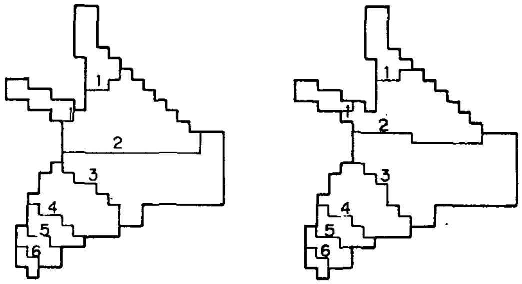

(a)Just after closing the gate

(b)After 7.8 hours

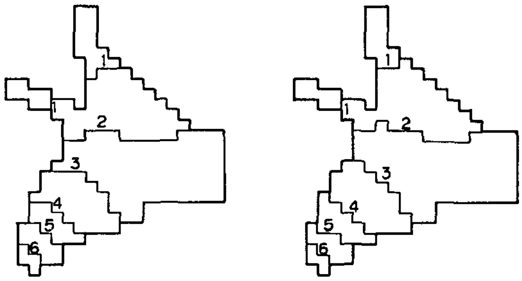

(c)After 19.8 hours

(d)Just before opening the gate (after 21.4 hours)

Fig.11 Concentration distribution for Case 3


(a)Just after closing the gate

(b)After 16.1 hours


(c)After 24.1 hours

(d)Just before opening the gate (after 37.2 hours)

Fig.12 Concentration distribution for Case 4 cause the summer was rainy.

Fig.14 and Fig.15 show the comparison of the water quality before and after the construction of the sewage treatment system. The water quality after the construction is obtained assuming that the sewage effluent of 6m^3/s, which contains COD of 9mg/ℓ, T-N of 7mg/ℓ and T-P of 0.3mg/ℓ, is discharged into Block 5, and that the pollutant loads and flow rates of the rivers decrease by the amount of waste water cut off by the system.

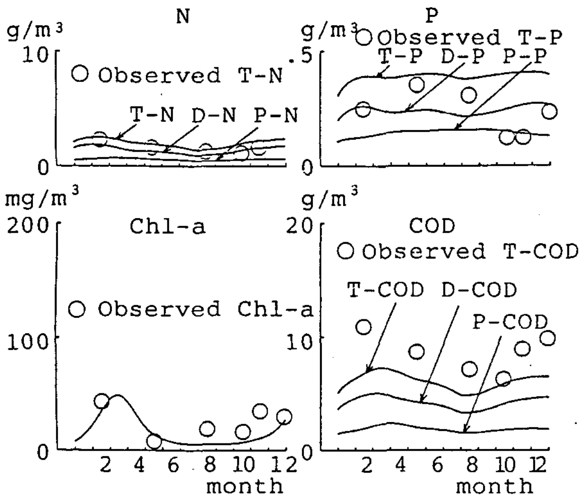


Fig.13 Comparison between simulation and observation

As may be seen from Fig.14, the water quality in Block 4 is improved except T-N. The similar results are obtained in the other blocks. COD in Block 5, where the effluent will be discharged, is somewhat improved as shown in Fig.15. Positive preventative countermeasures against T-N must be considered.

However the simulation results show relatively good agreement with the tendency observed, some of the parameters used in this study are considerably different from those previously reported [6,7]. We feel there is much room for further investigation on the parameters.

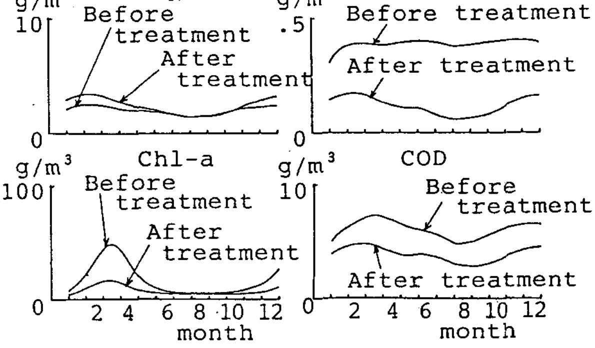


Fig.14 Influence of sewage treatment in Block 4

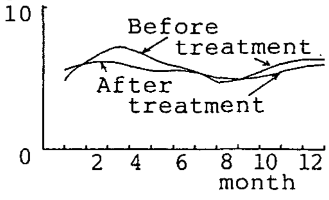


Fig.15 Influence of sewage treatment in Block 5

5. CONCLUSIONS

This study dealt with the characteristics of hydrodynamics of Kojima Lake and the influence of a regional sewage treatment system on the lake.

Clockwise and anticlockwise circulations are caused by seasonal winds in summer and winter, respectively. Under the assumption that the sewage effluent containing the conservative material of 10mg/ℓ is discharged off the shore of the treatment plant, the isolines more than 3mg/ℓ remain around the shore of the plant regardless of seasonal winds and river discharges. The sewage treatment system will improve the water quality of the lake except T-N.

As the retention period in the lake is short, the predicted water quality is significantly affected by the pollutant loads from rivers and their flow rates. Therefore, more of observation concerning the pollutant loads and flow rates are needed in order to improve the prediction accuracy.

ACKNOWLEDGEMENT

Thanks are giving to our colleagues for their assistance in computations and observations. The authors are also greatly indebted to a financial support by the Grant in Aid of Scientific Research from the Ministry of Education, Culture and Science.

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