La mer 40 : 191–202, 2002
Société franco-japonaise d'océanographie, Tokyo

On the Possibility of Improving the Flow and Water Quality in a Closed Inland Bay by Using Cooling Water for a Power Generating Plant

Tairyu TAKANO*, Michihiro SHIBAZAKI** and Akira WADA***

Abstract : A quasi 3-dimensional flow model and a water quality model (the Chesapeake Bay Model) were applied to a hypothetical power station to investigate whether it is possible that the intake and discharge of cooling water for a station located on a closed inland bay might bring beneficial change to the oceanic environment. The results of the flow and water quality calculations show that the intake and discharge of cooling water promote water exchange in the inland bay; in particular, there is accelerated exchange of the nutrient - enriched water inside the bay with cleaner water from outside the bay, so that there is at least a possibility that water quality will gradually be improved. In addition, bottom water pumped up continuously in front of the power plant brings about water quality changes in a concentric circular pattern: significant water quality changes are limited to the region within which the sea water temperature rises 1℃ or more.

Keywords : *Water flow and water quality analysis. Cooling water discharge*

1. Introduction

In Japan there are many thermal and atomic power plants, which are located along the coast so that they can use seawater for cooling. These power plants do not release pollutants into the water, but by affecting the water flow and temperature fields, they must have secondary effects on the marine environment. Until now most investigations on the environmental effect of the power plant discharges have been limited to investigating the extent of the area within which water temperature increases. But recent progress in methods of modeling water quality has made it possible to investigate the change of water quality as well.

When warm water is discharged from a power plant, the water temperature in the ocean in front of the power plant rises, causing photosynthesis to become more active and phytoplankton to multiply. If the water is rich in nutrients, this can give rise to more water pollution. However, at the same time intake and discharge of cooling water by the power plant promotes greater circulation of the water in the bay, which can be expected to have the effect of transporting nutrients out of the bay, (SUDO, 1993) so it is unclear what net effect there will be if the power plant is located at the shore of a closed inland bay. For this reason, we have performed calculations with a flow and water quality model to estimate the difference that can be expected between the present situation in such a bay and the situation that would exist if a power plant were built on its shore. There was particular interest in the possibility that the cooling water discharge might enhance the water flow and improve the water quality. We took as the object of our study Mikawa Bay (Fig. 1), where at present there is no power plant in the interior of the bay, in the summertime, when water quality is known to deteriorate.

* Laboratory of Aquatic Science Consultant Corporation, Kami Ikedai 1-14-1, Ota-ku, Tokyo, 145-0064, Japan
** Marine Ecology Research Institute, Kanda Jimbo-Cho 3-29 Chiyoda-ku, Tokyo, 101-0051, Japan
*** College of Industrial Technology, Nihon University, Izumi 1-2-1, Narashino, Chiba, 275-8575, Japan.

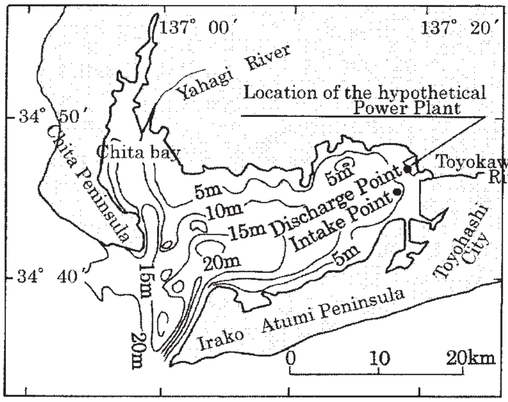

Fig. 1. Bottom topography of Mikawa Bay and the location of the hypothetical power plant.

2. The Model Calculation Method

2.1 The basic equations of the flow model

The tides in Mikawa Bay have strong cooscillating tide characteristics. The long axis of the M_2 tide is along the long axis of the bay; proceeding along this axis toward the interior of the bay, its amplitude decreases to 1/10 of its value at the mouth (UNOKI, 1978). The mean current, which consists of a component caused by the river inflow and the tidal residual current, primarily controls the transport of matter. In the flow calculation, the tide, density structure, river inflow and heat exchange at the sea surface are considered. The model consists of momentum, continuity and heat and salt diffusion equations.

- Equations of conservation of momentum

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv = -\frac{1}{\rho}\frac{\partial P}{\partial x}+A_x\frac{\partial^2 u}{\partial x^2}+A_y\frac{\partial^2 u}{\partial y^2}+A_z\frac{\partial^2 u}{\partial z^2}, \quad (1)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu = -\frac{1}{\rho}\frac{\partial P}{\partial y}+A_x\frac{\partial^2 v}{\partial x^2}+A_y\frac{\partial^2 v}{\partial y^2}+A_z\frac{\partial^2 v}{\partial z^2}. \quad (2)$$

- Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z} = 0. \quad (3)$$

- Surface boundary condition

$$\frac{\partial \zeta}{\partial t}+\left(u_s\frac{\partial \zeta}{\partial x}+v_s\frac{\partial \zeta}{\partial y}+w_s\right)_{z=\zeta_0} = 0. \quad (4)$$

- Hydrostatic equation and equation of state

$$P_z = g\int_z^{\zeta}\rho dz, \quad (5)$$

$$\rho = \rho_S(T, S). \quad (6)$$

- Heat diffusion equation

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z} = \frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial T}{\partial z}\right)+\frac{1}{C\cdot\rho}\frac{\partial}{\partial z}(Q_1-Q_0). \quad (7)$$

- Salt diffusion equation

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+v\frac{\partial S}{\partial y}+w\frac{\partial S}{\partial z} = \frac{\partial}{\partial x}\left(K_x\frac{\partial S}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial S}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial S}{\partial z}\right). \quad (8)$$

Here, t is time; x, y and z are the space coordinates; u, v and w are the velocity components in the x, y and z directions, respectively; u_s, v_s and w_s are the velocity components at the sea surface; A_x, A_y and A_z are the eddy viscosity coefficients in the coordinate directions; ζ is water level; P is pressure; g is gravitational acceleration; ρ is density; ρ_S is a reference density; C is specific heat; T is water temperature; S is salinity; K_x, K_y and K_z are the eddy diffusion coefficients in the coordinate directions; Q_1 is the flux of heat exchange with the atmosphere; Q_0 is the flux of heat exchange with the atmosphere at the initial water temperature, at grid points not on the sea surface $Q_1=Q_0=0$.

Q_1 and Q_0 are shown by the following equations

$$Q_1, Q_0 = Q_s-(Q_b+Q_c+Q_e),$$

$$Q_s = 0.239(1-\alpha)\beta Q_{s0}$$

$$Q_b = 0.315\times10^{-12}(273+T)^4-0.296\times10^{-17}(273+T_a)^6(1+0.17C_d^2)$$

$$Q_c = 0.0069C_H(T-T_a)u10$$

$$Q_e = 0.010C_E(e_w-e_a)u10.$$

Here Q_s is the absorptive solar radiation; Q_{s0} is the solar radiation; Q_b is the effective long wave radiation; Q_c is the sensible heat flux; Q_e is the latent heat flux; α is the heat reflection coefficient of sea surface (0.060 in August); β is the heat absorption coefficient of sea surface (0.69); T is the water temperature, T_a is the air temperature, C_d is Cloud amount (0~1); C_H is the sensible heat transport coefficient; C_E is the latent heat transport coefficient; u_{10} is the wind speed in 10m above sea surface; e_w is the saturated water vapor pressure at T and e_a is the water vapor pressure in the atmosphere.

2.2 Boundary conditions of the flow model

At the sea surface, $\partial u/\partial z=\partial v/\partial z=0$ and $\partial T/\partial z=\partial S/\partial z=0$. At the bottom, $u=v=0$ and $\partial T/\partial z=\partial S/\partial z=0$. Heat exchange with the atmosphere is treated as an external force. At the boundary with land, $u=v=0$ and $\partial T/\partial l=\partial S/\partial l=0$. Here l is vertical direction toward boundary. The tide at the open boundary is assumed to be the M_2 tide of a period of 12 hours with a sinusoidal curve. The flow is assumed to have zero first derivatives at normal to the boundary. Water temperature and salinity at this boundary are adjusted to the values of the open ocean when there is inflow; when there is outflow, the second derivative is assumed to be zero.

2.3 Basic equations of the water quality model

The water quality model consists of equations for the advection and diffusion of water quality elements (MULLIGAN, 1987). Letting C be the present value of one of the water quality elements, the equation for the local change with C over time is expressed in terms of advection, diffusion, inflow load, settling, deposition and biochemical processes by the following equation.

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(K_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right)-u\frac{\partial C}{\partial x}-v\frac{\partial C}{\partial y}-w\frac{\partial C}{\partial z}\pm\frac{\partial}{\partial x}\frac{\partial}{\partial y}\frac{\partial M(x,y,z,t)}{\partial z}. \quad (9)$$

Here C is the concentration of the component; t is time; K_x, K_y and K_z are the diffusion coefficients in the x, y and z directions; u, v and w are the velocity components in the x, y and z directions; and M is a quantity which expresses the change in the concentration due to inflow load, settling, deposition, biological and chemical processes.

We used the primary ecological model that was basically developed by the United States Environmental Protection Agency for Chesapeake Bay. This model includes 10 elements, which are shown in below.

1) Phytoplankton (p.p.) carbon (P_c)
$\partial(P_c)/\partial t$ = (P_c increase by p.p. growth) − (Oxidation of organic carbon by p.p. respi ration) − (p.p. death) + (p.p. sinking) + (p.p. advection and diffusion) (10)

2) Dissolved organic phosphorus (DOP)
$\partial(DOP)/\partial t$ = (p.p. recycle to DOP by p.p. respiration and death) − (DOP mineralization) − (DOP advection and diffusion) (11)

3) Particulate organic phosphorus (POP)
$\partial(POP)/\partial t$ = (p.p. recycle to POP by p.p. respiration and death) − (POP mineralization) + (POP sinking) + (POP advection and diffusion) (12)

4) Dissolved inorganic phosphorus (DIP)
$\partial(DIP)/\partial t$ = (p.p. recycle to DIP by p.p. respiration and death) + (DOP mineralization) + (POP recycle to DIP by POP mineralization) − (DIP uptake by p.p. growth) + (DIP elution from the sediment) + (DIP advection and diffusion) (13)

5) Dissolved organic nitrogen (DON)
$\partial(DON)/\partial t$ = (p.p. recycle to DON by p.p. respiration and death) − (DON mineralization) + (DON advection and diffusion) (14)

6) Particulate organic nitrogen (PON)
$\partial(PON)/\partial t$ = (p.p. recycle to PON by p.p. respiration and death) − (PON mineralization) + (PON sinking) + (PON advection and diffusion) (15)

7) Ammonia nitrogen (NH_4)
$\partial(NH_4)/\partial t$ = (p.p. recycle to NH_4 by p.p. respiration and death) + (DON mineralization) + (PON mineralization) − (NH_4 uptake by p.p. growth) − (NH_4 nitrification to NO_3) + (NH_4 elution from the sediment) + (NH_4 advection and diffusion) (16)

8) Nitrogen as nitrate and nitrite (NO_2 + NO_3 : NO_{23})
$\partial(NO_{23})/\partial t$ = (NH_4 nitrification to NO_{23}) − (NO_{23} uptake by p.p. growth) + (NO_{23} elution from the sediment) + (NO_{23} advection and diffusion) (17)

9) Carbonaceous biochemical oxygen demand (CBOD)
$\partial(CBOD)/\partial t$ = (CBOD production by p.p. death) − (CBOD decay by oxidation of organic materials) + (CBOD inputs from the sediment) + (CBOD advection and diffusion) (18)

Table 1. Flow calculation condition

Item	value
Horizontal grid	50m to 1000m transformed grid
Vertical grid	1m to 5.2m transformed grid
Initial Temperature	Observed average distribution
Initial Salinity	Observed average distribution
Horizontal eddy viscosity	Transformed value (Smagorinsky scheme)
Vertical eddy viscosity	10^{-3} ($m^2 sec^{-1}$)
Horizontal eddy diffusivity	1/5 of Horizontal eddy viscosity
Vertical eddy diffusivity	10^{-5} ($m^2 sec^{-1}$)
Tide level change	55.3cm at boundary (M_2 tide)
Yahagi River run off	$56.47 m^3 sec^{-1}$
Toyokawa River run off	$46.30 m^3 sec^{-1}$
Temperature of river water	Calculation Temp. of run off cell
Salinity of river water	Yahagi R.; 16.8 psu, Toyokawa R.; 17.6 psu
Meteorological condition	Observed average value by Nagoya,Tsu and Irako weather stations
Calculation period	20 cycles of M_2 tide

10) Dissolved oxygen (DO).

$\partial(DO)/\partial t$ = (DO production by photosynthesis) − (DO loss by p.p. respiration) + (DO input by aeration) + (DO loss by nitrification) − (DO loss by oxidation of organic carbon) − (DO loss by sediment oxygen demand) + (DO advection and diffusion) (19)

BOD is also treated in the calculation but since only measured values of COD are available in this region, the calculated values of BOD were converted to COD from the relationship between TOC and COD obtained from the relationship between observed values of TOC and BOD in the inland bay (Japan Environment Agency: 1989 The Oceanographical Society of Japan, 1985) and the model calculation. In this study, the magnification between CBOD and BOD were 1–3 and the relationship between COD and TOC, BOD and COD were as follows.

$$COD = 1.6TOC - 0.26 \quad (20)$$

$$BOD = 3(0.56COD - 0.06Chl\text{-}a + 0.14) \quad (21)$$

Here, $TOC = Pc + 1/a_{oc} \times BOD$, $Pc = 60/1000 \times Chl\text{-}a$ and $1/a_{oc} = 12/32$.

2.4 Boundary conditions of the water quality model

At the sea surface and the bottom, $\partial C/\partial z = 0$. At the boundary with land, $\partial C/\partial l = 0$. Here C is concentration of water quality. l is the normal direction toward the boundary. The water quality at the open boundary is adjusted to the value of the open ocean when it is inflow, and when it is outflow, the second derivatives are assumed to be zero. At the sea surface, sunlight intensity is given for photosynthesis. At the sea bottom, there is nutrients elusion from bottom mud. The other boundary conditions used for the water quality calculation follow those used for the flow calculation.

3. Results of flow calculation

3.1 Flow calculation conditions

The initial density distribution was given based on data observed by the Aichi Prefectural Fisheries Experiment Station from 1979 to 1984 and by the Aichi Prefecture Environment Department from 1979 to 1988. The river inflow data were obtained from the summertime average of measurements made by the River Bureau of the Ministry of Construction. Meteorological conditions were obtained as the averages from 1961 to 1990 of observations by Irako Weather Observatory. The average of the M_2 tides at Irako and Morozaki, 55.3cm, was used as the tide level at the bay mouth. The specifications of the hypothetical power plant were intake of 400 $m^3 s^{-1}$ of cooling water at the bottom, discharge of the same amount at the surface and temperature increase of 7℃ of cooling water passing through the power plant. Horizontal grid spacings gradually increased from 50m at the outlet of the power plant to

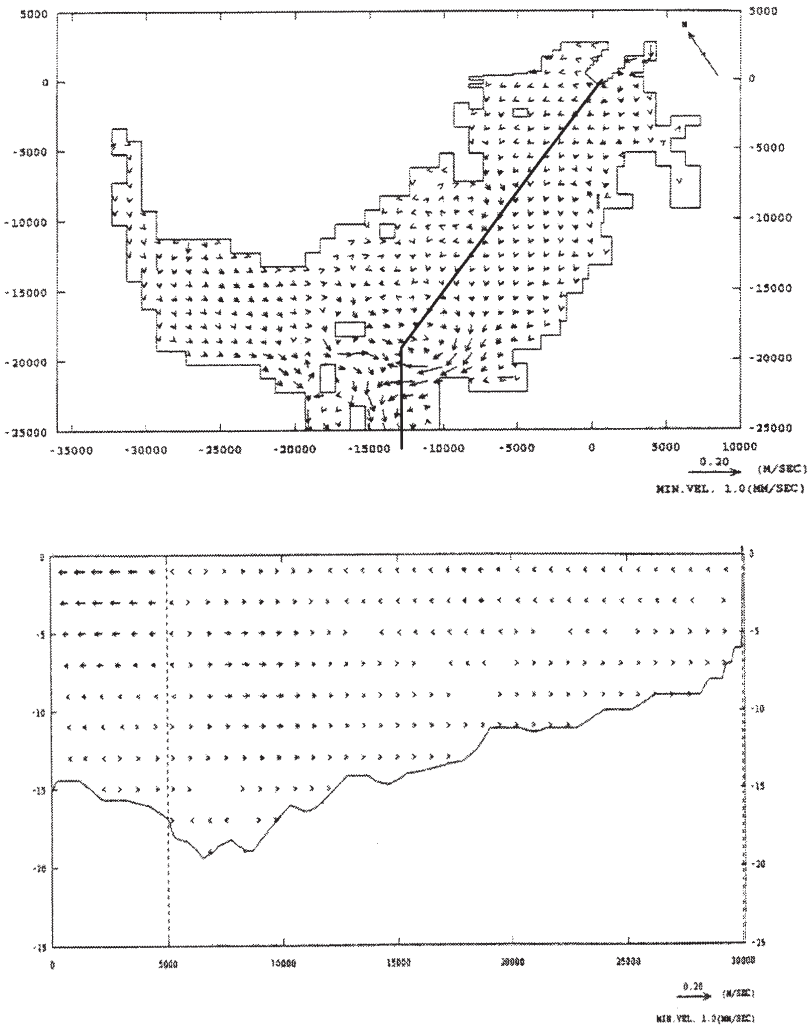

Fig. 2. Distribution of calculated horizontal mean flow and flow pattern of cross section. (Solid line in the upper panel shows the position of cross section below.)

1,000m in open water; there were 20 vertical layers, increasing from 1m thick at the surface to 5.2m thick at the bottom. These conditions are shown in Table 1.

3.2 Results of flow calculation

The mean current in Mikawa Bay was obtained by averaging over the tidal period of calculation in the present state, without a power plant. In most places the mean current was on the order of several cm s^{-1}, but at and around the bay mouth it reached 10cm s^{-1}. The mean current pattern shows outflow at the surface and inflow at the bottom (Fig. 2). This pattern, which is believed to be driven mainly by the density difference, agrees well with the summer mean current obtained from 15 days of continuous observation (Fig. 3). The tidal ellipse of numerical calculation agrees well with the observed M_2 tidal ellipse in axial direction and amplitude (Fig. 4).

From the difference between the mean currents at present and in the case with a hypothetical power plant installed, shown in Fig. 5, it is seen that the effect of the power plant discharge extends out horizontally from the

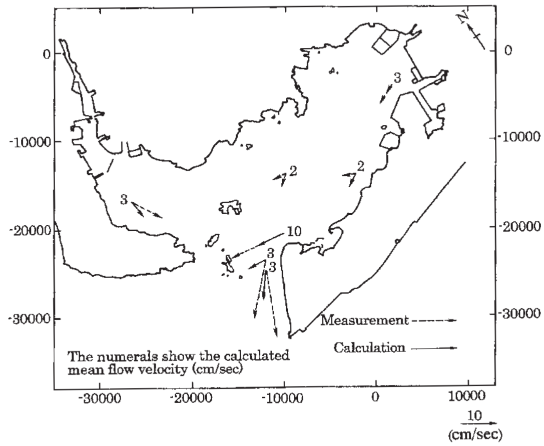

Fig. 3. Comparison of calculated mean flow and measured flow averaged over the measurement period.

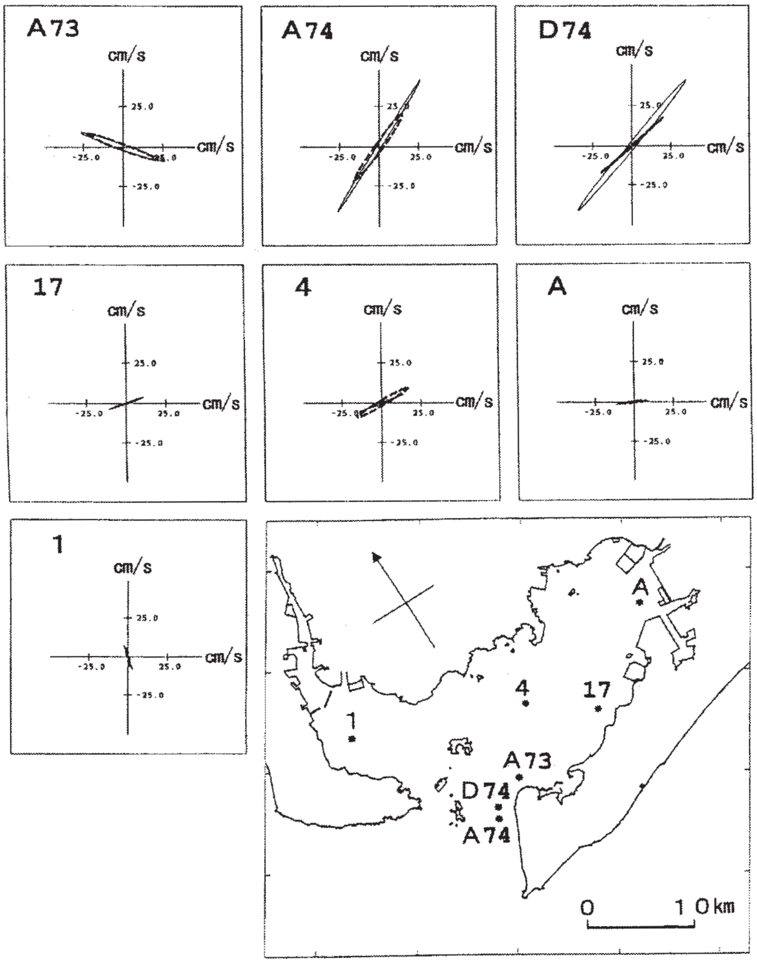

Fig. 4. Comparison of measured and calculated M_2 tidal ellipses. Solid lines: Measurements. Broken lines: Calculations.

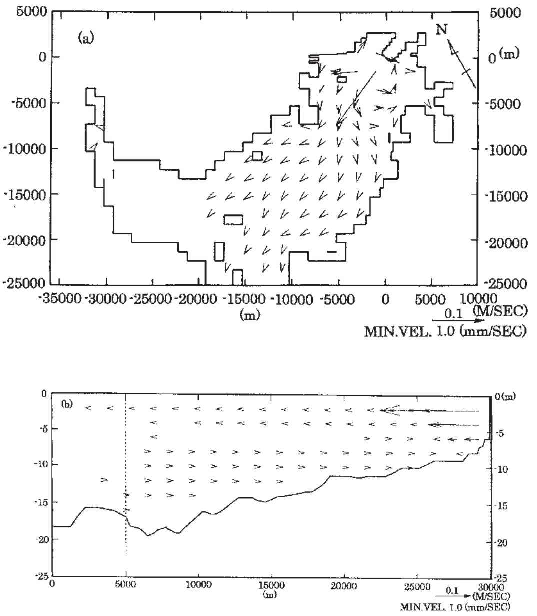

Fig. 5. Differences between the present flow and after construction of a hypothetical power plant.

discharge outlet, and vertically to a depth of 5m. It was found also that both the outflow from the bay in the upper layer and the inflow in the lower layer increased due to the intake and discharge. The effect of power plant discharge(UNOKI, 1998) is further shown by comparisons of the flow with and without discharge across cross sections in the bay interior and at the bay mouth in Fig. 6. In the bay interior, the lower layer inflow increases from 225 $m^3 s^{-1}$ without the discharge to 424 $m^3 s^{-1}$ with the discharge.

The increase corresponds to 50% of the amount of the discharge. In the cross section at the bay mouth, 27 km from the discharge outlet, the inflow increases about 40 $m^3 s^{-1}$, from 1316 $m^3 s^{-1}$ without the discharge to 1354 $m^3 s^{-1}$ with the discharge. This corresponds to 10% of the amount of the discharge and 3% of the inflow at the bay mouth, and is significant compared to the estimated error of 0.3% (Table 2) in the calculated inflow and outflow.

4 Water quality calculation

4.1 Calculation conditions

July average values computed from observations from 1979 to 1984 by the Aichi Prefectural Fisheries Experiment Station and from 1979 to 1988 by the Aichi Prefecture Environment Department were used as initial conditions for the water quality variables. Results of calculations without a power plant were compared against averages of observed values in August. The values calculated by the Aichi Prefecture Environment Department (1994) were used for the river load. Since the Irako Weather Observatory does not observe sunlight intensity or percentage of possible sunshine, averages of values observed from 1961 to 1990 by the Nagoya District Meteorological Observatory were used.

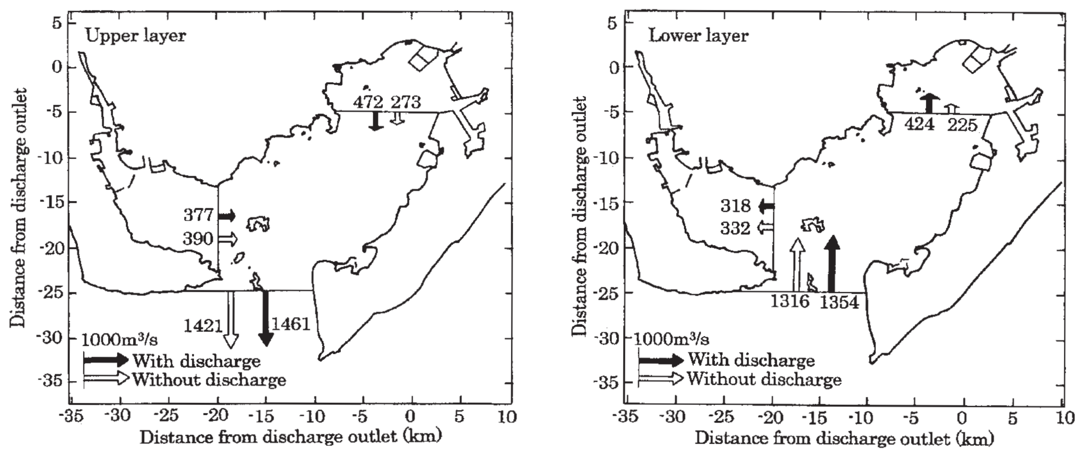

Fig. 6. Comparison of inflow and outflow rates at present and after construction of a hypothetical power plant.

Table 2. Inflow and outflow water volume through the Bay mouth and volume error of flow calculation

	Outflow (m^3/s)	Inflow (m^3/s)	Volume gap (m^3/s)	River run off (m^3/s)	Volume error (m^3/s)	Volume error/Inflow (%)
Without discharge	1421	1316	105	103	2	0.2
With discharge	1461	1354	107	103	4	0.3

Table 3. Water quality calculation condition

Item	value
Water Temp.	Result of heat diffusion calculation
Chl-*a*	3 $\mu g/\ell$
COD	Observed minimum value in each layer
Other variables of water quality	Observed average distribution
Toyokawa River load	T-N:5542;T-P:123;COD:7610;DIP:112;DIN:4990 (Kg day^{-1})
Yahagi River load	T-N:4823;T-P:448;COD:15653;DIP:215;DIN:1981 (Kg day^{-1})
NH_4 flux from bottom mud	2.054 (mgN $m^{-2}day^{-1}$)
NO_3 flux from bottom mud	2.054 (mgN $m^{-2}day^{-1}$)
PO_4 flux from bottom mud	0.456 (mgP $m^{-2}day^{-1}$)
Sediment oxygen demand	$SOD=400\times e^{-0.069\cdot T}$ T: water temp.
Sunshine intensity	397.5 (ly day^{-1})
Power plant cooling water volume	400 (m^3sec^{-1})
Δt of cooling water	7 (℃)
Other parameters	Omission

Values given by the Japan Environment Agency (1989) were used for the nutrient elution rate from bottom mud. Elution rate of DIN is 28.75 mg m^{-2} day^{-1} and elution rate of DIP is 14.60 mg m^{-2} day^{-1}. For oxygen consumption rate by bottom mud, we used a function [$SOD=400\times e^{-0.069\cdot T}$, where T is water temperature] given in Aichi Prefecture Environment Department (1994). These conditions are shown in Table 3.

4.2 Results of water quality calculation

Calculated values were compared with average values and standard deviations of water quality variables observed in the bay from 1979 to 1988, and the reproducibility of the results was investigated. The elements that were compared are Chl-*a*, DO and COD. The results of the comparison are shown in Fig. 7.

The calculated values for Chl-*a* in Chita Bay are a little small, but otherwise values for Chl-*a* show good agreement. The calculated values are within the standard deviations of the observed values at 12 to 17 points in the bay. Comparisons were done for DO and COD at 12 points in the bay. There is good agreement for DO at all points, and for COD except in the lower layer at 2 points. These 2 points are located near the calculation boundary; we believe that the effect of the boundary is responsible for the disagreement between these 2 points. Overall the agreement is good, and the water quality calculation gives good reproducibility.

Next, from comparison of water quality calculations before and after installation of the hypothetical power plant, the cause of the water quality change and the effectiveness in improving water quality were analyzed. For all of the water quality elements, the isolines spread out in concentric circles from the discharge outlet. After the water in the bottom layer upwelled and reached the surface, favorable conditions for primary productivity to become active were fulfilled, and as phytoplankton multiplied the water quality steadily changed. The changes in the various water quality elements are shown in Fig. 8. This figure compares the concentrations of these elements before and after installation of the hypothetical power plant along the water discharge axis.

When the water is discharged after having its temperature increased 7℃ as it passed

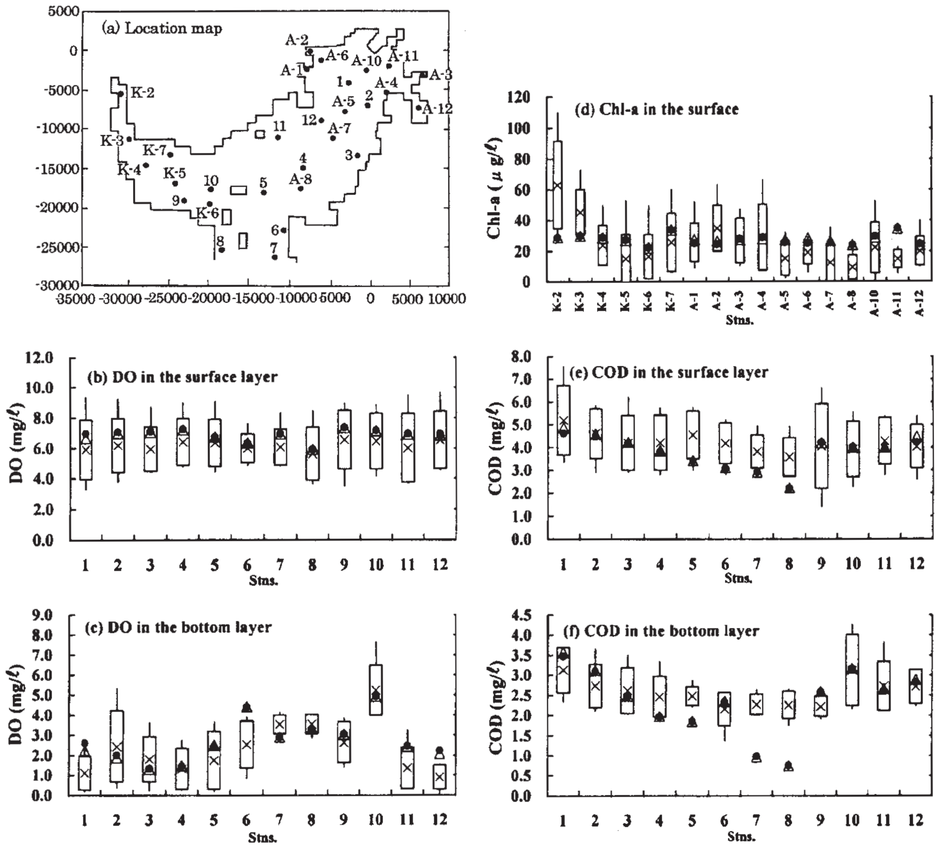

Fig. 7. Comparison between calculated values and observed average values of water quality variables. (● : Calculation value without discharge, △ : Calculation value with discharge, ×: Measured mean value, Box : Standard deviation around mean value, Line : Measured maximum and minimum value.)

through the power plant, the temperature drops to 1℃ 10km offshore.

The discharged cooling water has 2 times the DIN concentration and 1.5 times the DIP concentration compared with the ambient surface water; 6km offshore both are reduced to the levels in the ambient surface water due to consumption by phytoplankton en route. In the case of DIN, beyond 6km consumption by phytoplankton that have multiplied in the heated cooling water outflow exceeds the amount of DIN upwelled from deeper layer, causing the level to drop below the level before installation of the hypothetical power plant. The amount of phytoplankton at the discharge outlet is only 60% of the amount before installation of the hypothetical power plant, but increases rapidly until it exceeds the previous level 3km offshore. The phytoplankton concentration reaches a peak 6km offshore, then decreases gradually to the previous level.

In this calculation, the COD concentration essentially reflects the level of internally productive pollutants, and varies in a manner similar to the Chl-*a* concentration.

DO has a concentration of 3.5mg l^{-1}, 50% of the level before installation of the hypothetical power plant, at the discharge outlet, but due to multiplication of phytoplankton and aeration by 8km offshore it has returned to the previous level.

It is clear from these changes that the principal variations in water quality occur within the limits where the increase in water temperature

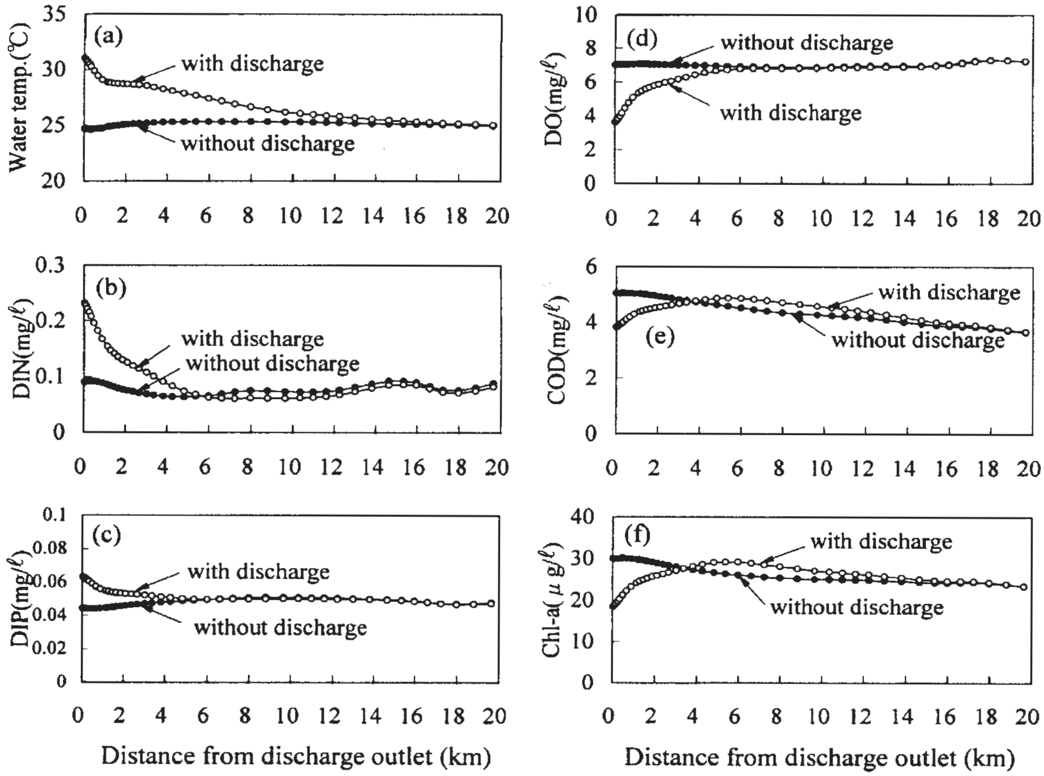

Fig. 8. Comparison of selected water quality concentrations before and after installation of the hypothetical power plant.

Table 4. Comparison of concentrations of selected water quality variables in a crossed section across the bay mouth at present and after construction of the hypothetical power plant.

Upper layer (0 to 9m depth)

	Chl-a (μg/l)	COD (mg/l)	DO (mg/l)	T-N (mg/l)	T-P (mg/l)
①Without discharge	12.2881	2.0996	5.0694	0.6299	0.0914
②With discharge	12.2992	2.107	5.0804	0.6278	0.0912
②−①	0.0111	0.0074	0.011	−0.0021	−0.0002
%	0.1	0.4	0.2	−0.3	−0.2

Lower layer (9 to 25m depth)

	Chl-a (μg/l)	COD (mg/l)	DO (mg/l)	T-N (mg/l)	T-P (mg/l)
①Without discharge	4.8526	1.1061	3.6151	0.6489	0.089
②With discharge	4.7882	1.0947	3.6298	0.6477	0.0887
②−①	−0.0644	−0.0114	0.0147	−0.0012	−0.0003
%	−1.3	−1	0.4	−0.2	−0.3

is 1℃ or greater. Chl-*a* and COD continue to change somewhat a bit farther offshore, but even in these cases the peaks are reached within the area of temperature increase 1℃ or greater.

Next, to investigate the effect of intake and discharge of cooling water on water quality throughout the entire bay, the changes in the average concentrations of water quality elements flowing in and out through a cross-section at the bay mouth were investigated (Table 4). As a result, it was found that after construction of the power station, in the upper layer, where the flow is outward from the bay, the concentrations of Chl-*a*, COD and DO increased, while in the lower layer, where the flow is into the bay, Chl-*a*, COD, T-N and T-P decreased. Accordingly, it appears that there is a net outflow of organic matters out of the bay. T-N and T-P decrease slightly both in the upper and lower layers; further investigation is needed to determine the cause of this (MATSUKAWA, 1993).

5 Summary

The changes in flow and water quality environment in a relatively large scale, nutrient - enriched, closed inland bay, were analyzed quantitatively using a quasi 3-dimensional flow model and a primary ecological model, when a power station is constructed in the innermost of the bay. We investigated how the intake and discharge of cooling water by the power plant would affect seawater exchange and water quality in the closed inland bay.

In this research, we found from the difference between the present flow in the bay and the flow after a hypothetical power plant is installed that, the heated cooling water discharged from the power plant clearly had the effect of increasing the inflow and outflow of sea water into and out of the bay. It is believed that this effect on sea water exchange varies with the amount of discharge water compared to the volume of the bay. Moreover, the location in where the power plant is constructed will also affect the sea water exchange. In the case of Mikawa Bay with a volume of $5.4 km^3$, the water exchange rate increases 3% at the mouth of the bay if the discharge flow rate is about 400 $m^3 s^{-1}$. Since the exchange of sea water at the mouth of Mikawa Bay in summer is about of 1300 $m^3 s^{-1}$, the effect of the intake and discharge of cooling water is expected to be large in small bays.

We studied the effect of power plant construction on the water quality environment from the calculated difference in water quality between the present and the case in which a power plant is constructed. We showed that there was a tendency for phytoplankton and COD, at high concentrations, to flow out through the bay mouth in the upper layer and, at low concentrations, to flow in through the lower layer, so that the water quality in the bay is improved, as the circulation intensifies. The concentrations of water quality parameters increase and decrease following a typical pattern around the discharge point, but these changes are limited to a relatevely narrow area where the water temperature increase 1℃ or more.

In this study we quantified the effect of a power plant cooling water discharge on the flow and water quality in a bay. It was shown clearly that there was at least a possibility that the water intake and discharge could improve the flow and water quality environment of a closed inland bay.

Acknowledgments

The authors would like to acknowledge the cooperation of Ms. Michiho MORI, Mr. Masakazu MIURA and Mr. Hiroshi INO of Japanese Union Institute of Scientists and Engineers for their assistances in the computational works and data processing. This study was partly supported by the Nuclear and Industrial Safety Agency, Ministry of Economy, Trade and Industry of Japan.

References

Aichi Prefectural Environment Department (1994): Report on 1993, Nutrient Enrichment Model of Ise Bay, 28–40.

Japan Environment Agency (1989): Report on Study of the Mechanism of Marine Pollution in a Closed Inland Bay. 66–68.

MATUKAWA, Y. (1993): Fluctuation and Transport in Mikawa Bay. Bulletin on Coastal Oceanography, **30**, 187–193.

MULLIGAN, T. J. (1987): A steady-state coupled

hydrodynamic/water quality model of the eutrophication and anoxia process in Chesapeake Bay. Hydroqual Inc., 400pp.
SUDO, S. (1993): On acceleration of seawater exchange by the intake of water by a power plant. Marine Ecology Research Institute News, **41**, 2–3.
The Oceanographical Society of Japan (1985): Methods of Investigating the Oceanic Environment. 7. Chemical Research, 7.5.2 TOC and DOC. Koseisha Kosei Kaku Co., Ltd., Tokyo, 291–300.
UNOKI, S. (1998): Relation between the Transport of Gravitation and River Discharge in Bays. Oceanography in Japan, **7**, 283–292.
UNOKI, S. (1978): Oceanographic Description of the Coast of Japan XV: Ise and Mikawa Bays (II), the physical environments. Bulletin on Coastal Oceanography, **15**, 143–154

Received February 14, 2002
Accepted December 9, 2002