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A numerical simulation method is developed to analyse the surface wave flow and nutritious processes in the closed water areas which include a bay area, marina, channel and lagoon in order to make a plan for water purification and quality preservation. The applicability and efficiency of this system are shown in the numerical examples in the Tokyo Bay area. The present method adopts a multi-level ocean wave model to simulate a marine water flow, water pollution and nutritious processes which are erected by wind forces, tidal residual flows and water inlet flows from rivers. In the planning stage of new water treatment plants located around the bay area, this system can provide an analytical tool to estimate the efficiency of the water purification system.

1 Introduction

Recent years have seen an increasing number of projects for forming "friendly-water" spaces that uses marinas, canals, lagoons, etc. However, water pollution by the abnormal formation of phytoplankton and algae is feared when seawater with a high degree of eutrophication along the coast of a big city is used as the source of water.

This paper presents part of achievements accomplished using Kawasaki Steel's techniques for environmental protection of water quality in coastal waters in which water pollution is feared.

Population is concentrated in districts near Japanese representative bays, such as Tokyo Bay and Osaka Bay, and brisk economic activities are developed there. Especially at the beginning of the 1990s, many regional development plans of marine districts were formulated in the name of water front development and marine resort development, and the public's interest in the utilization of coastal waters increased greatly. At the same time, however, the public took a strong interest in the environmental problem of coastal waters.

In all bays that have a big city at their base, fishery damage and hindrance to swimming in the sea due to the generation of red tides, occurrence of offensive odor, contamination of beaches, decrease in the oxygen in bottom layers, and other phenomena are becoming conspicuous owing to the eutrophication of seawater resulting from the inflow of household and industrial effluents, and the damage to and effect on the living environment are occurring in a wide range.

Against this background, it has become necessary to conduct a detailed technical examination of water purification measures or water quality preservation plans to prevent water pollution in bays when marine district development plans are implemented.

Research and technical development related to water purification in coastal waters are conducted by universities, government, private research institutes, etc., and the scope of such research and development is so wide that it ranges from the investigation of the flow condition and water quality in coastal waters to hydraulic experiments, simulations predicting flow conditions, development of structures for controlling flow conditions, and the development and design of purification plants. Domestic bodies interested in the problems in this field gathered and a research meeting related to the water purification in coastal waters (Blue Sea Plan Forum) was organized under the leadership of the Ministry of Transport. In 1989, a report of the Blue Sea Plan[1)] was prepared. This report describes the current condition of various purification techniques and techniques for the development of marine districts aimed at creating a comfortable marine

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environment in Japan and abroad. In this report, the effectiveness and applicability of a numerical simulation technique as a technique for predicting changes in the flow condition and water pollution resulting from marine development are demonstrated.

This study was conducted to develop an analysis system capable of predicting the flow condition in coastal waters necessary for formulating water purification measures or water quality preservation plans and conducting simulations of the processes of water pollution and purification based on the prediction.

2 Outline of Analysis Methods

2.1 Object of Analysis

The closed water area dealt with in this paper is a general term for bays and estuaries. It is a water area with a spatial distance of 1 to 100 km. In Japan, Tokyo Bay, Osaka Bay, Ise Bay, etc., fall under this category. The motion of seawater (waves) in these closed water areas is characterized by the fact that seawater is diluted by the fresh water flowing into the sea through rivers from land, and a moderate exchange of seawater with the ocean is continued by tidal and coastal currents.

In the closed water area, the motion of seawater generally occurs due to the interaction of various factors, such as the inflow of tides and fresh water, heat exchange between ocean winds and the surface of the sea, and inflow of ocean water. These motions are classified by the temporal scale into various waves, such as seiches with a cycle of about 1 h, tidal currents with a cycle of about 1 h to half a day, drift currents with a cycle of 1 day to 1 week, and density currents with a long cycle of 1 week to more than 1 month. **Figure 1** shows the features of ocean waves classified according to the temporal and spatial scales.

The above motion of seawater and process of transfer and diffusion of pollutants in the closed water area are phenomena that occur under the action of changes in the density of seawater as a driving force, and it is said that these phenomena are caused by density currents. Therefore, an analysis system capable of tracing the process of flow of density currents is necessary in order to predict the flow condition of seawater and the process of transport and diffusion of pollutants in the closed water area.

2.2 Technique for Analyzing Flow Conditions

The three-dimensional numerical analysis model adopted in this study is a numerical model suitable for the prediction of density currents in a closed water area, and is called the multi-level wave model.

This numerical model is composed of the following equations:

(1) Equation of motion that describes the motion of the fluid in the closed water area,
(2) Equation of continuity of flow rate,
(3) Equation that describes changes in tide level,
(4) Diffusion equation of chlorine concentration,
(5) Diffusion equation of heat and water temperature,
(6) State equation that describes the relationship between the density of seawater and the chlorine concentration and water temperature.

As the coordinates for formulating the model, the x-axis and y-axis are set on the plain water surface and the z-axis is set vertically upward as shown in **Fig. 2**. The following items are presumed as the preconditions for deriving basic equations of the model:

(1) The factors that drive the currents in coastal seas are tide, density gradient, inflow of river water from the coast, and stresses of winds blowing on the sea.
(2) The fluid is treated as a viscous incompressible fluid

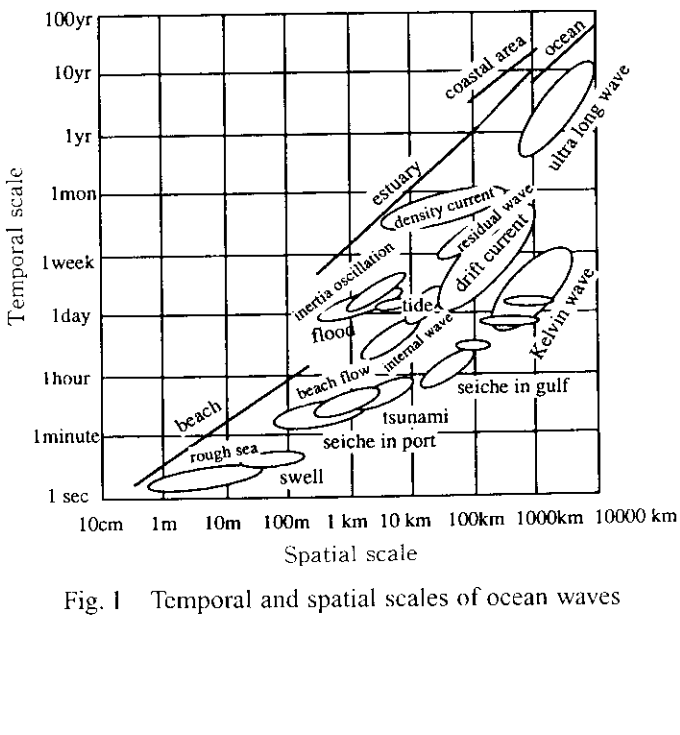


Fig. 1 Temporal and spatial scales of ocean waves

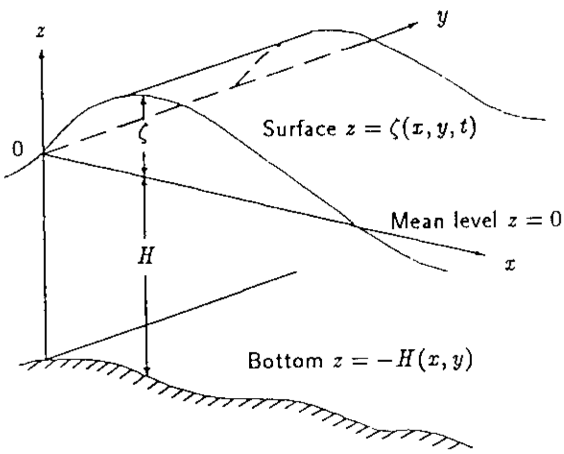


Fig. 2 Coordinates of the multi-leveled ocean wave model

on the rotating earth.

(3) The Coriolis parameter that expresses the rotation effect of the earth is constant in the whole production region.

(4) A static equilibrium is presumed in the vertical direction and motions are neglected. In other words, it is assumed that the gravitational acceleration is in static equilibrium with the pressure gradient.

(5) The heat flux on the sea surface is formulated as the balance of the amount of absorbed solar radiation (short wave radiation), net amount of long wave radiation, amount of transported sensible heat on the sea surface (amount of heat transfer by turbulent flow), and amount of transported latent heat (input and output of heat resulting from phase changes of water).

(6) The Knudsen equation is used as the relational expression (state equation) of density (ρ), water temperature (T), and chlorine concentration (Cl).

$$\rho = \rho(\mathrm{Cl}, T) = \frac{\sigma_t}{1\,000} + 1 \quad \cdots\cdots (1)$$

where,

$$\sigma_t = \Sigma_t + (\sigma_0 + 0.1324)\{1 - A_t + B_t(\sigma_0 - 0.1324)\}$$

$$\sigma_0 = -0.069 + 1.4708\,\mathrm{Cl} - 0.001570\,d^2 + 0.0000398\,d^3$$

$$\Sigma_t = -\frac{(T-3.98)^2}{503.570} \times \frac{T+283.0}{T+67.26}$$

$$A_t = T(4.7869 - 0.098185\,T + 0.0010843\,T^2) \times 10^{-3}$$

$$B_t = T(18.030 - 0.8164\,T + 0.01667\,T^2) \times 10^{-6}$$

(7) Stratification is conducted in the vertical direction and the quantities of various states (speed, temperature, chlorine concentration, etc.) averaged in each stratum are predicted and calculated.

When the above preconditions are used, the seven basic equations of the multi-level wave model can be formulated as the motion equation in the x and y directions, equation of continuity, equation of free surface (tide level), diffusion equation of temperature, diffusion equation of chlorine concentration, and Knudsen state equation.

2.3 Technique for Water Pollution Analysis

To predict the water pollution in the closed water area, it is necessary to trace the material circulation process of carbon (C), nitrogen (N), and phosphorus (P) present in the marine ecosystem. The circulation process of nitrogen and phosphorus in the ecosystem is schematically shown in **Fig. 3**.

Water pollution is caused by eutrophication in the ecosystem due to the material circulation in the marine ecosystem in coastal waters. Numerical analysis models for tracing such a pollution process in the ecosystem are generally called the eutrophication prediction model.

A low-order ecological model[2] for composing a numerical model for analyzing water pollution is adopted and the variables shown in **Table 1** are set as the compartments for tracing the eutrophication of the marine ecosystem in coastal waters.

The relational expression that describes changes with time in the existing quantity B of each compartment at an arbitrary point (x, y, z) is expressed by Eq. (2):

$\frac{\mathrm{D}B}{\mathrm{D}t}$ = [Term that indicates the effect of the transport by tidal currents (advection)]
+ [term that indicates the diffusion (mixing) by turbulent flow (diffusion)]
+ [term that includes various biological processes (biological and chemical changes)]

$$= -u\frac{\partial B}{\partial x} - v\frac{\partial B}{\partial y} - w\frac{\partial B}{\partial z} + \frac{\partial}{\partial x}\left(K_x\frac{\partial B}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial B}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial B}{\partial z}\right) + \frac{\partial B}{\partial t} \quad \cdots\cdots (2)$$

In other words, changes in the existing quantity of each compartment that occur moment by moment can be determined by calculating the amounts of generated and lost carbon in the circulation process in the ecosystem and gradually predicting the variations of each compartment by multiplying them by a conversion factor. On this occasion, the velocity components (u, v, w) of each compartment are calculated using velocity data on density currents obtained moment by moment as the result of the calculation of the flow condition analysis. For the term of biological and chemical changes, it is necessary to conduct a similar analysis after the formulation of the actual material circulation for each compartment. Each

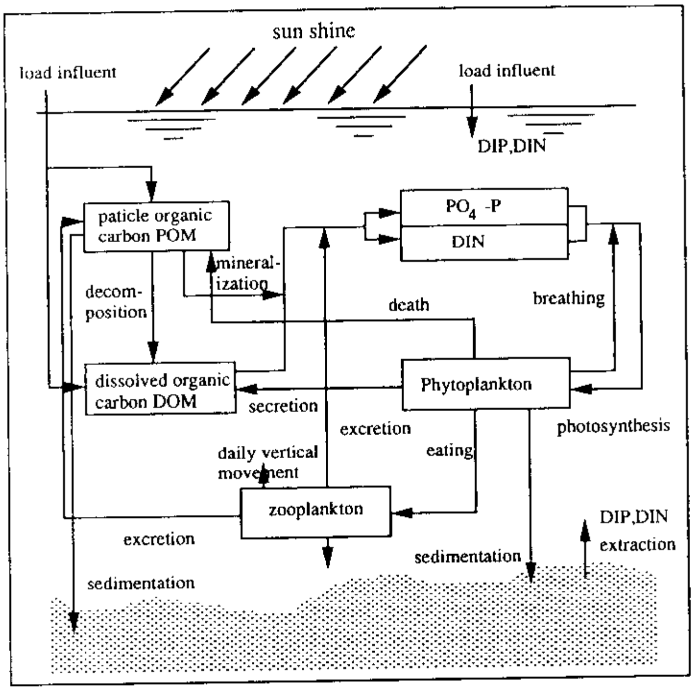


Fig. 3 Circulation process of nitrogen and phosphorous in the ecological system

Table 1 Compartments of nutrition process model

Classification	Compartments	Symbol	Unit
Organics	Phytoplankton	P	mgC/m^3
	Zooplankton	Z	mgC/m^3
	Particle organic carbon (detritus)	POC	mgC/m^3
	Dissolved organic carbon	DOC	mgC/m^3
Inorganics	Dissolved inarganic phosphorus	DIP	μg-atm/l
	Dissolved inorganic nitrogen	DIN	μg-atm/l
Oxygen	Dissolved oxygen	DO	mg/l
Water quality	Chemical oxygen demand	COD	mg/l

formula obtained by the formulation of the material circulation in this study conforms to a rule of thumb derived from experiments and observations, and the existing knowledge obtained from ecological researches is integrated in these formulae.

2.4 Technique for Purification Analysis to be Built in Plants

When a closed water area is given, the distribution condition of increase in the COD (internal production) resulting from production activities in the ecosystem can be obtained using the above technique for water pollution analysis. To improve the present condidtion of water quality, however, it is necessary to install a water purification plant and use a technique for predicting water purification capable of quantitatively evaluating the effect of the plant. In other words, it is necessary to develop a simulation system capable of tracing changes in water pollution conditions when purification is conducted by installing a purification plant on the basis of set conditions, such as the inlet point, quantity of water intake, pollutant removal rate (purification level), outlet point, and quantity of discharge.

In this study, a purification prediction system with the following additional functions (technique for purification analysis to be built in plants) was developed to achieve the above purpose:

(1) Setting of the functions of a purification plant (modeling)
  (a) The number of purification plants, inlets, and outlets can be set.
  (b) The quantities of water at inlets and outlets can be set.
  (c) It is possible to specify which purification plant is to be used to treat the water at each inlet.
  (d) It is possible to specify which outlet is to be used to discharge the treated water from each purification plant.
  (e) The level of treated water can be set for each purification plant.
(2) Setting of the functions of water treatment capacity (modeling)
  (a) The removal rates of each component (phytoplankton, POC, COD, etc.) of the water to be treated can be set.
  (b) Limit values of treatment can be set.

(c) The treatment efficiency (removal rate) corresponding to the concentration of each component can be set as a function.

(3) Others

(a) Changes with time in the quantity of water intake, river flow rate, and load amounts of nitrogen and phosphorus can be input.

(b) Treatment time can be set.

(c) Changes in the flow condition by intake and discharge can be taken into consideration.

3 Examples of Application

3.1 Work Flow of Simulation of Water Purification

To develop an optimum water purification system, it is necesssary to formulate an optimum water purification plan on the basis of site surveys, simulations for the prediction of purification, demonstration tests with a model plant, etc., after collecting data on the characteristics of the district surrounding the closed water area, water quality conditions desired, etc. The concrete work flow is shown in **Fig. 4**.

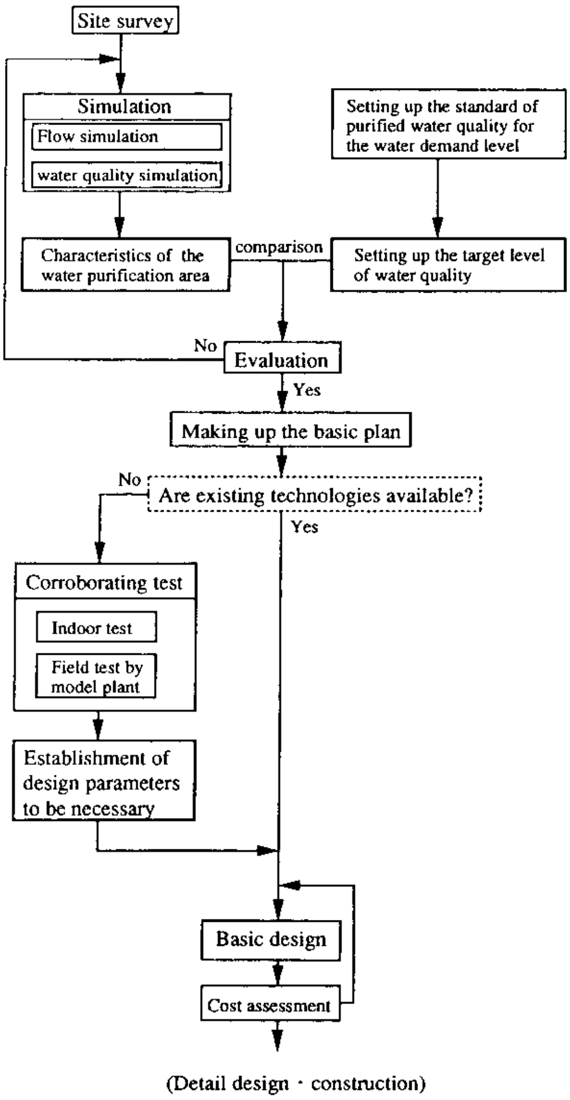


Fig. 4 Flow chart of water purification planning

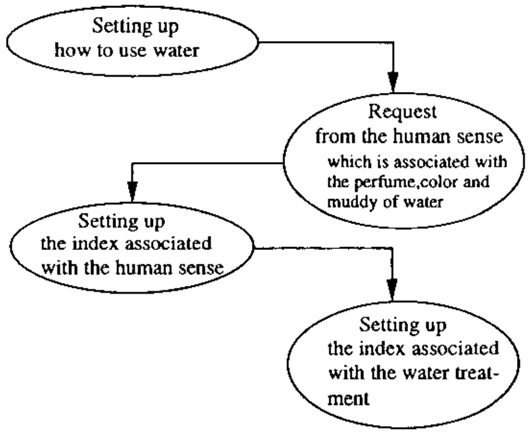


Fig. 5 Procedure to set up the water purification levels

The water purification simulation system described in this paper is a key technique for collecting data on the features of the water purification area in the figure and plays an important role in the quantitative evaluation of the water purification plan. The target water quality after purification varies depending on how the treated water is to be used. Basically, however, water purification levels are set according to the procedure shown in **Fig. 5**.

The results of simulations related to the flow condition and water purification in Tokyo Bay are shown below by way of example.

3.2 Simulation of Flow Conditions in Tokyo Bay

The area from Joga-shima and Iwai-fukuro in Tokyo Bay to the innermost part of the bay was taken into consideration as the object of the simulation. The tidal conditions based on the table of tidal harmonic constants along the coast of Japan[3] were adopted as shown in **Table 2**, and the flow rates of the rivers shown in **Table 3** were used as river flow rates. The values of the analytical mesh method shown in **Table 4** were used as analysis conditions. Drift currents by wind were not taken into consideration and the advection by the inflow of fresh water and the flow conditions by tides were analyzed.

Table 2 Boundary condition of tidal wave level

Location	Latitude	Longitude	Amplitude (cm)	Phase (degree)
Jouga-shima	35° 8′ N	139° 37′ E	38.0	146.0
Iwai-fukuro	35° 6′ N	139° 50′ E	35.0	148.5

Table 3 Rivers surrounding Tokyo Bay area

Name of river	Flow (m^3/day)
Edo River	6.022×10^6
Sumida River	4.087×10^6
Arakawa River	2.954×10^6
Naka River	1.986×10^6
Tama River	1.782×10^6
Shinagawa area	1.841×10^6
Oomori area	1.010×10^6

Table 4 Numerical modeling data

Item	Value
Mesh of horizontal components	72(length) by 46(width)
Mesh of vertical components	1st layer : surface to − 2 m 2nd layer : − 2 m to − 8 m 3rd layer : − 8 m to sea bed
Mesh width	1 km
Time step	ΔT = 10 sec

As shown in **Figs. 6** and **7**, the tide levels in the bay and the distribution of flow velocities were obtained as the results of the simulation of the flow conditions. Figure 6 shows the tide levels at high tide. The tide level increases gradually from the mouth of the bay toward its innermost part while the tide is rising. The tide level is the lowest in the innermost part of the bay while the tide is falling. The results of the calculation are in good agreement with observed values as shown in **Table 5**.

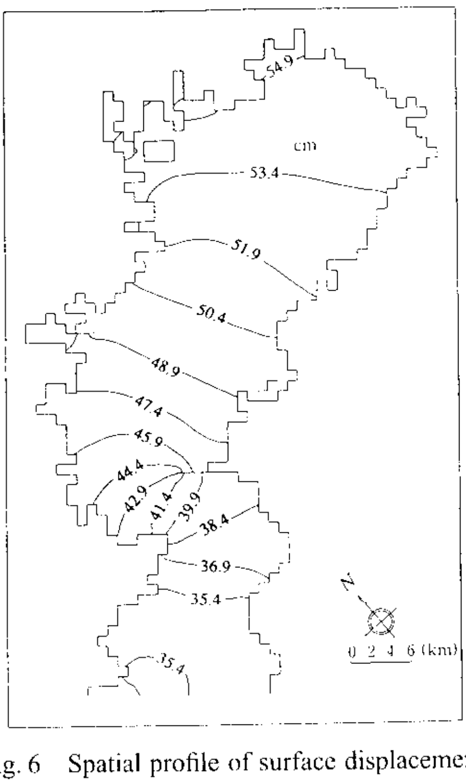


Fig. 6 Spatial profile of surface displacements

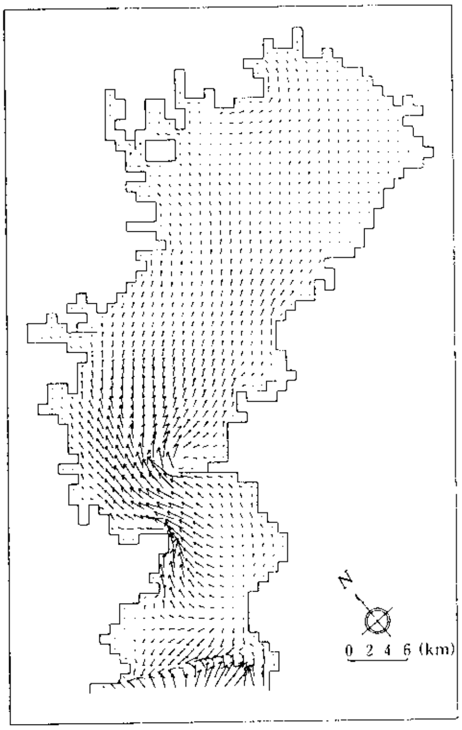


Fig. 7 Spatial distributions of flow velocities

Table 5 Comparison of flow velocity between the observed data and numerical results (cm)

Division	Daiichi -kaiho	Chiba touhyou	Tsukiji	Shinkou	Yokosuka
Calculated	45.7	52.2	52.2	48.0	43.7
Observed	45.0	50.9	50.1	46.7	41.2

Figure 7 shows the flow velocity vectors at rising tide. The water flows in toward the innermost part of the bay when the tide is rising, and it flows out toward the month of the bay when the tide is falling. The flow velocity is higher in the upper layers than in the lower layers, and it is evident from calculations that the flow velocity is highest (0.46–0.77 m/s) near Dai-1-Kaiho, Dai-2-Kaiho and Dai-3-Kaiho. This is in good agreement with the results of tidal current observation (0.4–1.1 m/s).

3.3 Simulation of Water Purification in Tokyo Bay

The effect of water purification on Tokyo Bay was examined by presuming various cases where a water purification plant is installed near Tokyo Bay.

Figure 8 shows the COD distribution obtained from an analysis of water pollution in the present Tokyo Bay, where no clarification plant is installed. This figure shows the condition on the 5th day after the day on

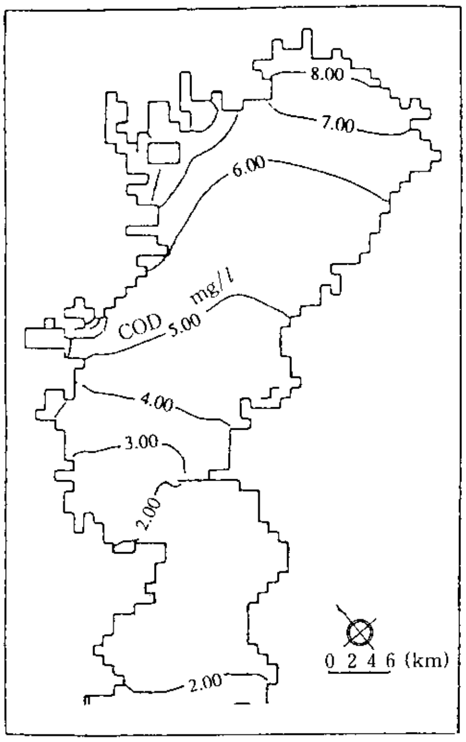


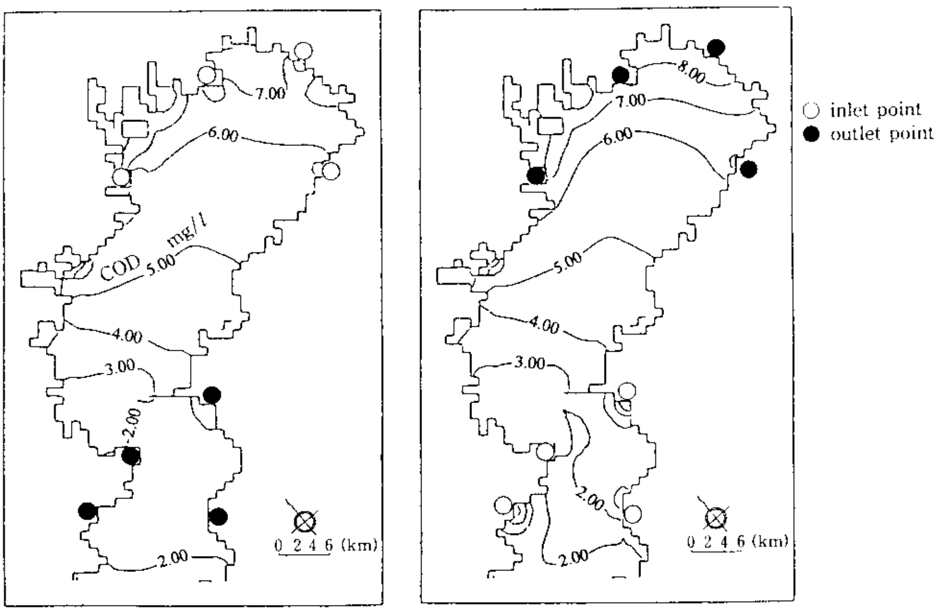
Fig. 8 Spatial profile of over-nourishment

which the calculation was supposed to start. COD is 2 mg/l at the mouth of the bay and 8 mg/l in the innermost part of the bay. The degree of pollution increases from the mouth of the bay toward its innermost part. The nearer to the innermost part of the bay, the lower the seawater replacement ratio; this suggests that eutrophication occurs in the innermost part of the bay.

To conduct water purification, it is necessary to transport the relatively clean seawater at the mouth of the bay to the innermost part of the bay and to discharge the seawater with a high degree of pollution in the innermost part of the bay to the mouth to the bay after purification, thereby increasing the seawater replacement ratio in the innermost part of the bay.

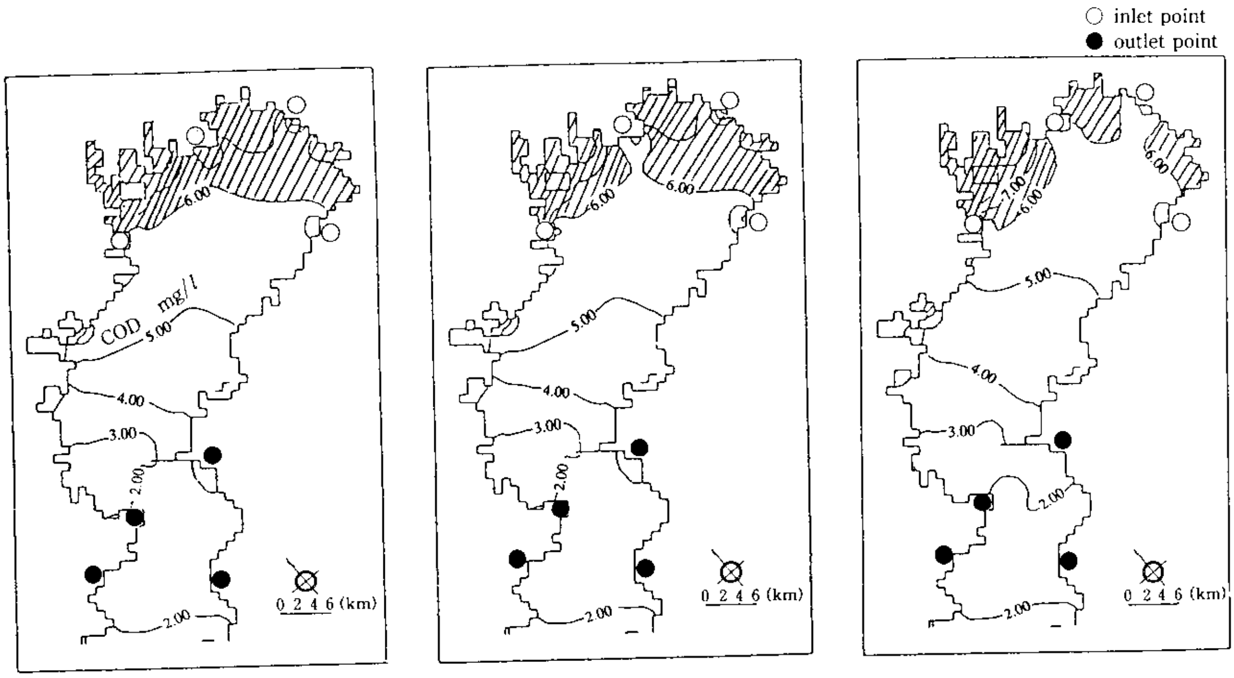
The degree of water purification is predicted first in a case where only seawater replacement is conducted without water purification. **Figure 9** (a) shows a case where inlets are installed in the innermost part of the bay and outlets (at four points) are installed at the mouth of the bay. Figure 9 (b) shows an opposite case where inlets are installed at the mouth of the bay and outlets are installed in the innermost part of the bay. It is apparent from the two figures that the effect of water purification is relatively small when outlets are installed in the innermost part of the bay and that it is more effective to take polluted seawater in the innermost part of the bay and discharge it from the mouth of the bay to outside the bay.

Next, **Fig. 10** shows the results of water purification in a case where taken seawater is treated and only COD is removed in specified amounts. Figure 10 (a) shows a case where 50% of COD is removed, and Fig. 10 (b) shows a case where 90% of COD is removed. The hatched portions in the two figures indicate areas with COD of 6 mg/l or more after 5 days. Figure 10 (c) shows the results on the 10th day, i.e., after a lapse of a further 5 days relative to (b), revealing that the water in this area has become cleaner.



(a) Model 1 (b) Model 2

Fig. 9 Inlet and outlet locations for the water treatment plants (a volume of the daily water treatment per single plant is 1×10^7 m^3)



(a) Elimination of 50% of COD (after 5 days)

(b) Elimination of 90% of COD (after 5 days)

(c) Elimination of 90% COD (after 10 days)

Fig. 10 Spatial profile of water purification

4 Scope of Application

The system developed in this study can be applied to the following fields in addition to large closed water areas such as Tokyo Bay:

(1) Evaluation of the effect of the discharge of industrial effluents at sea bottom.
(2) Evaluation of the effect of the discharge of treated sewage.
(3) Evaluation of the effect of reclamation, construction of offshore structures and artificial islands, and dredging along the coast.
(4) Evaluation of the utilization of water and water quality in marinas, lagoons, etc.
(5) Prediction of the improvement of water quality by the dredging of bottom layers and by aquatic plants.

A comprehensive environmental impact assessment that includes the prediction of variations in marine resources and fish distribution, control of biological production, and environmental assimilation capacity will be made possible in the future not only by environmental impact assessment using water quality indices, but also by techniques for environmental impact assessment using biological indices (plankton, benthos, fish on the sea bottom, fish on the sea surface, etc.) and the formulation of bottom material conditions.

5 Conclusions

A system for analyzing the flow condition in closed water areas and a system for analyzing water pollution and purification were developed in this study. The developed systems have the function of analyzing the flow conditions and processes of water pollution and clarification in representative large closed water areas in Japan, such as Tokyo Bay, Osaka Bay, and Ise Bay, and smaller closed water areas to be developed in these bays, such as harbors and marinas. The following results were obtained:

(1) The developed system for analyzing flow conditions showed a good correspondence between observed values and calculated values. Therefore, the effectiveness of this system was demonstrated.
(2) A system for water purification prediction to be built in plants was developed. This system is capable of predicting water pollution and examining the functions of a purification plant. The purification method and its purification effect were numerically examined by presuming a model plant in Tokyo Bay. As a result, it was possible to obtain qualitative information on the policy of installation of inlets and outlets for the optimum location of the clarification plant.

References

1) Sea Blue Technology Kenkyukai: "Sea Blue Keikaku (Plan)" (1989), (in Japanese)
2) T. Yanagi: "Engan Kaiyougaku," 1989, [Kouseisha-Kouseikan]
3) Marine Authority: "Nihon Engan Chouseki Chouwa-teisuhyou," (1992), 133 137, [Nihon Suiro Kyokai]