Study on Monitoring System of Coastal Environment (3rd Report) -Monitoring of Phytoplankton Concentration by Assimilation- *1

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In order to manage and assess coastal environment, developing of a monitoring system is becoming important and urgent theme recently. The authors emphasize that the monitoring system should include not only measuring and watching but also short-term prediction and assessment of environmental factors. The measuring techniques by using images of the sea surface have been developed and a new assimilation technique has also been proposed for Yura area in the previous paper. This paper deals with the monitoring method of phytoplankton by the assimilation, in which a simple mathematical model and the measured data are used effectively. The present method is explained in general form and examined in detail. The effectiveness of the method is shown by the field measurement at Yura.

Keywords : *Environment Monitoring, Short-Term Prediction, P-N Model, Kalman's Filter*

1. Introduction

Coastal area has a very rich biological productivity and is important for human life. Impact against coastal environment becomes stronger with development of social activities. Aggravation of coastal environment is caused and ecological function becomes worse. For example, the damage by the red tide is a very serious problem recently. In order to consider the adequate guideline for environmental change, the investigation and measurement of environmental factor are necessary. It means that the so-called monitoring is very important.

One of the difficulties in monitoring of coastal environment is a problem of few numbers and lack of measurement data owing to field noise. A number of troubles due to natural condition such as climate and so on, always cause some lack of the measurement. Furthermore, the conventional monitoring is of measuring and watching the environmental change and examine the comparison with standard value, which is always determined by government. It enables to give the information for long period. However, we recently need the short-term prediction, like a forecast in coast. It can be said that the monitoring system should include not only measurement of environmental change but also short-term prediction and assessment.

A monitoring method using assimilation has been proposed already by the authors[1),3)], particularly to make short-term prediction of tide and tidal velocity. In order to use the measured data effectively for monitoring, the assimilation method is a good solution. In that paper, the general explanation of the assimilation for monitoring was not shown clearly.

It is well known that the so-called dynamical system with state and observe equations is very useful for expression and understanding of the general measurement system. One of the authors, Okuno, has tried to develop a new measurement method for Particle Image Velocimetry (PIV) [2)], called "model based

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measurement". It can be understood an assimilation method from the viewpoints of the measurement using mathematical model. In this paper, the method is extended to the general assimilation. It is explained by using the dynamical system model and Kalman's Filter.

Another problem in monitoring is of simultaneous measurement in wide region. The image measurement method has been developed to visualize the distribution of chlorophyll and also to measure the coastal current[1]. For the monitoring in wide area, it is possible to use numerical prediction method with few measured data. In the case of Yura, the environment of the Bay area can be understood by using simulation, because the environment is almost determined by the factors at the two mouths. In this paper, a simple ecological model, P-N model, is employed with assimilated data at the mouths.

Many researchers have employed the so-called P-Z-D-N (Phytoplankton, Zooplankton, Detritus and Nutrient) model for the environmental simulation. This kind of the prediction method can be applied to the monitoring, if it is effective for short-term prediction. However, the P-Z-D-N model is not suitable for practical monitoring, because a number of empirical parameters should be determined by the measurement. For the short-term prediction of phytoplankton, which is important for the monitoring, the zooplankton and detritus do not play an important role in eco-system because of their long reaction time. The authors have developed a simple mathematical model, the so-called P-N model already [3] for this purpose.

In the case of environmental investigation at Yura, it is very important to measure the environmental factors at the two mouths of the Bay, Shinkawaguchi and Imagawa-guchi. These quantities will be the boundary condition for the simulation. It means that if the factors can be measured or estimated correctly at these two points, the simulation can give the flow and the other environment factors at any point in the bay. The present methods, the assimilation of environmental factors at the mouth and the short-term prediction by using simple eco-system model, are examined in detail and the effectiveness is shown by comparison of the measured data with the simulated results.

2. Data Assimilation in Monitoring

In order to assimilate the measured data into the predicted result, several mthod have been proposed already. One of the popular method is of Kalman's Filter[5]. It is possible to understand clearly by using the state space model. In this section, for applying this model to the measurement, it is assumed that the observation value can be divided into estimated by the mathematical model and the others such as field noise.

The observation values consist of the estimation by several mathematical models, which enable to express the observation with superposition of some weighted functions. The observation is expressed by the following equation.

$$y(t) = x_1 p(t) + x_2 q(t) + x_3 r(t) + \cdots \qquad (1)$$

where, $y(t)$ is observation value, $p(t)$ the estimated value by a mathematical model, $q(t)$ and $r(t)$ are the other variables, and x_1, x_2, x_3 are weight coefficients.

The difference between the estimated values by mathematical model and the measured values is regarded as time series data. The difference is written using the first term of Eq.(1),

$$z(t) = y(t) - x_1 p(t) \qquad (2)$$

The analysis technique for time series data is used widely in various research fields. Auto-Regression model (AR model) that Yule proposed in 1927[4] is the most popular one. Recently, the technique using state space model is introduced based on the AR model and AIC (Akaike's Information Criterion).

The state space model is essentially a recursive one and expression for good understanding of the measurement. This is given by the following two equations [5].

$$x(t) = Fx(t-1) + Gv \qquad (3)$$

$$z(t) = Hx(t) + w \qquad (4)$$

where the vector $x(t)$ is called space state, Eq.(3) is called system equation, F and G are the matrix of state space, v is noise of the system. Eq.(4) is called as the observation equation, and observation value $z(t)$ is expressed by the state space $x(t)$ and matrix H, w is the noise of observation.

In this algorithm, if we assume that vector $x_f(t)$ is the optimum $x(t)$ and vector $x_p(t)$ is the prediction of

$x(t)$ by system Eq.(3). $x_f(t)$ is expressed by the follow equation.

$$x_f(t) = x_p(t) + K(t)|z(t) - Hx_p(t)| \quad (5)$$

where, $K(t)$ is called by Kalman Gain, it can be determined by the next equation.

$$K(t) = P(t)H^T[HP(t)H^T + R]^{-1} \quad (6)$$

where, $P(t)$ is the covariance matrix of system noise, R is the covariance matrix of observation noise.

This method is an assimilation of the observation and the mathematical model. The examination results were shown using tide and current data already [3]. In this paper, the case of phytoplankton will be discussed. In order to monitor the phytoplankton concentration at the mouth of Yura Bay, Shinkawa-guchi, the mathematical model of phytoplankton concentration is considered at first. The change of phytoplankton concentration can be obtained in the following diffusion equation as well known.

$$\begin{aligned} \frac{\partial P}{\partial t} &= u\frac{\partial P}{\partial x} + v\frac{\partial P}{\partial y} + w\frac{\partial P}{\partial z} \\ &\quad + K_{xy}\frac{\partial^2 P}{\partial x^2} + K_{xy}\frac{\partial^2 P}{\partial y^2} + K_z\frac{\partial^2 P}{\partial z^2} \quad (7) \end{aligned}$$

where P is concentration, u, v, w the velocity, K_{xy}, K_z the diffusion coefficient. For the measurement at Shinkawa-guchi, northern mouth of Yura, the following equation can be assumed, because the concentration depends on the flux and current in one direction.

$$\frac{\partial P}{\partial t} = u\frac{\partial P}{\partial x} \quad (8)$$

It is understood that the change of phytoplankton concentration can be estimated when the spatial scale of phytoplankton distribution and the current is known.

As shown in Fig.1, the map of Yura, Shinkawa-guchi is the northern mouth of the bay. Since the closed sea of Yura is open to Osaka Bay through two mouths, the environment of the bay will be determined by not only the human activities in the village through rivers but also the inflow through the mouths. From the previous paper[6], it has been found that the effect of the inflow through the mouths is very stronger than the rivers in the bay.

The phytoplankton was measured at Shinkawa-guch by using an electric device. Fig.2 shows the measured data and the estimated. For the simple mathematical model, sinusoidal function is assumed here.

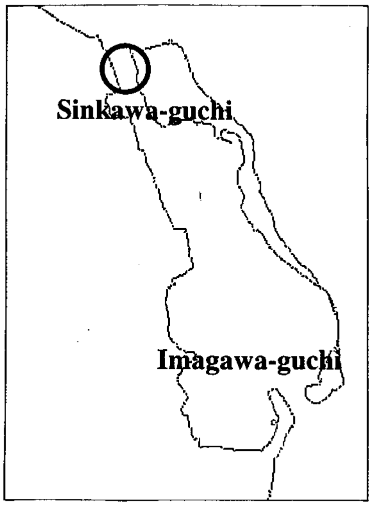

Fig. 1 Yura Area.

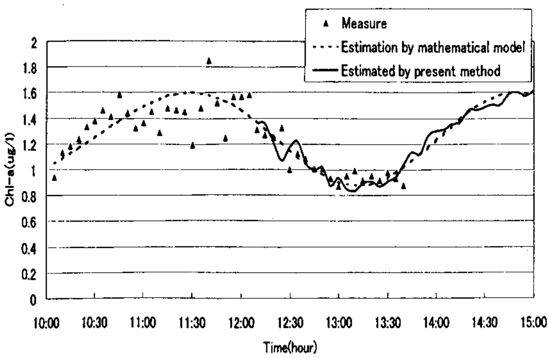

Fig. 2 Monitoring data of chlorophyll.

In the figure, the estimation is stared at around 12:00 by using the measured data from 10:00 through 12:00. It is found that the result of mathematical model shows outline of the rough change, and Kalman's Filter is really effective for obtaining the reasonable results. The spatial scale of the phytoplankton distribution is around 10km which is reduced from the figure. It can be said that this is reasonable in the Osaka Bay[3].

If we know the phytoplankton distribution, flow velocity and also other several factors at the mouth as the boundary condition in the Eq.(7), the environment in Yura can be estimated. It is important to examine these from the view point of the short-term prediction.

3. Monitoring by P-N Model

As mentioned in the previous sections, in the case of Yura, the environment of the bay area can be obtained by using the numerical simulation, because the environment of the bay area is almost determined by the important factors, phytoplankton, nutrient and flow, at Shinkawa-guchi and Imagawa-guchi. In this paper, these are measured or predicted by using assimilation. These values are used as the boundary condition of the simple eco-system model, which is constructed with phytoplankton (P) and nutrient(N), the so-called P-N model, It is understand This is a monitoring in the bay area.

The equations for prediction of the phytoplankton and nutrient, eco-system model, can be written as

$$\frac{\partial P}{\partial t} = -\frac{\partial}{\partial x}(u\cdot P)-\frac{\partial}{\partial y}(v\cdot P)-\frac{\partial}{\partial z}(w\cdot P) +K_{xy}\left(\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial x^2}\right)+K_z\frac{\partial^2 P}{\partial z^2}+\left(\frac{dP}{dt}\right)^* \quad (9)$$

$$\frac{\partial N}{\partial t} = -\frac{\partial}{\partial x}(u\cdot N)-\frac{\partial}{\partial y}(v\cdot N)-\frac{\partial}{\partial z}(w\cdot N) +K_{xy}\left(\frac{\partial^2 N}{\partial x^2}+\frac{\partial^2 N}{\partial x^2}\right)+K_z\frac{\partial^2 N}{\partial z^2}+\left(\frac{dN}{dt}\right)^* \quad (10)$$

$$\left(\frac{dP}{dt}\right)^* = V_m(I,T)\frac{N}{K_s+N}P-\alpha(T)P-\gamma(T)P^2 \quad (11)$$

$$\left(\frac{dN}{dt}\right)^* = -\left(\frac{dP}{dt}\right)^* \quad (12)$$

where P and N are the phytoplankton and nutrient, I is the intensity of sunlight, T the temperature. V, a, and r are the parameters of P-N model.

According to the examination on the P-N model, it is found that it can be apply to the prediction of change of phytoplankton for one or two days. This means that when the flow, phytoplankton and nutrient can be measured or estimated correctly at two mouth of Yura bay, the environment at any point of the bay can be obtained reasonably.

In this paper, several prediction results are shown as the so-called "case study" to examine the present method. The two cases are considered here, Case 1: there is a phytoplankton pulsed inflow from 10:00 to 13:00 at Shingawa-guchi, and Case 2: there is such inflow from 13:00 to 16:00 at Imagawa-guchi. The maximum values of both pulse are 3.6(μg Chl-a/l) and 11.0(mgN/m^3), which are the two times larger than that of usual value. The nutrient at mouths is set constant value of 42.0(mgN/m^3).

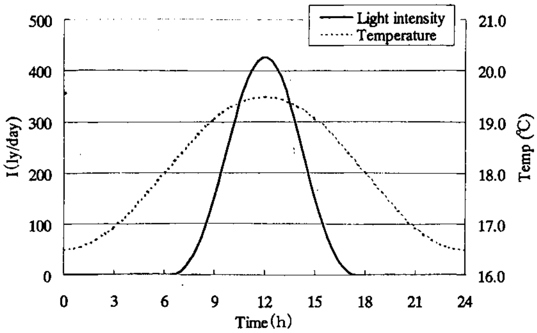

Fig. 3 Numerical conditions of sunlight and temperature variation.

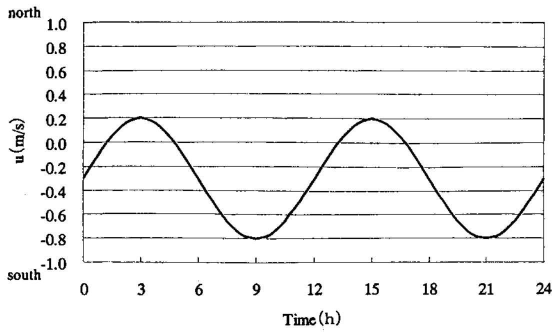

Fig. 4 Velocity distribution at Shinkawa-guchi.

Fig.3 shows the sunlight intensity and temperature in the model, which are normally used in the eco-system model. The peak values are in the noon and gradually decrease toward the night.

The current speed is shown in Fig.4. This is estimated by using the model that has been proposed in the previous paper[3]. The velocity depends strongly on the tide. It was found already that the accuracy is fairly good with the measurement.

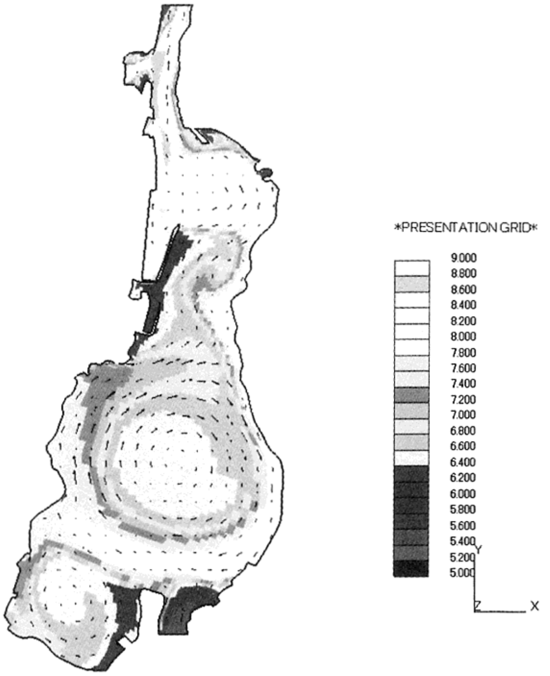

Fig. 5 Phytoplankton distribution in Yura in case of pulsed like input at Shinngawa-guchi(15:00).

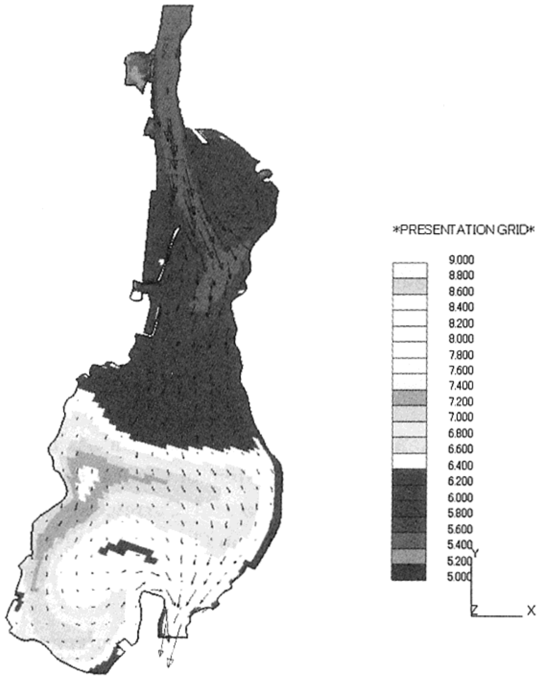

Fig. 6 Phytoplankton distribution in Yura in case of pulsed like input at Imagawa-guchi(20:00).

4. Results and Discuusion

Figs.5 and 6 show the predicted results of phytoplankton distribution by using the so-called P-N model and the parameters mentioned before.

The distribution of phytoplankton shown in Fig.5, the Case 1, shows that the inflow causes a current and diffusion in the bay. The flow from the mouth meanders owing the breakwater and the hollow region near the hill. The flow reaches the other mouth, Imagawa-guchi, in around a few hours theoretically. Of course, however, all of the water lumps does not flow out from the mouth. The averaged concentration will be higher gradually in the bay during the time. The behind of the breakwater and hollowed region at northeast and also the similar region at southwest of the bay, the clear dead water are formed by flow separation. In these regions, the higher concentration values of the phytoplankton remain. The phytoplankton in the bay is formed as patch like shape and it gives the spatial scale of the distribution. The length of the scale is around a few hundreds meter which is estimated by image measurement. These are shown in good agreement with the observation.

It has been known that the red tide of outside of Yura flowed from Imagawa-guchi when southern wind is strong, even though the mean flow owing to the tide is north to south. It makes many troubles such as the quick annihilation of young yellowtail and so on. In Fig.6, the Case 2, which shows the inflow from Imagawa-guchi, it can be found that the high concentration of phytoplankton flowed from Imagawa-guchi concentrated to the southwestern of Yura. These results show not only simulation but also the possibility of short-term prediction like a forecast.

5. Conclusions

This paper deals with the monitoring methods using assimilation of measured data with the prediction. A general formation of the assimilation has been shown by using dynamical system, state and observe equations. Kalman's Filter theory is employed to express the short-term prediction.

The phytoplankton concentration is monitored at the mouth of the bay using one-dimensional monitoring system, which is expressed by the mathematical model with Filter. Furthermore, in the case of two-dimensional monitoring, in wide range of the plane, the ecosystem model, the P-N model, is employed. It is found that it is possible to understand the change of environmental at any time and point of coast by using few measurement values and mathematical model. The authors would like to express their thanks to Mr. Hanano, who always help us to measure at Yura, and also to the students in the laboratory.

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