43. Statistical analysis on alga blooming in Mikawa Bay, Central Japan using simulation results of hydrodynamic and ecological model

流動／生態系モデルのシミュレーション結果を用いた三河湾の藻類増殖に関する統計解析

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ABSTRACT; The excessive algal bloom and oxygen-depleted water which are frequently observed in Mikawa Bay, have led to the growing public concern. On many marine systems, nutrient has been identified as the pollutant of concern, and is believed to stimulate the excessive alga growth. This study investigated by numerical simulation which factors may regulate the production of chlorophyll-a in the bay. We, therefore, analyze the three years calculated results using statistical method to investigate the relationship between river flow, riverine total nitrogen (TN) inputs, water temperature, bay nutrient concentration and primary productivity. Both hydrodynamic and water quality variables were calculated using a dynamic model which includes hydrodynamic equations and 13 mass conservation equations for chlorophyll-a, dissolved oxygen, etc. The obtained result are as follows: (1) chlorophyll-a has the strongest correlation with TN, and temperature, and additionally with total phosphorus (TP), (2) the flow rate of fresh water from land area was one of the most important factors to regulate TN concentration in the bay.

KEYWORDS: Mikawa Bay, alga blooming, nutrient, long term analysis, temperature, flow rate

1. INTRODUCTION

Mikawa Bay is a semi enclosed bay located in the middle of Japan and approximately 700.000 people live near the watershed. The watershed area is used intensively for agricultural and livestock production, where nutrient from the land area is loaded through two major rivers Toyokawa and Umedagawa, and the municipal waste water treatment at Noda and Nakashima. The eastern half of Mikawa Bay is called Atsumi Bay, on which we will focus in this study. Atsumi Bay can be divided into 3 different characterictic areas based on its topography. They are the uppermost section near the Toyokawa River and Umeda River, the middle section, and the lowest section that connects to the ocean. The uppermost section is largely influenced by fresh water and shows the highest nutrient. The middle is much wider and deeper than the uppermost section. The lowest section is further wider and deeper and is generally affected by open sea flush.

In the last decades increased human activities in the watershed and the bay area have resulted in damage to the ecosystem of Mikawa Bay. The excessive algal bloom or red tides and oxygen-depleted waters have been frequently observed in this bay. These problems have led to Mikawa Bay being declared as one of the most threatened bays in Japan (Boesch, 1998). On many marine systems, nutrient has been identified as the pollutant of concern, and is believed to stimulate the excessive alga growth.

In our previous study, in which effect of various nutrient-reduction measures on the alga blooming in Mikawa Bay was investigated, it was found that the nitrogen is a limiting factor for the growth of alga (Anggara and Kitada, 2003). While nitrogen limitation has been demonstrated (Anggara and Kitada, 2003), a predictive relationship between nitrogen inputs and alga biomass in the system has not been demonstrated. Therefore, in this study, we develop predictive relationships between river flow, riverine total nitrogen (TN) inputs, water temperature, bay nutrient concentrations and primary productivity using the three years calculated results. In this study, both hydrodynamic and water qualities variables were simulated using a model which includes a series of hydrodynamic equations and 13 mass conservation equations related to water quality such as chlorophyll-a, dissolved oxygen, etc. In the following sections, a brief description of the studies site, the input data and the model development are presented. The results and the conclusions are given at the end of this paper.

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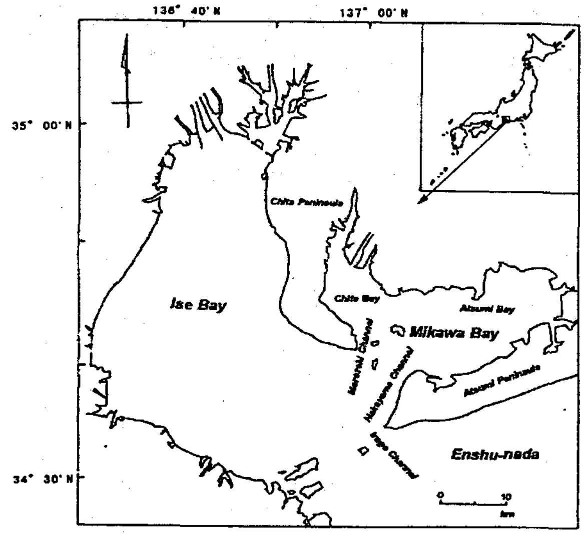

Fig. 1: The watershed of Mikawa Bay

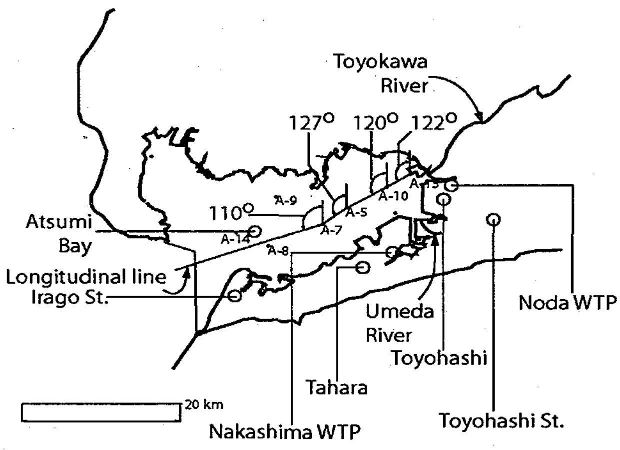

Fig. 2: The segmentation model of Mikawa Bay, the thick solid line indicates longitudinal axis in two-dimensional model; A5-A14 show monitoring points. Two waste water treatment plants are shown as "Noda" and "Nakashima" WTPs. Two AMeDAS (Automatic Meteorological Data Acquisition System) stations are also indicated as "Toyohashi St." and "Irago St."

2. METHOD

2.1 Data description

Measurement of the variables such as chlorophyll-a, TN, TP, salinity and temperature were performed at 5 sites of A13, A10, A5, A7 and A14 as shown in Fig.2 (DE-APO, 2002). The locations of these points roughly correspond to the segment 2, 5, 11, 16, and 29 in the numerical simulation, respectively.

The physical input data for the calculation were the river flow rate and the water temperature at the Toyokawa and Umeda River (TO-MLIT, 2002), and the discharge flow rate and the temperature at the waste water treatment plants of Noda and Nakashima (TCO, 2002). The observed chemical data in river water and in discharge of waste water treatment plants were TN, TP and other water quality indices (TO-MLIT, 2002 and TCO, 2002). The meteorological data by Japan Meteorological Agency (JMA) were precipitation, wind, and temperature (JMA, 2002). Figure 3 a and b show the seasonal variations of TN and TP concentrations, temperature and flow rate from April 1, 1998 to March 31, 2001.

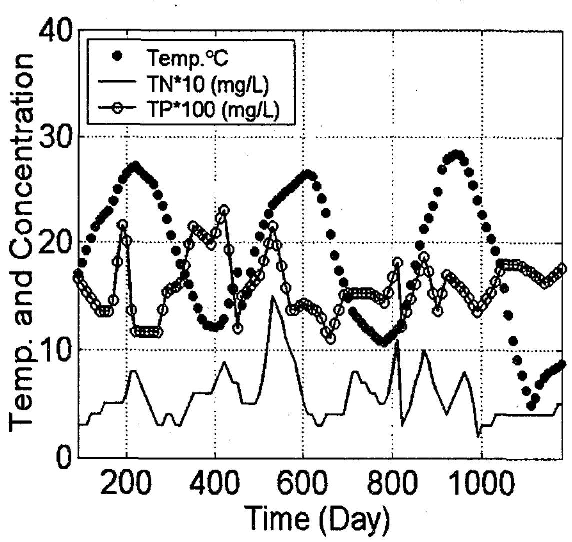

Fig.3a Temperature, TN and TP in input fresh water, the weighted – average of Toyokawa, Umeda rivers and waste water treatment plants in 1998-2001. The "day" starts from April 1, 1998.

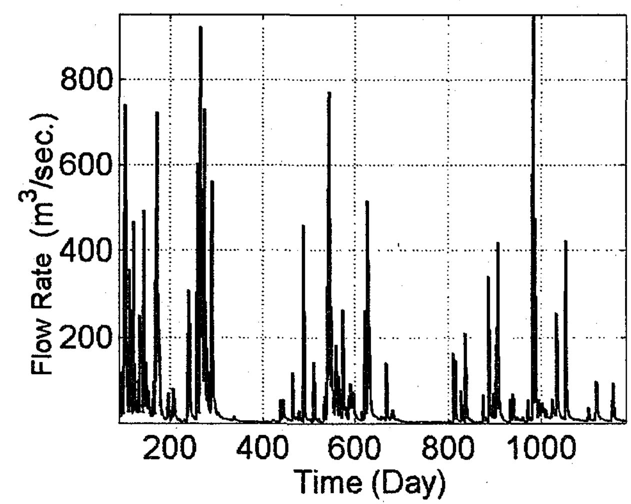

Fig.3b Input flow rate of Toyokawa River in 1998-2001. The "day" starts from April 1, 1998.

2.2 Model development

Hydrodynamic variables and water qualities in the bay were simulated using a software CE-Qual-W2 (Cole and Wells, 2000). The model laterally integrates governing equations and thus the calculation is performed in 2-dimensional space with longitudinal and vertical axes. The model includes 13 water quality constituents, and has a simple model of sediment.

In this study, the water body was discretized into 30 equally spaced longitudinal segments and 24 vertical cells. Each segment has the same length of 855 m and each cell has uniform thickness of about 1.1 m. Each middle segment has multiple active cells and two boundary cells, i.e., one at the sea surface and another at the bottom of sea. The depth of the each segment varies from 6.6 m (6 active cells) to 24 m (22 active cells). The inshore segment is divided into 8 cells with 6 active cells and the outer segment is divided into 24 cells with 22 active cells. In the study, the numerical simulation was done for three years; it started from April 1, 1998 until March 31, 2001. The time step for integration was 350 s.

In this analysis, as mentioned previously, we analyzed correlation among three years; calculated quantities. At first, we evaluated relative importance in the growth of alga, of the factors of TN and TP concentrations, temperature, and salinity in the bay. From this step the controlling factor was determined. In the second step, we further examined the element that, in this time, affects most is "controlling factors"; we tested the effect of river flow rate, nutrient concentration in the river water, and temperature.

3. RESULT AND DISCUSSION

3.1 Comparison of model calculated with observation

Numerical calculation in this study did well reproduce the seasonal variation in the observation data. Figure 4 is one example of the outputs and shows temporal variation of observed (symbols) and calculated (solid line) chlorophyll-a for near surface water at segment 2 (a) and segment 29 (b). Chlorophyll-a at A13 (segment 2) near the mouth Toyokawa River (Fig. 4a) is general higher than that at A14 (segment 29) near the open sea (Fig. 4b), and chlorophyll-a at A13 and A14 show their seasonal variation; high in warm season and low in cold season. The measurement of chlorophyll-a for near surface was performed at around 1 m below the surface level. In general, the model reproduced the seasonal variation found in the observation although on several occasion the model failed to predict bloom condition as seen in the observation. Based on these judgments, we used the calculation results in the following analysis.

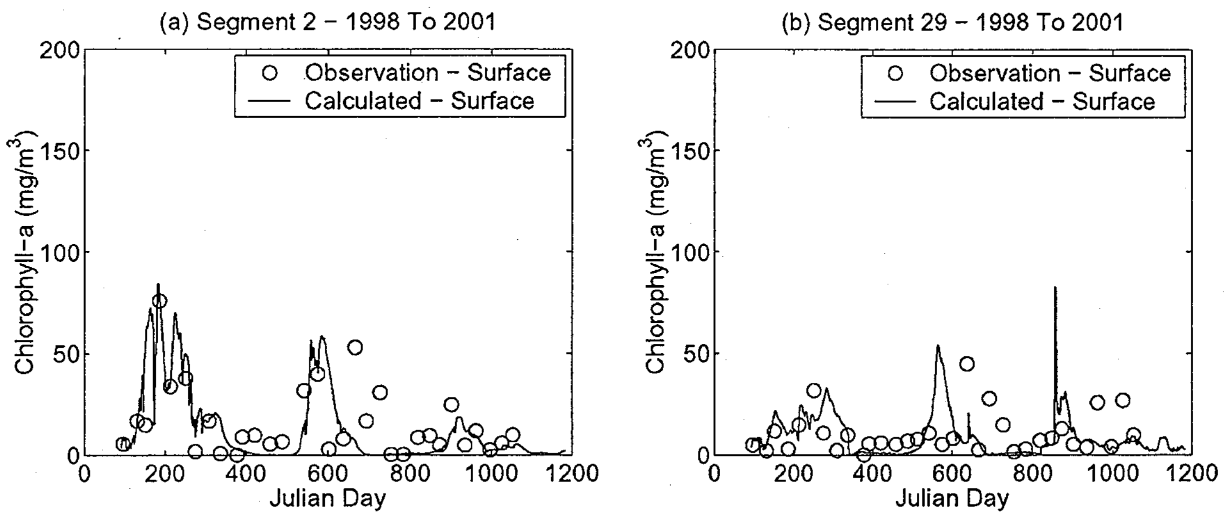

Fig. 4 Temporal variation of observed (symbols) and calculated (solid line) chlorophyll-a for near-surface water at (a) segment 2 (calculation) and A13 (observation) near the mouth of Toyokawa River and (b) segment 29 (calculation) and A14 (observation) close to the interface between Atsumi Bay and open sea.

3.2 Characteristic of bay water quality as revealed by correlation analysis

In this analysis, first, as listed in Table 1 we calculated correlation coefficients of chlorophyll-a vs. TN, TP, temperature, and salinity in the bay. In Table 1, the coefficients were obtained at several segments using the simulation results for three years from 1998 to 2001. Table 1 shows that, chlorophyll-a has strong positive correlation with TN, and temperature, and moderate correlation with TP. On the other hand, salinity shows understandably negative value with the chlorophyll-a, reflecting that high salinity means influence of non-polluted ocean water.

Table 1 Correlation coefficients [b] between chlorophyll-a and TN, TP bay concentration, bay water temperature, or salinity

Chlorophyll-a [a]	Seg.2	Seg.5	Seg.11	Seg.16	Seg.29
Bay TN concentration	0.801	0.882	0.856	0.818	0.741
Bay TP concentration	0.597	0.544	0.529	0.502	0.437
Bay water temperature	0.758	0.784	0.751	0.749	0.627
Salinity	-0.461	-0.617	-0.788	-0.860	-0.828

[a] Chlorophyll-a concentration at surface cell of each segment.
[b] The coefficients were derived using daily values of three year simulation.

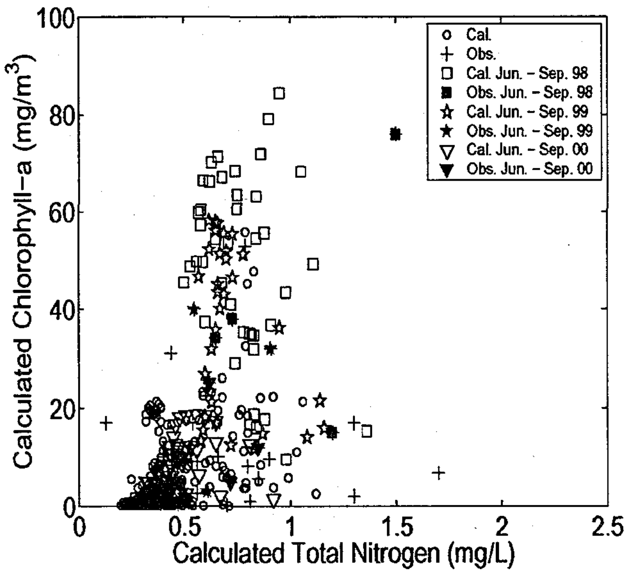

Fig.5 Correlation coefficient of calculated TN and chlorophyll-a at segment 2 for three years calculation; data points during warm season (June to September).

To further illustrate the dependence of chlorophyll-a on TN and water temperature, Fig. 4 plots relation of calculated TN and chlorophyll-a at segment 2 for three years; data points during warm season (June to September) are written with the symbols □,*, and ∇ for 1998, 1999, and 2000, respectively. The figure suggests that although there is change in chlorophyll-a concentration from year to year, chlorophyll-a much higher in warm season (June to September) than the other season. In addition, Fig. 4 shows a situation over-saturated with TN may exist and the TN concentration of about 1 mg/L maybe the critical concentration at which chlorophyll-a can reach into maximum.

Since chlorophyll-a has the strongest dependence on TN and temperature in Table 1 and Fig. 4, the factors potentially affecting TN concentration in the bay were further studied; that is, correlation coefficients of TN in the bay with TN in input fresh water, the flow rate of the fresh water and temperature of the input fresh water were calculated.

Table 2 Correlation coefficients [a] between daily averaged TN concentration (simulation derived) and observed TN, temperature, and flow rate of rivers and WTPs

TN [b]	Seg.2	Seg.5	Seg.11	Seg.16	Seg.29
Daily TN in input fresh water [c]	-0.067	-0.064	-0.057	-0.49	-0.048
Daily temperature of input fresh water [d]	0.429	0.385	0.294	0.273	0.258
Daily flow rate of input fresh water [e]	0.704	0.614	0.610	0.581	0.478

[a] These correlation coefficients were calculated by using daily values obtained during three years from 1 April 1998 to 31 march 2001. Hence each coefficient was obtained from about 100 data points.
[b] TN concentration at surface cell of each segment.
[c] Obtained as average of those in two rivers and two waste water treatment plants (WTPs) discharge.
[d] Same as TN but for temperature.
[e] Daily total flow rate which is sum of the flow rates of two rivers and two WTPs.

Table 2 suggests that TN in the input fresh water has little effect on the TN concentration in the bay, as indicated by the negative correlation coefficient with their small absolutes values. The positive correlation can be seen on the temperature of input fresh water and its flow rate. Figure 6a, b and c show the daily trend of TN and chlorophyll-a in the bay water during warm season. In Fig. 6, all the variables are plotted every 6 hours starting from 00LST on 1 May to 00LST on & July, 1998. TN near surface level in Fig. 6a shows large variation in short time span and slightly increasing trend on a monthly basis, the large variation of TN at surface is associated with increased TN loading due to increased river flow rate shown in Fig 3b. At those figure, chlorophyll-a at surface level is also largely affected by river flow rate, although in contrast to TN, chlorophyll-a at surface decreases when the river flow is large. On the other hand, TN near the bottom layer in Fig. 6b shows rather monotonic increase with time. Since chlorophyll-a is not a primary species but a product of biological reaction and yet its concentration steadily increases similar as TN concentration, thus the correlation between TN and chlorophyll-a may again be suggested. Figures 6c also show that chlorophyll-a generally increases from 1 May to 7 July, reflecting increase in solar radiation and sea water temperature.

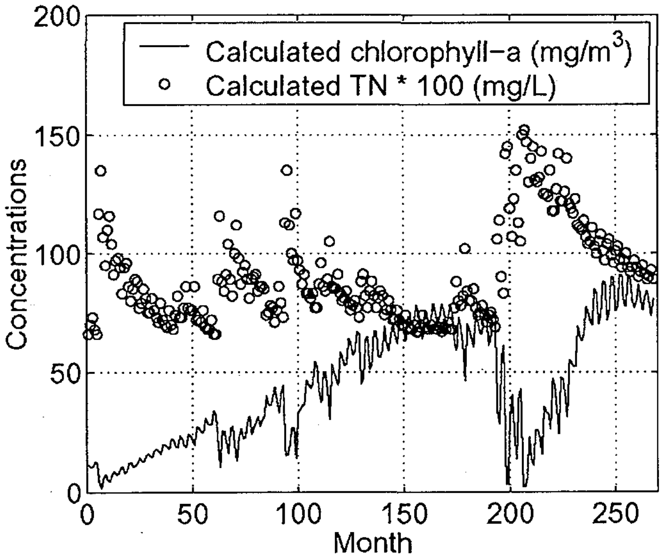

Fig. 6a Daily trend of calculated chlorophyll-a and calculated TN near surface level at segment 2 (measurement point A13) during warm season.

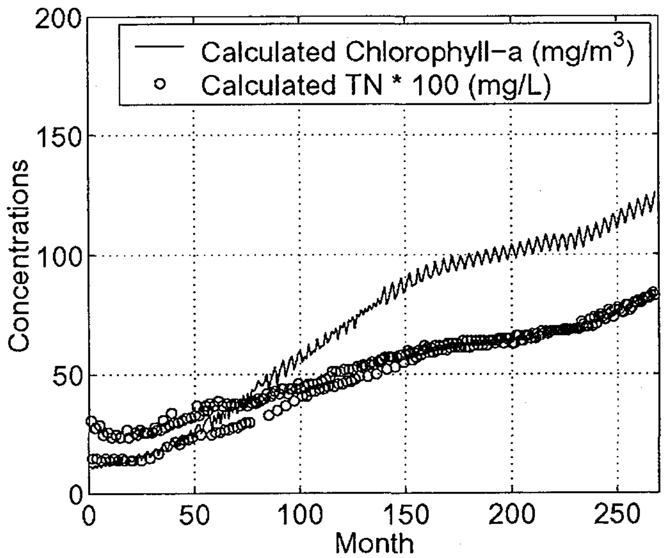

Fig. 6b Daily trend of calculated chlorophyll-a and calculated TN near bottom level at segment 2 (measurement point A13) during warm season.

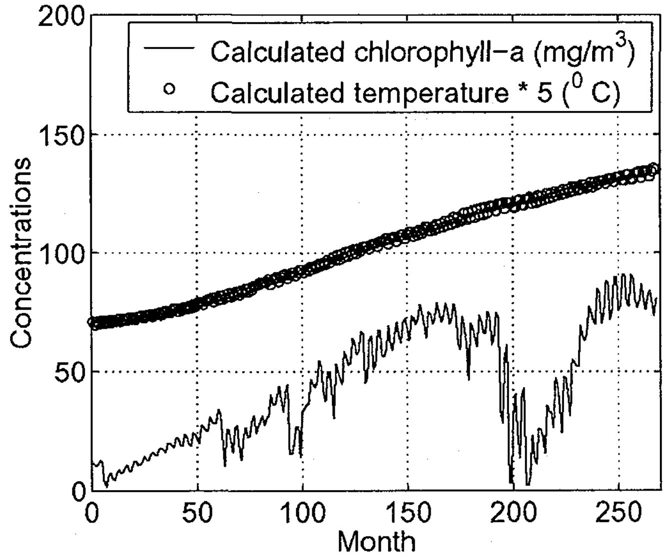

Fig. 6c Daily trend of calculated chlorophyll-a and calculated temperature near surface level at segment 2 (measurement point A13) during warm season.

This fact may suggest that daily TN input itself, from land area, is not cause for short term high TN concentration in the bay water but high flow rate of fresh water may generate the short term high TN by enhancing re-suspension of sediment.

Furthermore, as showed in Table 1, TN concentration in the bay is the most important factor which regulate the production of chlorophyll-a in the bay, and bay temperature is the second. Thus, these two tables may suggest a scenario of high chlorophyll-a as follow: (1) large volumetric flow rate of fresh water by strong precipitation causes enhanced re-suspension of nutrients from the sediment and leads to short term high TN concentration in the bay, and (2) after the end of the high flow rate associated with strong precipitation, low volumetric flow of fresh water form longer residence time of high TN water mass with high water temperature in the summer time, and then enhanced biological activity result in algal bloom.

4. CONCLUSION

In this paper, we have investigated long term analysis of eutrophication and alga blooming in Atsumi Bay (the eastern half of Mikawa Bay) by a statistical analysis using three years calculated results. The obtained results are as follow:

(1) Chlorophyll-a in Mikawa Bay understandably has correlation with TN and temperature, and moderate correlation with TP.
(2) Furthermore, the riverine TN concentration alone has only a minor role in determining bay TN concentration and chlorophyll-a concentration.
(3) River flow has a stronger influence, likely through its effects on nitrogen delivery, residence time and salinity.

These results imply that using riverine nitrogen load as the measure to evaluate watershed nutrient management is not adequate. In the short term, river flow is the dominant component of load for nutrient condition in the bay, though the watershed nitrogen controls may reduce loads in the long term.

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