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IMPACT ANALYSIS OF RAINFALL ON WATER QUALITY AND PRIMARY PRODUCTION IN OSAKA BAY

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SYNOPSIS

Water quality and primary production in enclosed bays are dependent on inflow loads from rivers and the outer ocean as well as nutrients released from the sea bottom. The nutrient supply from rainfall also plays an important role in the primary production. This research study focuses on influence of precipitation on the water quality and primary production in Osaka Bay and conducted water-quality analyses of rainwater and river water.

The rainwater had a high concentration of dissolved inorganic nitrogen, and the ratio of rainfall load to Yodo River load was about 20% in the summer of 2007, although the annual average of the ratio was about 3%. This finding suggests that the precipitation may increase the phytoplankton biomass in the surface layer with nitrogen limitation. Therefore, we also examined the changes in the water quality and primary production using a system dynamics model to evaluate the precipitation effect quantitatively.

INTRODUCTION

Measures to improve the water quality in enclosed bays, such as Tokyo Bay and Osaka Bay, have been implemented according to plans for reduction in total pollution loads. However, the water pollution phenomena, such as red tide and blue tide, still occur frequently despite pollutant control. Although the water quality of the bay depends primarily on the inflow load from land, enclosed bays in Japan have not yet reached the water-quality standards because of the nutrient release according to the decomposition of organic sediment in the benthic layer.

A recent study [1] shows that intrusion of the nutrients from the outer ocean is significantly related to the water quality in the bay. Also, our observation findings [2] indicate a high concentration of nutrient inflow to Osaka Bay through the Kitan Strait, which is located at the bay mouth. Thus, it is clear that the water quality in enclosed bays depends on the river load, release from the bay bottom, and intrusion from the ocean.

Moreover, various researchers have pointed out that materials of an atmospheric origin also have an effect on the water quality, *e.g.*, Paerl [3], Tada [4], Caccia and Boyer [5], and Calderon *et al.* [6]; the supply of nitrogen and iron from the atmosphere contributes to the primary production, especially in oligotrophic waters. Caccia and Boyer [5] evaluated nutrient loadings into Biscayne Bay from atmospheric, cannel, and groundwater sources. They showed that the wet atmospheric deposition was about 12 % of the total DIN input to the bay. Calderon *et al.* [6] estimated DON flux to Tampa Bay to be about 7 % of the total rainfall nitrogen flux.

Little research has been carried out on the biochemical dynamics of nutrients loaded into Osaka Bay, although Hoshika *et al.* [7] estimated the amount of the nutrients loaded by deposited matter falling on Osaka Bay. Hoshika *et al.* also showed that 77% of the benthic sediments in Osaka Bay were loaded from rivers during floods. However, we could not obtain an accurate estimation of inflow loads because the observations of the water quality during floods have been rarely performed by the relevant organizations due to various difficulties, including the difficulty of water sampling.

In this study, we made observations of the water quality of rainwater and floodwater, and also clarified the influence of nutrient loads on the water quality and primary production in Osaka Bay by using a system dynamics model.

OBSERVATION OF RAINFALL AND FLOOD

Observation and analysis of rainwater

Sampling of rainwater was performed at three places (Suita City shown in Fig. 1, Osaka City, and Kashiwara City) in the Osaka Prefecture from June 2007 to May 2008, and the water qualities (DIP (PO_4–P), DIN (NH_4–N, NO_2–N, NO_3–N), TP, and TN) were analyzed using the auto-analyzer *swAAt*. In this study we made the analysis by using the data obtained at Osaka University in Suita City, where all the rainfalls were sampled.

The average concentration and the deposition flux of DIN and DIP for each rainfall are shown in Fig. 2. The nitrogen concentrations are considerably high due to the absorption of nitrogen oxides in the atmosphere, although the rainwater has very low phosphorus levels that are about two orders less than nitrogen levels. The amount of the nitrogen load per rainfall occasionally exceeds 20 mg/m^2. This finding suggests that the rainfall may contribute to primary production, especially in nitrogen-limited waters.

Caccia and Boyer [5] show the atmospheric loads of DIN in estuaries of United States. The DIN load for Osaka Bay is comparable to that for Chesapeake Bay, although the concentration of NO_3-N is higher than that of NH_4-N for Chesapeake Bay.

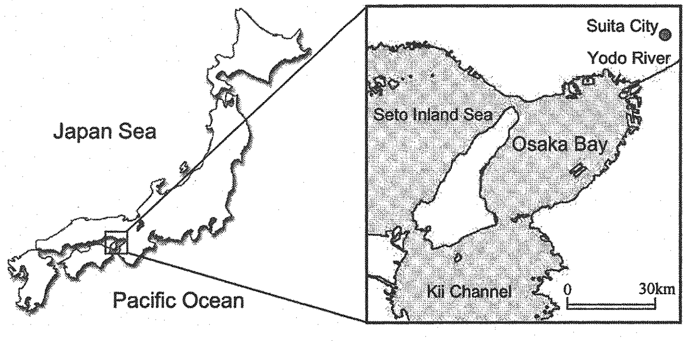

Fig. 1. Location of Osaka Bay and observation points

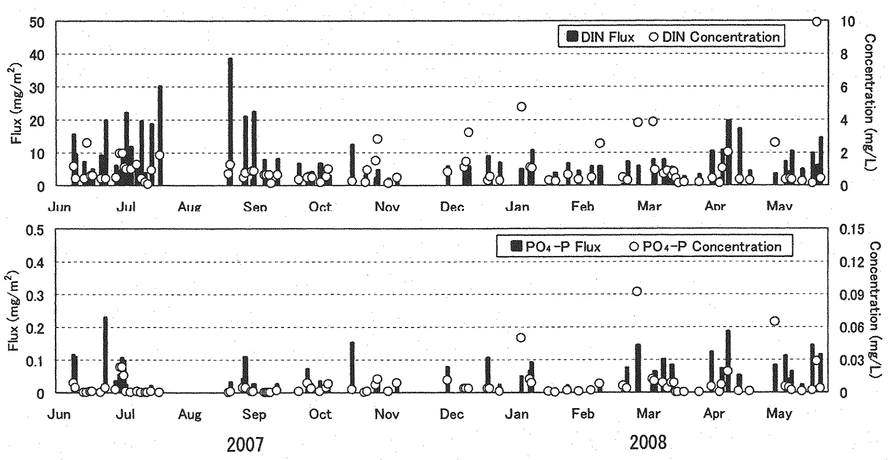

Fig. 2. Average concentration and deposition flux of TN and TP for each rainfall

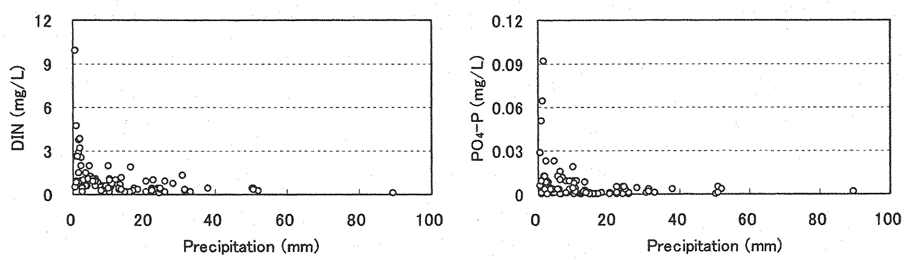

Fig. 3. Relationship between the precipitation and the average concentration for each rainfall

The relationships between precipitation and average concentration for each rainfall are shown in Fig. 3. The concentration tends to decrease as the precipitation increases because of the decrease in the concentration of nitrogen oxides in the atmosphere with increasing precipitation, *i.e.*, the washout effect. However, we were unable to determine the relationship between the concentration of the nitrogen oxides in the atmosphere measured by the Osaka Prefectural Government and that of nitrogen in rainwater, because the concentration of nitrogen oxides is strongly dependent on advection and dispersion in the atmosphere, and data sampling is taken at a ground-based observatory.

Observations on floods and estimations of inflow loads

The observations were performed at Toyosato Bridge at about 14 km upstream from the mouth of the Yodo River. A Sampling of the surface water was taken near the center of the river. To understand the water-quality distribution in the cross-section, we also took samplings at a maximum of 10 points in the section. The nutrients were analyzed by using the auto-analyzer *swAAt*. In addition, analyses for SS and the grain size were also performed.

The observations of floods were performed from June 2007 to May 2008. The floods that exceeded 1,000 m^3/s during the observation period were generated two times, and the maximum discharge was 3,120 m^3/s on July 15, 2007; the annual mean discharge of the Yodo River measured at the Hirakata observatory is about 300 m^3/s. Figure 4 shows the hydrograph and the hyetograph of the largest flood recorded at the Hirakata observatory. The total precipitation reached 121 mm in 5 days from July 13 to 17 due to typhoon No. 4, although the maximum hourly precipitation was only 9 mm.

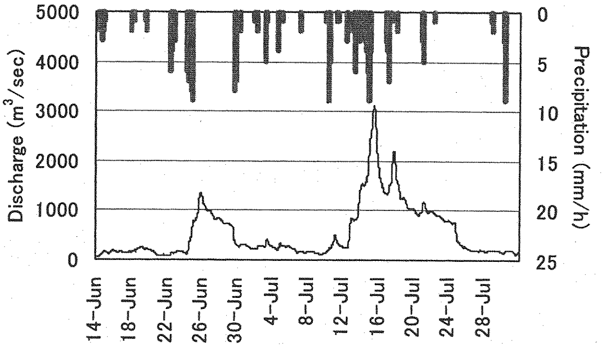

Fig. 4. Hydrograph and hyetograph for the largest flood in 2007 at the Hirakata Observatory

Table 1. Water quality during the flood in July 2007

	Discharge (m^3/sec)	SS (mg/L)	NH_4-N (mg/L)	NO_2-N (mg/L)	NO_3-N (mg/L)	DIN (mg/L)	TN (mg/L)	PO_4-P (mg/L)	TP (mg/L)	SiO_2-Si (mg/L)
14-Jul	1568	43.7	0.060	0.005	0.580	0.645	0.86	0.027	0.110	2.69
15-Jul	3109	99.6	0.027	0.006	0.714	0.747	1.20	0.026	0.160	3.38
16-Jul	1396	34.2	0.024	0.003	0.579	0.606	0.74	0.012	0.073	2.68
18-Jul	1231	23.1	0.022	0.003	0.574	0.599	0.92	0.015	0.049	2.22
20-Jul	908	18.0	0.017	0.003	0.495	0.515	0.76	0.012	0.046	1.88

Table 1 shows the results of the water-quality analysis of the samples taken in July, when the river discharge recorded its maximum value. The nutrient loads calculated using the river discharge at Hirakata station are also shown in the table.

The load–discharge (L–Q) curve obtained from these results is shown in Fig. 5. In the figure, we also plot the data on ordinary discharges observed by Osaka Prefectural Government in the summer of 2005 and 2006 near the Toyosato Bridge. The inflow load on the flood is significantly large, as pointed out in previous studies, and the impact on coastal water is extremely large because the fresh water, SS, and the nutrients will be supplied in a short term.

River management organizations rarely perform observations during floods because of the difficulty in measuring water quality, and they do not need data of water quality in the extraordinary state, but in the ordinary state. Also, very little observation data on flooding is available for the Yodo River. However, the importance of data sampling for floods has been recognized recently, and observations have been started in some rivers.

Mishima *et al.* [8] estimated the inflow load from the Yodo River into Osaka Bay using their observation data. They presented the L–Q curve using the data including flood data from 1995 to 1996 at the point of about 10 km upstream from the mouth of the Yodo River. The amount of loaded SS at the flood peak of our observed data was about 2.7 times larger than that calculated using the L–Q curve of Mishima *et al.* The difference between the observed load and calculated load was found to be large even considering the differences in observation year and observation point; the cause has not been identified.

The flood flow exceeding 500 m^3/s had continued for about two weeks in July, and the amount of loaded SS in this period reached about 53,000 ton. Mishima *et al.* reported that the total annual amount of the inflow load for the year from the Yodo River into Osaka Bay was 142,000 ton. It was found that about 33% of the total loaded SS flowed into Osaka Bay in the short period of only two weeks. In order to improve the calculation's accuracy of the amount of the inflow load into Osaka Bay, it is necessary to collect more flood data and information including the water quality of Lake Biwa, which is located upstream of the Yodo River, and to consider the measuring method of the water quality during flooding.

Table 2 shows the inflow load from the Yodo River in the summer of 2007 and the rainfall load on Osaka Bay. The inflow

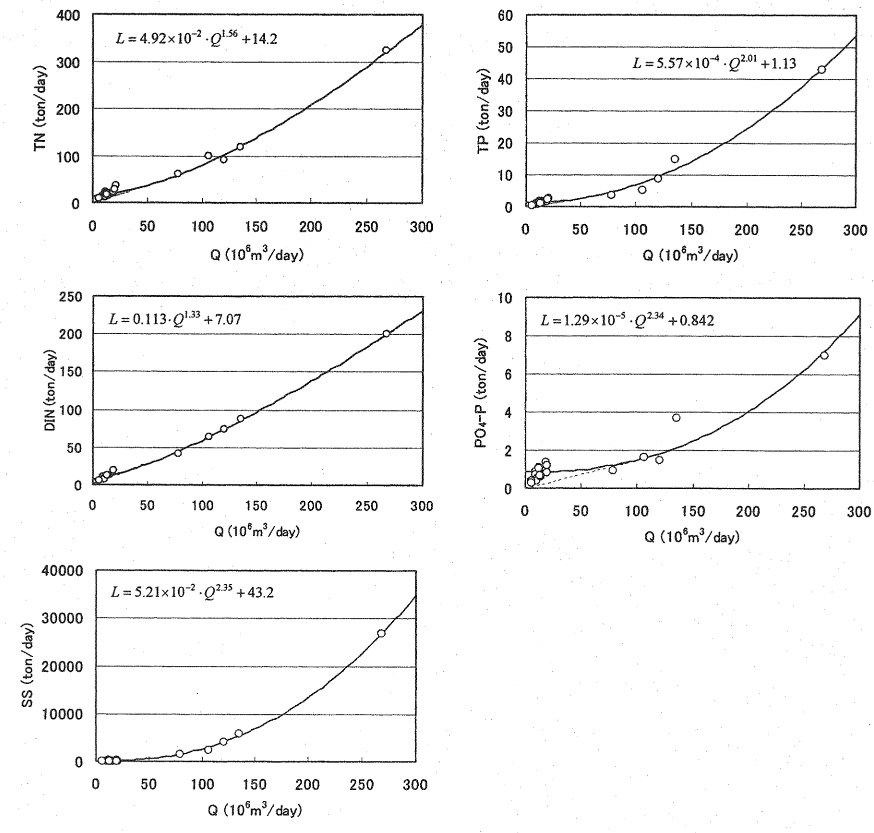

Fig. 5. L–Q curve at Toyosato Bridge, including the data obtained by the Osaka Prefectural Government

Table 2. Inflow load from Yodo River and rainfall load on Osaka Bay in the summer of 2007

Load	June			July			August			Total (June to August)		
(ton/month)	Inflow (a)	Rainfall (b)	b/a	Inflow	Rainfall	b/a	Inflow	Rainfall	b/a	Inflow	Rainfall	b/a
NH_4-N	26.13	62.99	2.41	59.44	82.33	1.39	14.08	32.40	2.30	99.65	177.72	1.78
NO_2-N	6.96	0.64	0.09	9.88	0.45	0.05	6.68	0.69	0.10	23.53	1.78	0.08
NO_3-N	567.16	57.01	0.10	1116.84	109.17	0.10	424.54	66.80	0.16	2108.54	232.98	0.11
DIN	600.25	120.63	0.20	1186.15	191.96	0.16	445.31	99.89	0.22	2231.71	412.48	0.18
TN	698.51	201.69	0.29	1535.78	215.75	0.14	498.54	128.29	0.26	2732.83	545.73	0.20
PO_4-P	27.08	0.74	0.03	38.89	0.47	0.01	26.19	0.26	0.01	92.16	1.47	0.02
TP	53.04	1.40	0.03	140.57	1.45	0.01	37.11	1.11	0.03	230.72	3.96	0.02

load was calculated from hourly-observed discharge data at Hirakata station using the L-Q curve shown in Fig.5, and the rainfall load was estimated to be a nutrient flux on the surface multiplied by a surface area of 1,400 km^2. Here, we used the on-land data collected in Suita City to estimate the rainfall load, because there was no data available in the nearshore or offshore region; the difference of measured T–N loads at three places was about ±30%. In general, the difference in deposition flux of non-sea-salt ion such as NH_4^+ between land area and sea area is not great.

Due to floods, a large amount of nutrients is supplied to Osaka Bay through the Yodo River in June and July compared with other months. As for P, the rainfall load is an insignificant compared with the inflow load from the Yodo River. However, the rainfall load of N is not negligible, especially NH_4–N, which exceeds the inflow load from the Yodo River.

IMPACT ANALYSIS ON OSAKA BAY

Present state of water quality

Figure 6 shows the seasonal change of water quality; N, P, COD, and Chl.a of the surface layer in Osaka Bay, which are the average values of the routine survey by Osaka Prefectural Government for 10 years (1996 to 2005). Moreover, typical spatial distributions of the water qualities in August are shown in Fig. 7. It is thought that the rainfall on the sea surface hardly affects the increase in the concentration of N and P directly in the head of the bay because this area is already eutrophic. However, in the western bay, where the concentration of N and P is low, there is a possibility that the primary production could increase because of the rainfall load. If the rainfall observed on July 20 supplies N and P to the sea surface layer of 1 m thickness with N = 0.04 mg/L and P = 0.01 mg/L, the concentrations of N and P in surface layer will increase by 0.038 mg/L and 0.0003 mg/L and become 0.078 mg/L and 0.0103 mg/L, respectively. This results in an increase of the Chl.a growth rate of about 14% for N and 0.7% for P.

The inflow load from rivers also does not have a significant effect on the increase in the primary production in the bay head because the concentrations of N and P are already enriched in that area. It is much more likely that the species and growth rate of phytoplanktons will decrease due to the inflow of huge volumes of fresh water with high SS. In offshore waters, however, the concentrations of nutrients will increase due to the spreading diffusion of river water so that the primary production becomes more active. Furthermore, it is thought that the sedimentation of loaded SS makes the supply of adsorbed phosphorus into the lower layer and the benthic layer.

Figure 8 shows the surface distributions of Chl.a observed on July 10 by the Osaka Prefectural Government and on July 20 by the Japan Coast Guard. It can be clearly seen that the Chl.a concentration in the offshore after the flood is higher than that before the flood. The increase of Chl.a due to the flood was evident also on the Terra satellite image on July 19.

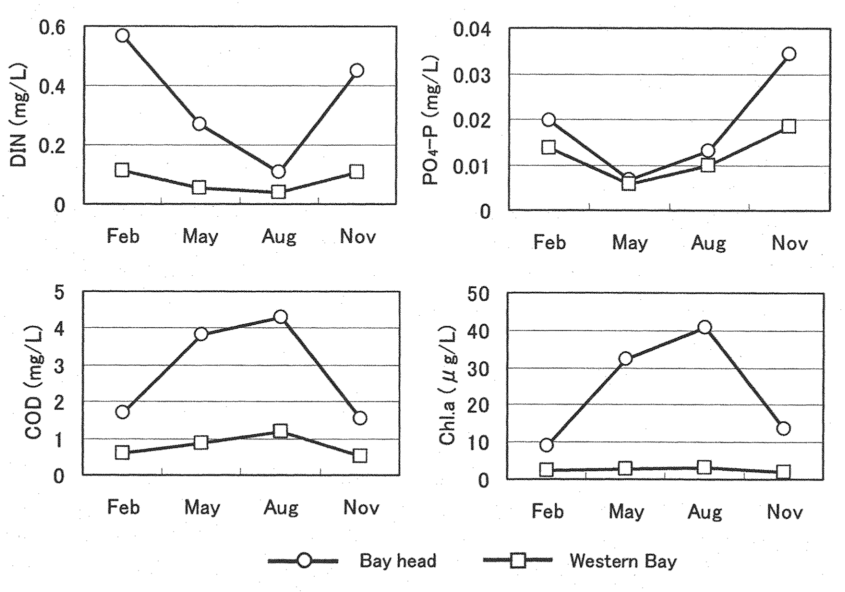

Fig. 6. Seasonal change of water quality of the surface layer in Osaka Bay; ten-year average from 1996 to 2005 using the data of the Osaka Prefectural Government

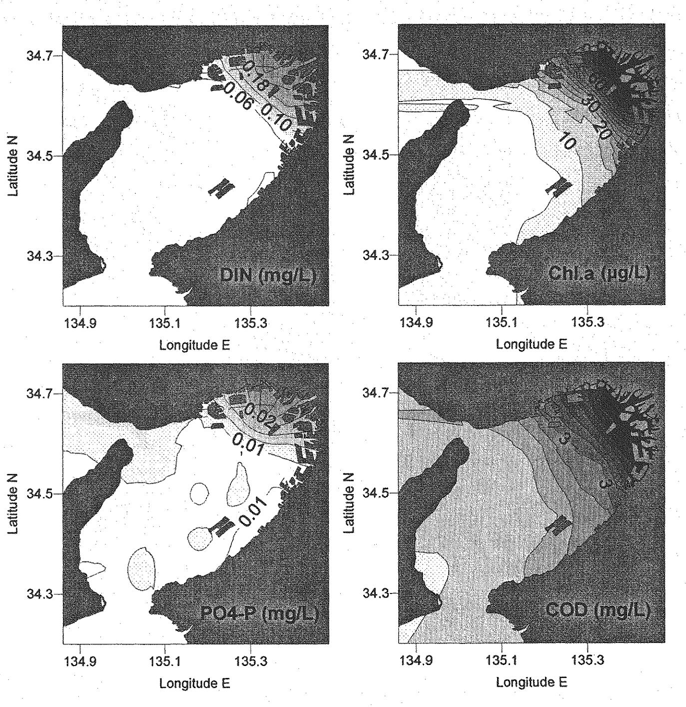

Fig. 7. Typical spatial distributions of the water quality in August using the data of the Osaka Prefectural Government

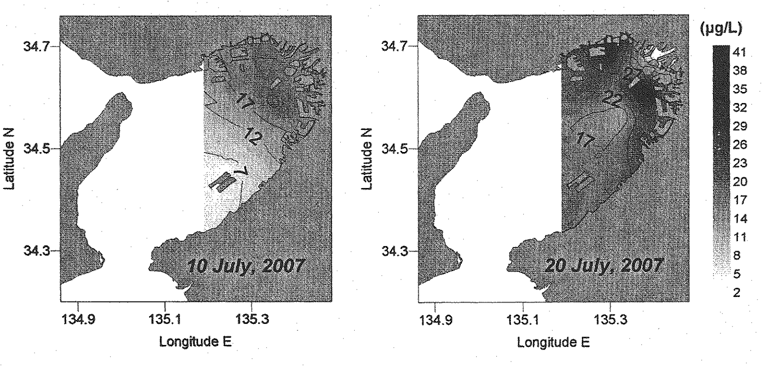

Fig. 8. Surface distributions of Chl.a observed on 10 July by the Osaka Prefectural Government and on 20 July by the Japan Coast Guard in 2007

System dynamics (SD) model analysis

A simple SD model was applied to verify the influence of the rainfall and the flood on the water quality in Osaka Bay. The model schematic is shown in Fig. 9.

First, the response of the water quality in the surface layer of thickness 1 m to the weather change was examined. The water quality was calculated under the weather conditions of the rainfall and insolation measured from July 1 to July 31, and the initial conditions were set as N = 0.02 mg/L, P = 0.005 mg/L, and Chl.a = 3 μg/L, which are the values in the western bay, where the primary production would be affected by the weather.

Second, the water-quality response to the flood in the bay head was examined by using the same model; the rainfall was disregarded and the salinity sets 15 psu in the surface layer. The salinity dependency was given to the maximum growth rate of phytoplankton based on research[9] about Rafid alga (*Chattonella Antiqua*).

In both cases, the water-quality parameters of our previous study[10] were adopted.

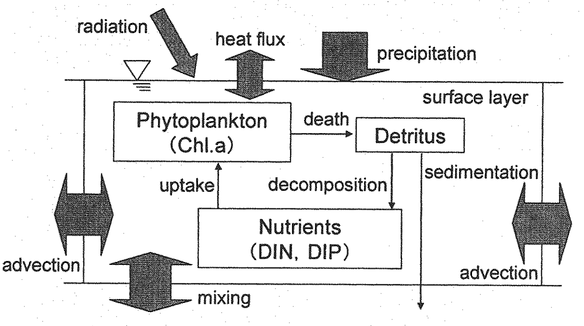

Fig. 9. Schematic of system dynamics model

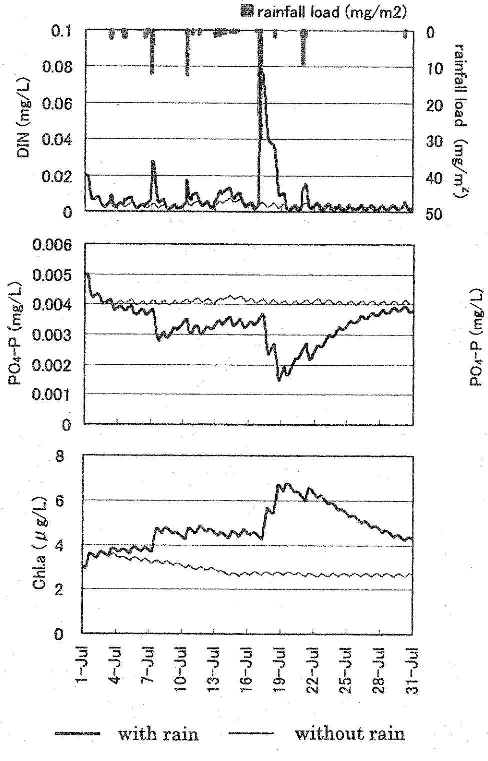

Fig. 10. Calculation results for the influence of rainfall on water quality

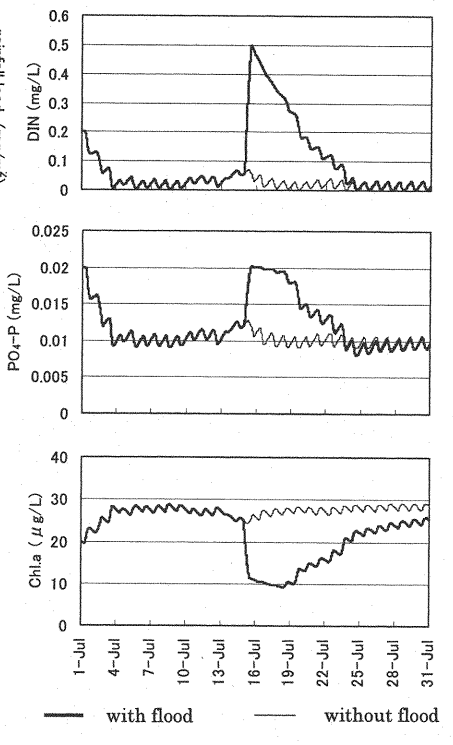

Fig. 11. Calculation results for the influence of floodwater inflow on water quality

Calculation results

Figure 10 shows the results calculated using the SD model. In the case where the rainfall load was disregarded, the concentrations of nutrients show an almost steady state under the nitrogen limitation, and the change in Chl.a is also small. On the other hand, the concentration of N increases in the case in which the rainfall load is considered, so that Chl.a increases. The rapid growth of phytoplankton was found on July 17 due to an increase in insolation after the rainy days, and the calculated phytoplankton population was about two times or more of that for no rainfall load. This growth continues until nitrogen is depleted again, and then the phytoplankton population declines and shifts to a stable state where the nitrogen is limited if none is supplied through rainfall.

Although the influence of rainfall load is usually small and short-term on the phytoplankton growth, the calculated phytoplankton population was maintained at a high level for a long time due to a rainy July of 2007. Thus, there is a possibility that the rainfall load affects the primary production in some areas of Osaka Bay, even though Osaka Bay is considerably eutrophied. This suggests that the rainfall might contribute to the maintenance of primary production in the nitrogen-limited area. It is necessary to make a 3D hydrodynamic simulation in the future to verify the present results.

Figure 11 shows the results of the water-quality change in the bay head caused by floods. In the case where there is no flood inflow, the water quality is in an almost steady state under the nitrogen limitation, and Chl.a also changes little. On the other hand, considering the flood inflow, N and P increase due to the inflow of the river water with high concentration of nutrients, and the mixing effect leads to a decrease in the salinity and Chl.a. Moreover, phytoplankton growth is suppressed for about three days after the flood in the bay head, because solar radiation in water attenuates due to inflow of river water with high SS. The phytoplankton growth becomes activated with a decrease in SS, and the concentration of the nutrients is restored to the same level as it was before the flood in about one week. Thus, the floodwater inflow has a short-term impact and has significant influence on the concentrations of nutrients and the primary production in the bay head.

CONCLUSIONS

In this study, we investigated the influence of nutrient loads (rainfall load and river inflow load) on the water quality and the primary production in Osaka Bay. The main findings of this study are as follows:

(1) The amount of the nitrogen load per rainfall occasionally exceeded 30 mg/m^2. This suggests that the rainfall might contribute to primary production, especially in the nitrogen-limited region.

(2) The L–Q curve in the lower reach of the Yodo River obtained by our observation was very different from those of other researchers, especially during floods. The cause has not been identified, although it could be due to the differences in observation year and observation point.

(3) Although the rainfall load on the sea surface hardly affects the water quality in the bay head, the primary production could increase due to rainfall in the western bay. The reason for this is that the nutrient concentrations in the surface layer are very low in this region.

(4) The calculation results of tests to determine the influence of the rainfall load using the SD model showed that the phytoplankton population would increase to about two times or more in the western part of the bay.

(5) The calculation results of the influence of the inflow load from the rivers using the SD model showed that the nutrient concentration and the phytoplankton population significantly changed.

ACKNOWLEDGMENTS

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APPENDIX – NOTATION

The following symbols are used in this paper:

Chl.a	= chlorophyll *a*;
COD	= chemical oxygen demand;
DIN	= dissolved inorganic nitrogen;
DIP	= dissolved inorganic phosphorus;
DON	= dissolved organic nitrogen;
L	= loading amount;
NH_4-N	= ammonium nitrogen;
NO_2-N	= nitrite nitrogen;
NO_3-N	= nitrate nitrogen;

PO_4-P	= orthophosphate phosphorus;
Q	= river discharge;
SS	= suspended solid;
TN	= total nitrogen; and
TP	= total phosphorus.

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