研究論文

Environmental Impact Due to the Fifth Stage of the Total Pollutant Load Control in the Inner Area of Tokyo Bay

— Approach by the Model of Red Tide Index-PON —

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ABSTRACT

The nutrient effluent load to Tokyo Bay has been decreasing in recent years due to the enactment of the Water Regulations. However, it is difficult to establish whether there is any direct effect of the reduction in nutrient loading on red tide frequency. In the present study, I constructed the model using parameters of the red tide criteria (red tide index) and assessed the suitability of this model to predict future red tide occurrences in the Tokyo Bay based on changes in the coefficient of determination (R^2) of the model. Using the stepwise method, I developed a stable multiple regression model with a high R^2 for data from 1986 to 1998 from a computerized database. Particulate organic nitrogen (PON), an index of red tide, was used as the target variable. The adjusted R^2 (R^2_{adj}) of the model based on data from 1986 to 1998 was 0.772. Application of this model to new annual data from 1999 to 2003 could be well explained by the model based on previous data. However, from 2004 when the regulations were implemented, there was a substantial decrease in R^2 , suggesting that environmental changes arising from the introduction of total loading control may affect the model developed in this study.

Keywords : red tide index, multiple regressions, PON

1. Introduction

Investigation into and countermeasures against red tide, a secondary water pollutant, are necessary to preserve ecosystems and to ensure 'ocean health' (EPA, US, 2003) ¹⁾. As part of the red tide forecasting investigation project of the Fisheries Agency, studies based on numerical modeling and statistics have been conducted since the 1980s, with a more famous example being Ouchi's multiple regression study on Hiroshima Bay^{2, 3)}. By comparison to Hiroshima Bay, the inner area of Tokyo Bay is thought to be 'the most hypertrophied inner bay in the world' ⁴⁾. However, studies based

on the 'Investigation into Secondary Contamination in Tokyo Bay' by the Water Quality Protection Division, Bureau of Environmental Protection, Tokyo Metropolitan Government in 1984⁵⁾ and on the 12 years data regarding red tide and nutrients collected by Yoshida et al. ⁶⁾ have reported that, 'Water quality conditions in the inner area of Tokyo Bay show considerable variation over time. The emergence of a high density of major microalgae does not only depend on climatic conditions, but is also significantly influenced by the characteristics of various factors related to water quality during the year.' Fluctuations in nutrient concentrations linking to red tide, which are contributing factors of

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red tide occurrences that tends to be more pronounced in inner bay area, are thought to be difficult because red tide occurs frequently in the eutrophic Tokyo Bay (Fig. 1). This suggests that the relationship between nutrients and red tide indices could be expressed mathematically.

Red tide, in the general sense, is visually confirmable as 'a phenomenon of sudden and abnormal proliferation of microalgae floating in the sea water that causes the water to change color.' However, this term is insufficient to quantitatively understand red tide and does not fully clarify the definition of red tide. Recently, there has been a shift toward using harmful algal bloom (HAB) as an alternative term for red tide, but this still does not help understand the phenomenon. It is evident that guidelines are necessary in order to model the red tide occurrences.

The criteria for red tide differ among researchers; however, in the present study constituents that were demonstrated to be predictive of red tide in the literature were set as indices. The relationship between PON (Particulate organic nitrogen) and the following red tide indices included in the database⁸⁾ were investigated by multiple regression analysis: chlorophyll-a (Chl-a), total organic carbon (TOC), and chemical oxygen demand (COD).

PON is produced in surface sea water and primarily originates from phytoplankton, including organic detritus. Previous studies^{2, 3, 9-11)} have

Fig.1 Observation days and times of the red tides in the inner Tokyo Bay (1978 to 2004)

Data⁷⁾ provided by Tokyo Metropolitan Government.

identified PON as an index of red tide. Based on this index, red tide is regarded to occur for a PON concentration exceeding a cut-off value of 0.25 mg/ℓ. In the present study, I focused on PON as a red tide index and constructed a multiple regression model for the inner area of Tokyo Bay with PON as the target variable. Using this model based on the existing results of research¹²⁻¹⁴⁾, I assessed the relationship between the fifth stage of the Total Pollutant Load Control Regulations and red tide occurrences and aimed to deduce the environmental impact of controlling the total pollutant load.

2. Analytical methods

A computerized database was constructed from the data of the Water Quality Measurement Surveys of Public Water Areas (Tokyo Metropolitan Government)⁷⁾ recorded for over 35 years from 1969 to 2005, from 8 sampling sites in the inner area of Tokyo Bay (Fig. 2). With the 74 survey items for 2005 (base items for multiple regression analysis (Table)), the data for the years 1986 to 2005 were selected from the overall database based on high item sufficiency rates.

Fig.2 Location of sampling sites in the inner area of Tokyo Bay

Observation points: St.5, 6, 8, 11, 22, 23, 25 and 35¹⁵⁾.

Table List of survey items for water quality measurement survey of Tokyo Bay^{s)} in 2005

() :unit

Wind direction velocity (m/s)	Sal	PCB (mg/ℓ)	Iprobenfos (mg/ℓ)
Total depth (m)	Cl ⁻ (mg/ℓ)	CCl ₄ (mg/ℓ)	Cd (mg/ℓ)
Collection depth (m)	Conductivity	Trichloromethylene (mg/ℓ)	MBAS (mg/ℓ)
Weather	PON (mg/ℓ)	Tetrachloroethylene (mg/ℓ)	NH ₄ -N (mg/ℓ)
Low water time (t,m)	TOC (mg/ℓ)	1,3-Dichloropropylene (mg/ℓ)	NO ₂ -N (mg/ℓ)
High water time (t,m)	D-TOC (mg/ℓ)	Thiuram (mg/ℓ)	NO ₃ -N (mg/ℓ)
Temperature (°C)	DOC (mg/ℓ)	Simazine (mg/ℓ)	PO ₄ -P (mg/ℓ)
Water temperature (°C)	Chl-a (mg/m ³)	Thiobencarb (mg/ℓ)	1,2-dichloroethane (mg/ℓ)
Color	Quantity of plankton Deposition (ml/m ³)	Benzene (mg/ℓ)	1,1-dichloroethylene (mg/ℓ)
Odor		Se (mg/ℓ)	Cis-1,2-dichloromethylene (mg/ℓ)
Transparency (m)	Chl-a + phaeopigment (mg/m ³)	F (mg/ℓ)	1,1,1-trichloromethane (mg/ℓ)
pH	DCOD (mg/ℓ)	B (mg/ℓ)	1,1,2-trichloromethane (mg/ℓ)
DO (mg/ℓ)	Cyanide (mg/ℓ)	Phenols (mg/ℓ)	Dichloromethane (mg/ℓ)
COD (mg/ℓ)	Org-P (mg/ℓ)	Cu (mg/ℓ)	Normalhexane extracts (mg/ℓ)
Coliform group bacteria (MPN/100ml)	Pb (mg/ℓ)	Zn (mg/ℓ)	Trihalomethane (mg/ℓ)
	Cr (VI) (mg/ℓ)	D-Fe (mg/ℓ)	Ignition loss (mg/ℓ)
T-N (mg/ℓ)	As (mg/ℓ)	D-Mn (mg/ℓ)	Dry loss (mg/ℓ)
SS (mg/ℓ)	Total Hg (mg/ℓ)	Cr (mg/ℓ)	Total sulfide (mg/ℓ)
T-P (mg/ℓ)	R-Hg (mg/ℓ)	EPN (mg/ℓ)	Oxidation reduction potential (mV)

The units are based on the JIS method established by Ministry of the Environment

From the selected data without deficit, all 1,248 data of the 1986 to 1998 data were analyzed and all 672 data of the 1999 to 2005 data were applied to the multiple regression.

The definition of optimal regression model was performed by the following methods.

- 1) The following items were excluded from the base items for multiple regression analysis; the items including deficit data, physically meaningless items and the items which do not show normal distribution after transform.
- 2) In consequence, the following eight items were selected; air temperature, water temperature, pH, dissolved oxygen (DO), salinity (sal.), dissolved organic carbon (DOC), total nitrogen (T-N), and total phosphorus (T-P).
- 3) A total of 245 multiple regression models were generated using all possible combinations of eight variables. These were narrowed down by step-wise method with a threshold criteria of $\alpha = 0.15$.
- 4) The model for multiple regression analysis was obtained using the combination of six variables; air temperature, pH, DO, DOC, T-P, sal.
- 5) The explanatory variable in the selected model indicated that VIF was less than 10. This result provided undisputed evidence that this model does not occur multicollinearity.
- 6) From the result with statistical precondition (Later description: Fig.6-8), I confirmed that this model was acceptable.

Finally, PON was estimated by applying the multiple regression model to the new data for 1999

to 2005. Scatter diagrams for annual data sets were created in order to compare the extent of the correlation between estimated and actual values of PON, and estimated values for each year were verified. The analysis was accomplished by Minitab14.

3. Results

The correlation between PON and log-transformed red tide indices Chl-a, TOC and COD ($\log(\text{Chl-a})$, $\log(\text{TOC})$ and $\log(\text{COD})$, respectively) with $\log(\text{PON})$ showed adjusted coefficient of determination (R^2_{adj}) values of 0.762 ($\log(\text{Chl-a})$; Fig. 3), 0.783 ($\log(\text{TOC})$; Fig. 4), 0.767 ($\log(\text{COD})$; Fig. 5). From high correlation of many items related to red tide and conventional documents, PON is valid as an objective variable. It is proper to choose PON as an objective variable for red tide indices.

Fig. 3 Scatter diagram of $\log(\text{Chl-a})$ and $\log(\text{PON})$ derived from the data (1986 to 1998)

Fig. 4 Scatter diagram of $\log(\text{TOC})$ and $\log(\text{PON})$ derived from the data (1986 to 1998)

Fig. 5 Scatter diagram of $\log(\text{COD})$ and $\log(\text{PON})$ derived from the data (1986 to 1998)

Followings are the multiple regression model equations for the data set 1,248 values:

$$\log(\text{PON}) = -10.3 + (0.199 \text{ DOC}) + (0.967 \text{ pH}) - (0.0311 \text{ sal.}) + (1.08 \text{ T-P}) + (0.0261 \text{ air temperature}) + (0.0562 \text{ DO})$$

The result of T test with regard to coefficients of regression model indicated that P value was less than 0.000 ($|t| > 10.43$: more than critical value), and the result of ANOVA was $P = 0.00$ ($F = 703.41$: more than critical value) as well. P value was smaller than 0.05 together, and this model was statistically significant. Fig. 6-8 indicate the results of precondition test of this model. Normal probability plot of the residuals (Fig. 6) shows the residual obeys a straight line and the result does not deviate from the normal distribution. Fitted values and Residuals (Fig. 7) show the peculiar pattern is nothing and variance is constant. The order of the

Fig. 6 Normal probability of the residuals: $\log(\text{PON})$ response (1989 to 1998)

Fig. 7 Fitted values and the residuals: log (PON) response (1989 to 1998)

Fig. 8 Order of the data and the residual (1989-1998) : log (PON) response

data and residual (Fig. 8) shows the residual obeys a random pattern and an error has independence. For the reasons mentioned above, the result of multiple regression model was accepted.

In this case, the contribution rate adjusted by the degree of freedom was $R^2_{adj} = 0.772$. Therefore, measured log(PON) shows that this multiple regression model can explain approximately 80% of the variation in actual measurement values (Fig. 9). The correlations of actual measurements averaged over the years 1986 to 1998 to estimated log(PON) gave a mean coefficient of determination (R^2) of 0.772. The R^2 values over the period from 1999 to 2003 of 0.752 (1999), 0.768 (2000), 0.70 (2001), 0.766 (2002), 0.766 (2003), 0.614 (2004), and 0.205 (2005) showed that approximately 70~80% of the coefficient of determination was maintained between 2001 and 2003. Conversely, in 2004 and 2005, R^2 decreased sharply.

Fig. 9 Scatter diagram of log(PON) observed and log(PON) estimated from the multiple regression model (1986 to 1998)

4. Discussion

In the 'Investigation into Secondary Contamination in Tokyo Bay' by Tokyo Metropolitan Government (1984)⁵⁾, log(COD) was selected as the target variable and 5 variables (water temperature, global solar radiation, sal., phosphate ($\text{PO}_4\text{-P}$), dissolved inorganic nitrogen (DIN)) were selected as explanatory variables. The resulting R^2_{adj} of 0.5688 was smaller than the value (0.772) obtained in this study by Suzuki, and the number of data was 246. The multiple regression model produced by Ouchi²⁾ used different explanatory variables for every month; R^2 was 0.14 to 0.66 and the number of data was approximately 92.

Compared to these previous models, the multiple regression model obtained in the present study was stable and showed good agreement with the measured values from 1986 to 1998. The slight variation in R^2 from 2001 to 2003, and the sharp decrease in 2004 and 2005 can be attributed to the following two points; 1) pull from outliers in the data; and 2) fluctuation in parameters due to water quality control. Points 1) and 2) can be refuted as the variation in R^2 between the estimated and actual measurement values was small, even after eliminating the possibility of the effect of outliers.

Conversely, the relation between T-P as the subject to regulation averaged over the years 1986 to 1998 and log(PON) gave a mean partial correlation

coefficient of 0.222. The partial correlation coefficient values over the period from 1999 to 2003 (ave.) of 0.289, from 2004 to 2005 (ave.) of 0.416 showed changing relations with T-P and PON.

The decrease in R^2 is marked from 2004 for the two years following the establishment of the fifth stage Total Pollutant Load Control Regulations (2001: bulletin, 2002: apply to new and enlargement factories, 2004: apply to existing factories). Lake Biwa, an enclosed water area similar to Tokyo Bay, provides another example; two years later of the 'the Ordinance on Prevention of Eutrophication of Lake Biwa,' the concentration of T-P in the water decreased definitely¹⁶⁾. Even in the 'Total Load Interannual Variability Report'¹⁷⁾ released every five years by the Tokyo Metropolitan Government, in the period after the regulation was enacted, the decrease of T-P load in the inner area of Tokyo Bay can be seen as having drastically decreased, in conjunction with a decline in R^2 (Fig. 10). The effect of T-P decrease in Tokyo Bay is estimated to appear approximately two years after regulation enactment, in the same way as in Lake Biwa. It is quite likely that this case involves the effect of step-by-step enforcement of the regulation and the change of physical chemical material flow. Therefore, it is believed that the decline of T-P due to anthropogenic

T-P loading reduction resulted in parameter fluctuation in the multiple regression model, and therefore, the large decrease of R^2 in 2004 and 2005.

Well, The Chesapeake Bay in the United States is facing the problem to achieve the environmental standards by Environmental Protection Agency (EPA) for the entire Chesapeake Bay by the year 2010^{18, 19)}. This Bay constitutes the closed material flow as Tokyo Bay²⁰⁾. The results of the present study suggest that this technique can be applied to environmental impact assessment in regulation area including Chesapeake Bay.

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Fig.10 R^2 and gross T-P discharge from 1995 to 2005 estimated by the multiple regression model derived from data from 1986 to 1998

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東京湾湾奥における第5次水質総量規制に起因する環境影響

－赤潮指標 PON モデルによるアプローチ－

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要 旨

東京湾は赤潮が慢性的に発生する富栄養化域である。栄養塩の排出負荷は減少しているものの赤潮発生との因果関係が見出しにくい水域のひとつである。本研究では赤潮判定基準とされている物質（赤潮指標）をモデル化し、モデルの説明率の変化から東京湾湾奥部における第5次水質総量規制と赤潮との関係について類推した。東京湾水質調査結果を電子化したデータベースを用い、1986年度－1998年度のデータから逐次選択法を用いて赤潮指標 PON（溶存態有機炭素）を目的変数とする安定かつ高説明率をもつ重回帰モデルを決定したところ気温、pH、溶存酸素、DOC、全リン、塩分を説明変数とするモデルの R^2_{adj} （補正されたモデルの説明率）は0.772となった。そのモデルを1999年度から2003年度の新規データへと適用したところ各年度の R^2 （モデルの説明率）はおよそ0.75となり、新規データは既存モデルによりよく説明され得た。一方で、第5次水質総量規制施行年2004年度からは R^2 が大幅に減少し、総量規制の導入による環境変化がモデルに影響を与えた可能性が示唆された。

キーワード：赤潮指標，重回帰，PON