Study of water quality distribution in Lake Biwa in consideration of runoff pollutant loads from its catchment basin

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Abstract Many strategies for water quality conservation in Lake Biwa are being carried out mainly by reducing runoff pollutant loads into the lake. But influence of the runoff load reduction on the water quality in Lake Biwa has not been clarified enough so far. This study is aimed at discussing methodology to estimate water quality distribution in Lake Biwa using runoff pollutant loads from its basin. The runoff loads from the basin are calculated by Macro Model with GIS database of the Lake Biwa basin, and the water quality distribution in the lake is estimated by the spline technique with the calculated runoff loads. As a result, it has been proved that the methodology has enough reproducibility to estimate the water quality distribution in Lake Biwa and is available to examine the water quality in the lake.

Keywords GIS; Lake Biwa; Macro Model; spline technique; water quality distribution

Introduction

Lake Biwa is the largest lake in Japan and used as a drinking water resource by 14 million people in the Kinki area of Western Japan. Water quality improvement projects in Lake Biwa are being carried out mainly on reduction of inflowing loadings, but effects of such load reduction projects on water quality in Lake Biwa have not been clarified enough so far. GIS databases around Lake Biwa have been arranged in recent years (Ichiki and Yamada, 1999a; Masuda, 2000). The authors developed a management support system of pollutant runoff into Lake Biwa by combining the GIS database with the Macro Model to calculate runoff pollutant loadings from catchment basins (Ichiki *et al.*, 1996, 2001a) and made it possible to predict the inflowing loadings into Lake Biwa which vary according to basin characteristics (Ichiki *et al.*, 2001b). However, there is no procedure to discuss a method of Lake Biwa basin managements for water quality preservation because relationships between the inflowing loadings into Lake Biwa and water quality in the lake are not clear. This study is aimed at developing a series of calculation methodologies to estimate water quality distribution in Lake Biwa based on the inflowing loadings from its catchment area calculated from the basin characteristics. So, first it estimates the inflowing loadings using the Macro Model with the basin characteristics of Lake Biwa, and then it predicts water quality distribution in the lake based on the estimated inflowing loadings. Figure 1 shows a procedure of the inflowing loadings and water quality calculations. The inflowing loadings are calculated using the Macro Model at one-day intervals, and annual water quality distribution in the lake is estimated by a spline technique model. The calculations are done for TN and TP. Nagare implemented 3 dimension surveys on water quality in Lake Biwa (Nagare *et al.*, 2002), but in most

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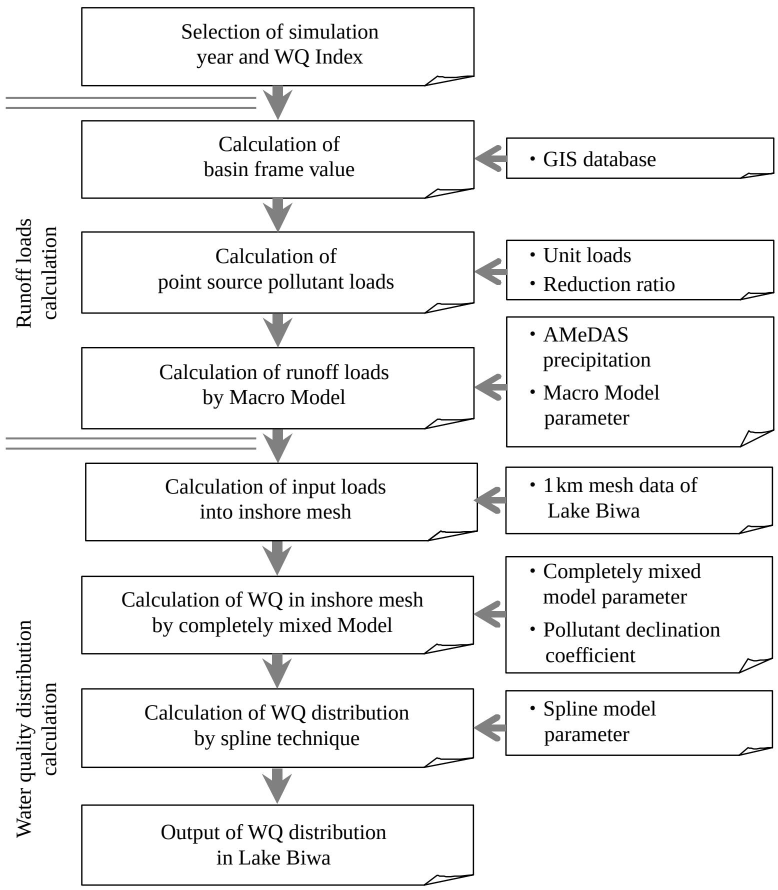


Figure 1 Estimation procedure of runoff loads and water quality distribution in Lake Biwa

cases, water quality assessments are done based on observations in the upper water layer (0.5 m depth) at environmental standard points. Therefore in this study, the calculations of water quality are implemented for the surface water in Lake Biwa.

Estimation of inflowing pollutant loadings into Lake Biwa

In the section of inflowing loadings calculation in Figure 1, the inflowing loadings from the Lake Biwa basin are calculated respectively for each tributary basin of the lake. The Macro Model is developed taking consideration of pollutant behavior which differs greatly with its source and weather. The authors showed the model constitution and parameter identification process in previous literature (Ichiki *et al.*, 1996, 1998, 2001a, 2001b; Ichiki and Yamada, 1999b). Figure 2 and Equations (1)–(11) show outlines of the Macro Model, and Table 1 shows the model parameters. Because Lake Biwa has a certain ratio of paddy field areas in its catchment basin, the model is improved to calculate runoff loadings from the paddy fields during an irrigation season (L_{ns4}).

$$L_{pv} = (L_{po1} + L_{po2} + L'_{po2})X/100 \tag{1}$$

$$L_{pu} = (L_{po1} + L_{po2} + L'_{po2})(1 - X/100) \tag{2}$$

$$L_{ps} = L_{pu}(1 - y/100) \tag{3}$$

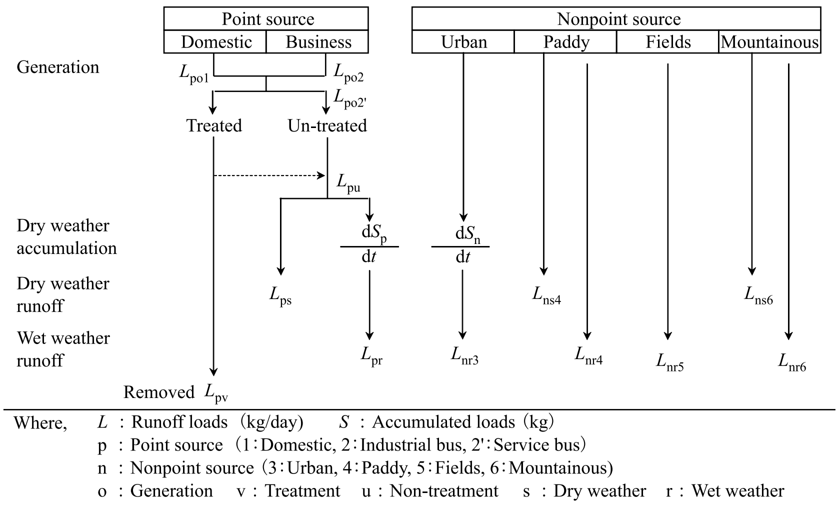


Figure 2 Outline of Macro Model

Table 1 Macro Model parameter

		Indices		TN	TP
		Accumulation ratio y (%)		48.60	65.10
Dry period	Accumulation	S_{nui}/A_{3i}(t/km^2)	Residential	0.014	0.003
			Commercial	0.027	0.001
			Industrial	0.064	0.027
			Highway	0.019	0.016
			Roof	0.007	0.001
		K_{n3}' (1/day)		0.095	0.121
	Runoff	L_{ns4}/A_4	Irrigated	2.713	0.175
		(kg/km^2 day)	Not-irrigated	0.000	0.000
		L_{ns6}/A_6	Irrigated	1.726	0.040
		(kg/km^2 day)	Not-irrigated	1.726	0.040
Wet period	Runoff	k_p ($\times 10^{-4}$/km^2)		8.969	3.360
		k_{n3} (d/mm)		0.048	0.067
		k_{n4}/A_4 ($\times 10^{-2}$/km^2)		1.938	0.272
		k_{n5}/A_5 ($\times 10^{-2}$/km^2)		6.308	6.142
		k_{n6}/A_6 ($\times 10^{-2}$/km^2)		0.915	0.131
		h_a ($\times 10^{-3}$)		2.386	3.998
		h_b		0.800	0.837

$$dS_p/dt = L_{pu}\, y/100 - L_{pr} \tag{4}$$

$$L_{pr} = k_p\, S_p^a\, Q_r^b \tag{5}$$

$$dS_n/dt = k'_{n3}\, S_{nu} \exp(-k'_{n3}\, T) \tag{6}$$

$$L_{nr3} = S_n(1 - \exp(-k_{n3}\, R)) \tag{7}$$

$$L_{nsi}(i = 4, 6) = \text{constant per unit area in each land use} \tag{8}$$

$$L_{ns4}\ \text{during non-irrigation season} = 0 \tag{9}$$

$$L_{nri} = k_{ni}\,Q_r^b\,(i = 4\text{–}6) \quad (10)$$

$$b = h_a X + h_b \quad (11)$$

Here, X is a removal ratio of point source pollutants (%), y is an accumulation ratio of point source pollutants during dry weather periods (%). Input data here are unit loadings, GIS database of the Lake Biwa basin and time series of precipitation observed by *Automated Meteorological Data Acquisition System* (AMeDAS).

Output loadings are calculated at one-day intervals for each tributary basin respectively. Simulations of pollutant runoff into Lake Biwa were done during the last 16 years from 1983 to 1998. Figure 3 shows the relationships between calculated loadings by the simulations and observed loadings during dry weather periods. The observed data during the dry weather periods were obtained for 24 rivers in Lake Biwa tributaries. Here, the irrigation season is from May to September, and the non-irrigation season is from October to April. Average relative errors (= |Calculated − Observed| / Observed x 100 (%)) are 68.53% for TN and 75.73% for TP during the irrigation season, while they are 76.84% for TN and 112.42% for TP during the non-irrigation season. Figure 4 shows relationships between calculated and observed loadings during wet weather periods. The observed data during the wet weather periods were obtained for five characteristic rivers during 182 storm events. While the calculated loadings are likely to be larger than the observed loadings in the Isasa R. and the Yamasina R., the differences in the other rivers

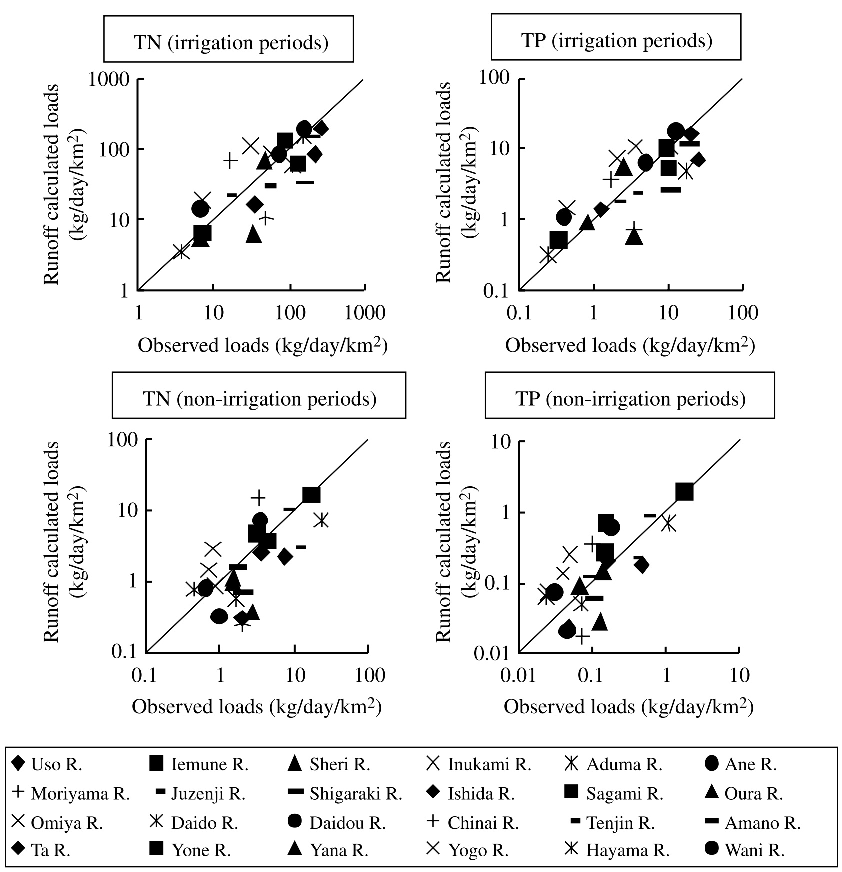


Figure 3 Relationships between calculated and observed inflowing loads during dry periods

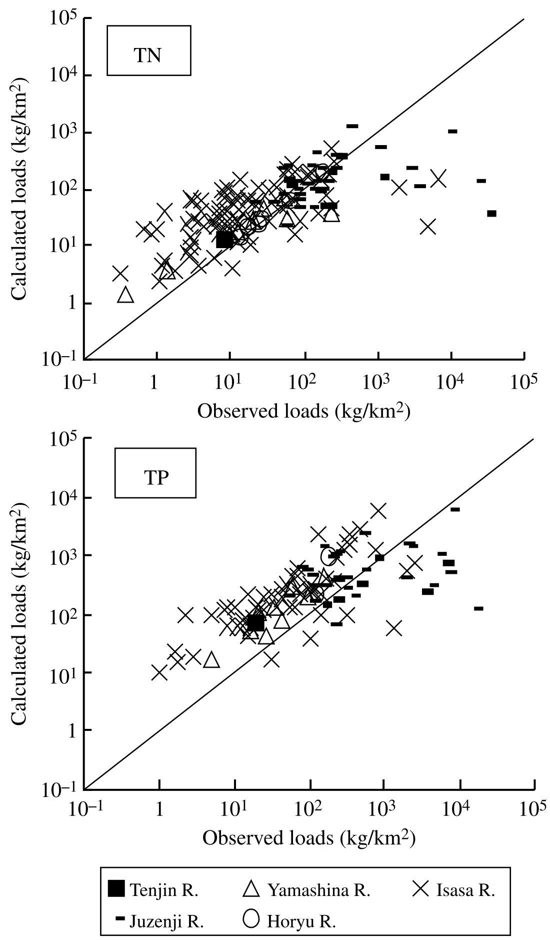


Figure 4 Relationships between calculated and observed inflowing loads during wet periods

are within single figures. Therefore, it can be regarded that the model simulation has enough replicability for rough estimations taking consideration of the dispersion of the observed data.

Estimation of water quality distribution in Lake Biwa

Estimation of water quality distribution by spline technique model

In order to understand the water quality situation in Lake Biwa, one of the most effective ways is to estimate two dimensions of water quality distribution in the lake. However, water quality data are usually monitored at some limited observation points (47 points in Lake Biwa) as shown in Shiga Environmental White Book (Shiga, 1984–1999). Therefore, it is important to select an appropriate method for interpolation of the limited observed data, in order to estimate two dimensions of water quality distribution in the lake. Fujiwara *et al.* examined an interpolation methodology for water quality distribution in Southern Lake Biwa using the spline technique, and showed an influence of the observation points on water quality distribution patterns (Fujiwara *et al.*, 1985). The spline technique makes it possible to interpolate smoothly from relatively sparse data by appropriate parameter settings, so this study also used the spline technique model for the discussion below. A basic equation of the spline technique model for water quality data

$C_{x,y}$ (mg/L) in a 2-dimensional coordinate system is shown as equation (12).

$$C_{x,y} = \{(8 + nh^2)(C_{x+1,y} + C_{x-1,y} + C_{x,y+1} + C_{x,y-1}) - 2(C_{x+1,y+1} + C_{x-1,y+1} + C_{x+1,y-1} + C_{x-1,y-1}) - (C_{x+2,y} + C_{x-2,y} + C_{x,y+2} + C_{x,y-2})\}/(20 + 4nh^2) \quad (12)$$

Here, $C_{x,y}$ is a concentration in a mesh at a coordinate (x, y), n is a spline parameter ($n = 1.0$) and h is width of a mesh ($h = 1$(km)). The estimations were done by continual calculations which were not completed until differences between calculated concentrations before and after the calculation became less than 0.00001 mg/L for TP and 0.001 mg/L for TN in all meshes. Using the observed data during 1984–1998 at 25 observation points selected randomly from the 47 observation points in Shiga Environmental White Book, the spline technique model calculated water quality distribution. And the rest of the 22 observation points were used for verification of the spline technique model calculation. Figure 5 shows the relationships between calculated and observed annual mean concentrations in the 22 observation points. It shows a certain replicability as the correlation coefficient is 0.875 for TN and 0.864 for TP, and average relative error is 7.1% for TN and 18.8% for TP.

Estimation of water quality along lakeshore by complete mixing model

In the water quality distribution calculation section in the estimation procedure of runoff loads and water distribution (Figure 1), the water surface of Lake Biwa was divided into 1 km^2 meshes (Figure 6). And the runoff loads/water from the basin and discharged loads/water from wastewater treatment plants in the basin were input into 233 inshore meshes which are bounded on outlets of inflowing rivers and wastewater treatment plants. Each inshore mesh is considered to be a complete mixture box with 1 m depth, and loads/water balance in the mesh is calculated by equation (13) as shown in Figure 7.

$$CV = \{C_0V + C_{in}Q_{in} - (C_0V + C_{in}Q_{in})/(V + Q_{in})Q_{out}\}(1 - m) \quad (13)$$

Here, m is attenuation coefficient (1/day) of pollutants, which shows pollutant dose variation due to sedimentation/elution onto/from sediments. Matsunashi and Imamura determined the attenuation coefficient for each environmental criterion in waters by drawing a specific load curve shown by a Vollenweider type equation (14) with z for water

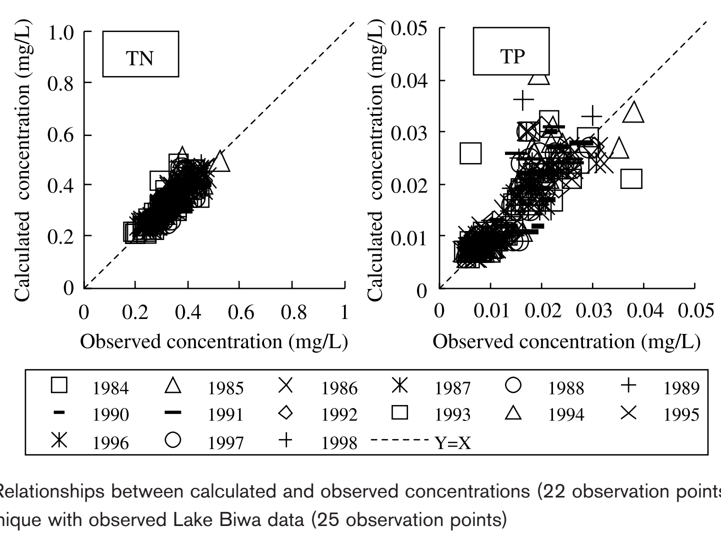


Figure 5 Relationships between calculated and observed concentrations (22 observation points) using spline technique with observed Lake Biwa data (25 observation points)

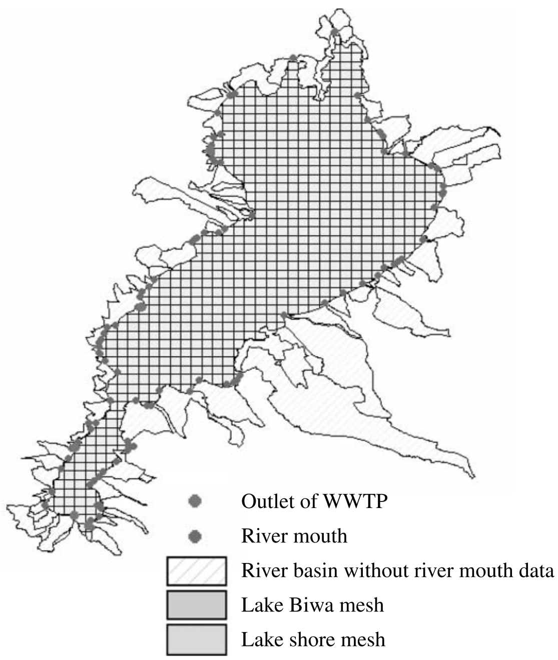


Figure 6 Mesh segmentation in Lake Biwa

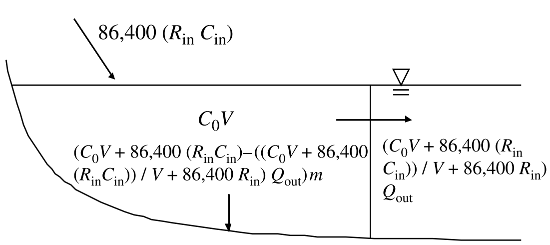
depth (m), f for water replacement rate (1/day) and L/A for specific loads (ton/km^2/day) (Matsunashi and Imamura, 2000).

$$L/A = (C - C_0)fz + Cmz + C_0Q_{in}z/V \qquad (14)$$

Figure 8 shows relationships between the specific loads (L/A) and product of water replacement rate (f) and water depth (z) in the Lake Biwa inshore meshes. So, the attenuation coefficient (m) for each inshore mesh was determined by drawing the specific load curve to fit each inshore mesh.

Verification of estimated water quality distribution in Lake Biwa

Based on the calculated concentration in inshore meshes, the spline technique model calculates pollutant concentration in all meshes in Lake Biwa. The estimation system (Figure 1) implemented runoff loads – water quality distribution simulation for 13 years during 1986–1998, using the water quality distribution in 1985 estimated by the spline technique model with observed data as an initial condition. Figure 9 shows relationships between



$CV = (C_0V + 86{,}400\ (R_{in}C_{in}) - ((C_0V + 86{,}400\ (R_{in}C_{in}))/V + 86{,}400\ R_{in})\ Q_{out})\ (1-m)$

$Q_{out} = R_{in}$

$V = \text{const.}$

Figure 7 Mass balance in a lakeshore mesh

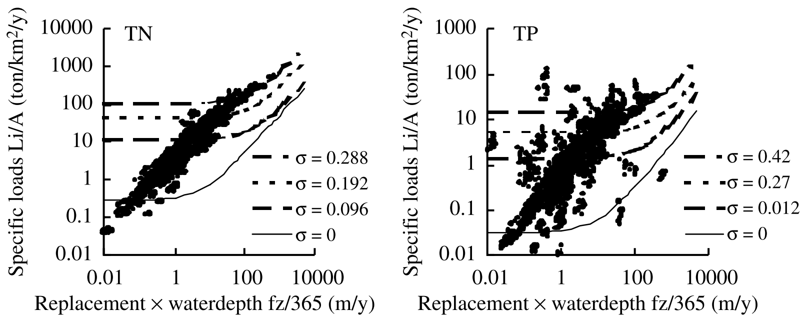


Figure 8 Inflowing load curve in lakeshore meshes

calculated concentration by the system and observed concentration at water quality observation points during the period. Correlation coefficient is 0.476 for TN and 0.638 for TP, and average relative error is 17.0% for TN and 50.6% for TP. The system replicability tends to be worse with elapsed time. However, considering that the runoff loads input into the inshore meshes already have some errors, the results of the water quality distribution estimation here can be considered to have enough reproducibility for the discussion.

Characteristics of water quality distribution in Lake Biwa

Among simulation results since 1986 to 1998, Figure 10 shows water quality distribution in Lake Biwa and inflowing loads from every tributary basin in 1994 as a drought year (1,254 mm/y of annual precipitation) and 1998 as a flood year (1,981 mm/y of annual precipitation). According to the observed data (Shiga, 1984–1999), influence of 1994 drought on annual mean concentration is remarkable for low TN concentration in Northern Lake Biwa and for high TP concentration in Southern Lake Biwa. This is caused by complex effects of decrease in concentration due to decrease of inflowing loads during dry periods and increase in concentration due to runoff loads flushed from catchment basins by storms right after the dry periods. According to the simulation for TN, both the inflowing loads and water quality in Lake Biwa have little difference between the annual precipitations, and the low concentration in Northern Lake Biwa due to the drought is not so remarkable. On the other hand, for TP, the inflowing loads decrease in the drought year, and it makes the concentration in the eastern part of Northern Lake Biwa decrease. But the concentration in Southern Lake Biwa increases in the drought year because of highly concentrated runoff from the basin and small capacity of Southern Lake Biwa. Thus, this procedure makes it possible to estimate and examine inflowing loads and water

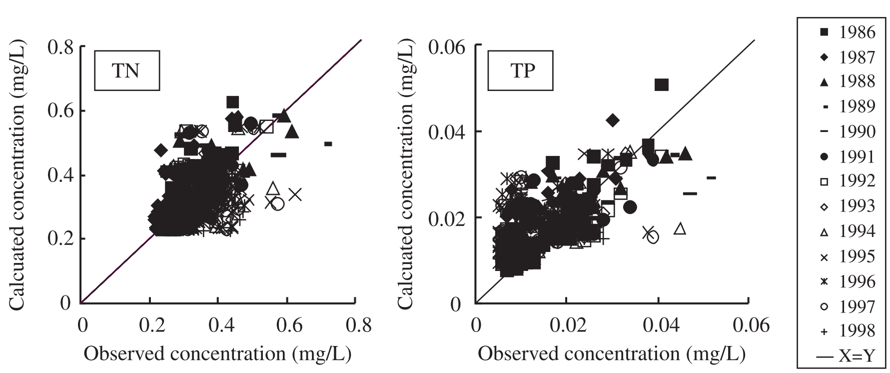


Figure 9 Relationships between calculated and observed concentrations using spline technique with calculated inflowing loads

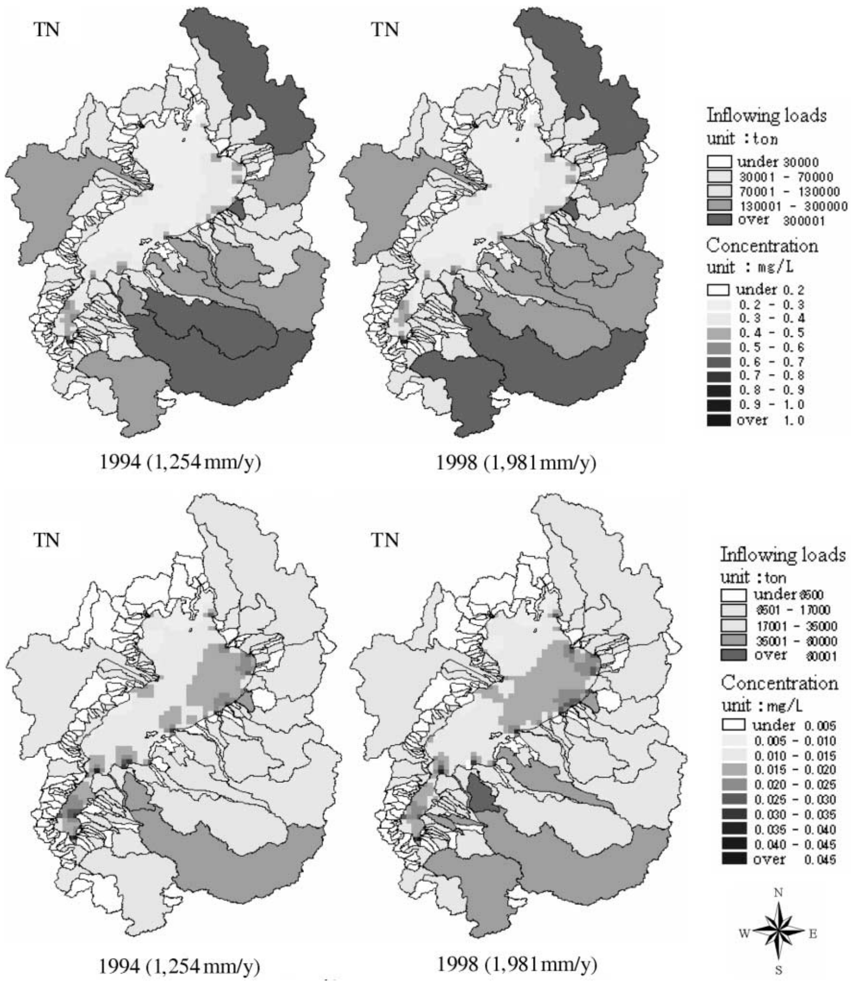


Figure 10 Results of simulation on inflowing loads and water quality distribution

quality distribution into/in Lake Biwa which vary according to change in basin characteristics and natural conditions.

Conclusions

A fundamental examination was implemented on a methodology to estimate inflowing loads into Lake Biwa using its basin characteristics and water quality distribution in the lake using the estimated inflowing loads. And it is shown that the methodology has enough reproducibility and is available to examine the water quality in the lake.

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