Estimation of pollutant loads from urban roadway runoff

K. Wada and S. Fujii

ABSTRACT

A simulation model consisting of a deposition process and a wash-off process was proposed to evaluate the pollutant loads from urban roadways, and was verified based on field survey data obtained over a 5-year period in the Lake Biwa watershed. The model parameters were determined by minimizing the total sum of squares of differences between the observed data and simulated ones. By applying this model to all roadways in the watershed, the calculated amounts of COD$_{Mn}$, organic carbon, nitrogen and phosphorus in particulate forms were 15.9, 15.7, 0.88 and 0.15 kg/(km$^2$·d), respectively, and those in dissolved forms were 14.1, 12.5, 2.62 and 0.03 kg/(km$^2$·d), respectively. From the results, the pollutant loads of COD$_{Mn}$, TN and TP obtained for the Lake Biwa watershed (total roadway area of 98.9 km$^2$) were estimated to be 2,950, 350 and 18 kg/d, respectively.

Key words | Lake Biwa, nutrients, organic matter, pollutant wash-off model, stormwater, urban roadways

INTRODUCTION

There are several urban runoff quality models such as the Storm Water Management Model (SWMM) (U.S. EPA 1971) and the Storage Treatment Overflow Runoff Model (STORM) (U.S. Army Corps of Engineers 1976), which were developed for simulation of quality in urban storm and combined sewer system. In case of Japan, the Modified Rainfall Runoff Library (M-RRL) method (Japan Sewage Works Association 2002) and Hijioka’s distributed model (Hijioka et al. 1999) were proposed, which can contribute to the estimation in Japanese cases. These models have a strong point in quantitatively dealing with runoff process in overall. However, if we use these models for loading comparison of several discharge path processes, or for precise loading estimation of a specified discharge path process such as roadway runoff, these models are not so effective because these models are designed to explain a variety of different processes with a few common and simple reactions. In case of roadway runoff, model development has been placed behind the others because there were insufficient survey data, and the available data were very strongly dependent on regional characteristics (Furumai 2002). It is necessary to develop a simulation model to be able to estimate the specified pollutant load from roadways, coupled with enough observation data for verification. The model will be effective in consideration of measures necessary to reduce contamination from the roadways against the eutrophication of lakes.

Lake Biwa is the source of drinking and domestic water for 16 million people living in the Kyoto-Osaka-Kobe metropolitan area in Japan. The watershed is 3,174 km$^2$, where pollutant load from urban roadways has increased as a result of increases in population and traffic due to urban development and the impervious land surface (Ichiki et al. 1996; Shiga prefecture 2001; Yamamoto et al. 2005). As the watershed was very large and the available data were limited, past studies only referred to the unit load of roadways, which were obtained by experiment in another area.

The objective of this study is to estimate the pollutant loads of organic matter and nutrients from roadways into lakes. A fundamental and simple simulation model was proposed with combination of two principal processes of...
deposit and wash-off, and its analytical solutions were successfully obtained with integration of basic differential equations. The solutions provided a sole set of parameter values in the model by minimizing the sum of differences of simulated data from observed ones, which were obtained in the watershed of Lake Biwa over a 5-year period. Finally, the model was applied to the entire watershed, and the roadways load was estimated in Lake Biwa.

**OVERVIEW OF SURVEY STATIONS**

Field surveys of stormwater runoff were set up in three urban roadway stations to collect data for wash-off phenomena analysis and model verification. They were conducted during two rainfall events (Oct. 2004 and Oct. 2005) at St. 1, during six events (Jan. 1999–Sep. 2000) at St. 2, and during four events (Sep. 2001–Nov. 2001) at St. 3 (Wada & Fujii 2006). These roadways experienced heavy traffic, with an average of more than 10,000 vehicles every weekday (7:00 a.m. – 7:00 p.m., Mon – Fri). The traffic on each survey station was as much as average traffic of urban roadways, so that the roadway runoff of survey stations was considered as to be typical data in the watershed. The surrounding areas had undergone rapid urban development. Table 1 shows the specifications of the survey stations and Figure 1 shows their location.

### Table 1 | Specifications of survey stations

<table>
<thead>
<tr>
<th>Station</th>
<th>Run</th>
<th>Roadway area (m²)</th>
<th>Sidewalk area (m²)</th>
<th>Total area (m²)</th>
<th>Dry weather period (day)</th>
<th>Rainfall amount (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. 1</td>
<td>1-1</td>
<td>40</td>
<td>35</td>
<td>75</td>
<td>1.4</td>
<td>29.0</td>
</tr>
<tr>
<td></td>
<td>1-2</td>
<td></td>
<td></td>
<td></td>
<td>1.5</td>
<td>5.5</td>
</tr>
<tr>
<td>St. 2</td>
<td>2-1</td>
<td>600</td>
<td>150</td>
<td>750</td>
<td>4.6</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>2-2</td>
<td></td>
<td></td>
<td></td>
<td>14.4</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td>2-3</td>
<td></td>
<td></td>
<td></td>
<td>4.0</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>2-4</td>
<td></td>
<td></td>
<td></td>
<td>23.2</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>2-5</td>
<td></td>
<td></td>
<td></td>
<td>2.9</td>
<td>20.5</td>
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<tr>
<td></td>
<td>2-6</td>
<td></td>
<td></td>
<td></td>
<td>6.4</td>
<td>51.5</td>
</tr>
<tr>
<td>St. 3</td>
<td>3-1</td>
<td>243</td>
<td>42</td>
<td>285</td>
<td>2.1</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>3-2</td>
<td></td>
<td></td>
<td></td>
<td>3.2</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>3-3</td>
<td></td>
<td></td>
<td></td>
<td>5.6</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>3-4</td>
<td></td>
<td></td>
<td></td>
<td>17.5</td>
<td>8.5</td>
</tr>
</tbody>
</table>
represented by very simple differential equations, analytical solutions were obtained by parameters. These parameter values were determined in order to minimize the total sum of squares of differences (TSS) between observed data and simulated ones. The survey items were COD\text{Mn} as index of organic matter (COD obtained by the potassium permanganate method), total nitrogen (TN), and total phosphorus (TP), which were covered by the Environmental Quality Standards regarding the Eutrophication Management. Total organic carbon (TOC) was also included as an index of organic matter. As the wash-off behavior varied depending on the particulate and dissolved portions \cite{Wada & Fujii 2007}, the model was applied to each fraction of the particulate and dissolved (0.45 \text{\mu m} membrane filter) portions for COD\text{Mn}, TOC, TN and TP, which were measured in the surveys.

**Dry weather deposit model**

During dry weather, the specific pollutant deposit amount on a roadway surface, $S(t)$ (mg/m$^2$), is considered to be increased by dry fallout load at a constant rate $D_0$ (mg/(m$^2$.hr)), but to be reduced by sweeping effects such as winds and cars in proportion to the deposit amount. $S(t)$ is expressed as follows:

$$\frac{dS(t)}{dt} = D_0 - k_f S(t) \quad (1)$$

where $t$ is the time (hr) and $k_f$ is the loss effect constant of the roadway surface deposit amount (1/hr).

Equation (1) can be integrated by $t$ and Equation (2) is obtained by using $S(0)$ as the initial pollution load on the roadway surface (at $t = 0$) \cite{Alley & Smith 1981}. $S(0)$ can be given to the residual amounts of constituents remaining after the previous period of storm wash-off just before the rainfall event.

$$S(t) = S(0)e^{(-k_f t)} + \left(\frac{D_0}{k_f}\right)[1 - e^{(-k_f t)}] \quad (2)$$

**Stormwater wash-off process model**

The wash-off process during rainfall periods consists of both a surface wash-off and a very small infiltration flow from the pavement at the onset of rainfall. These phenomena are expressed by a tank model (Figure 2) and the hydrological equation is described in the following form:

$$\frac{dh(t)}{dt} = r - q_1 - q_0 \quad (3)$$

where,

$$q_0 = k_0 h$$

$$q_1 = \begin{cases} k_1(h - h_1) & (h > h_1) \\ 0 & (h \leq h_1) \end{cases}$$

where $h(t)$ is the storage level at time $t$, $r$ is the rainfall intensity (mm/hr), $q_1$ is the surface wash-off rate (mm/hr), $q_0$ is the infiltration rate (mm/hr), $k_1$ is the surface wash-off rate constant (mm/hr), $k_0$ is the infiltration constant (mm/hr), $h_1$ is the storage level at time $t$ when the rainfall starts, and $h$ is the storage level at time $t$.
$q_0$ is the infiltration rate (mm/hr), $k_1$ is the surface wash-off coefficient (1/hr), and $k_0$ is the infiltration coefficient (1/hr). $h_1$ includes such storage factors as the surface depression storage, interception storage and the surface detention, and its effect appears at initial rainfall loss.

Assuming that $r(t)$ is constant for any time $\tau$ during a unit integration period ($0 \sim t$), Equation (3) can be integrated and Equations (4), (5), (6) and (7) are obtained as follows:

For $h(\tau) > h_1$ ($\tau : 0 \sim t$)

$$h(t) = \frac{r + k_1 h_0}{k_1 + k_0} \left( 1 - e^{-k_0 t} \right) + h(0) e^{-k_0 t}$$

(4)

$$Q(t) = \frac{k_1 [k_1 h(0) + k_0 h(0) - r - k_1 h_1]}{(k_1 + k_0)^2} \left[ 1 - e^{-k_0 t} \right]$$

$$+ \left[ \frac{k_1 (r - k_0 h_1)}{k_1 + k_0} \right] t$$

(5)

for $h(\tau) < h_1$ ($\tau : 0 \sim t$)

$$h(t) = \frac{r}{k_0} \left[ 1 - e^{-k_0 t} \right] + h(0) e^{-k_0 t}$$

(6)

$$Q(t) = \left[ h(0) - \frac{r}{k_0} \right] \left[ 1 - e^{-k_0 t} \right] + rt$$

(7)

where $h(0)$ is the initial storage level (at $t = 0$), and $Q(t)$ (mm) is the amount of cumulative surface wash-off during a unit integration period ($0 \sim t$), ($= \int_0^t q(\tau) d\tau$).

When $r$ is small, the storage level $h(t)$ may fall below $h_1$ in unit integration increments $\tau$, despite being initially higher than $h_1$. In such cases, the time $t_1$ when $h(t)$ decreases to $h_1$ is first calculated by setting $h(t_1) = h_1$ in Equation (4), and then the cumulative surface wash-off amount is obtained with the sum of $Q(t)$ in Equation (5) by $t_1$ and the sum of $Q(t)$ in Equation (7) by $t_1$. In contrast, the storage level $h(t)$ may rise above $h_1$ in unit integration increments if $r$ is large, despite being initially lower than $h_1$. In these cases, after calculating the time $t_2$ when $h(t)$ increases to $h_1$ by setting $h(t_2) = h_1$ in Equation (6), each $Q(t)$ value is obtained by Equations (7) and (5) in times $t_2$ and $\tau - t_2$, respectively (Figure 3). The sum gives the cumulative amount. Analytic solutions of $t_1$ and $t_2$ are given by the following equations:

$$t_1 = \frac{1}{k_1 + k_0} \ln \frac{k_1 h(0) + k_0 h(0) - r - k_1 h_1}{k_0 h_1 - r}$$

(8)

$$t_2 = \frac{1}{k_0} \ln \frac{k_0 h(0) - r}{k_0 h_1 - r}$$

(9)

### Wash-off load model

During rainfall periods, the pollutant deposits on the roadway surface $S(t)$ (mg/m²) are reduced only by the surface wash-off caused by rainfall. The rate of decrease is considered to be proportional to both the deposit amount and the surface wash-off rate. This phenomenon can be modeled (Sartor & Boyd 1972) as Equation (10):

$$\frac{dS(t)}{dt} = k_2 S(t) q(t)$$

(10)
where \( k_s \) is the wash-off rate constant of the roadway surface deposit (1/hr). This equation can be integrated to give the next equation.

\[
S(t) = S(0) e^{-k_s Q(t)}
\] (11)

The total pollutant loads is considered to involve not only the wash-off load from the roadway surface deposit but also the wet fallout in the rainfall. When the water quality of the rainfall is assumed to be constant at \( C \) (mg/L), the cumulative loads from 0 to \( t \), \( L(t) \) (mg/m\(^2\)) can be calculated by the following equation:

\[
L(t) = S(0) \left\{ 1 - e^{-k_s (Q(t) - Q(0))} \right\} + [Q(t) - Q(0)]C
\] (12)

**VERIFICATION OF MODELS**

These models can estimate the amount of pollutant deposit and wash-off load at any time, \( t \), by providing Equations (2), (4), (6) and (11) with suitable parameters and initial values. The simulation results calculated with these models were compared with the data observed in each field survey (St. 1 ~ St. 3).

**Stormwater wash-off process model**

The parameter values of stormwater wash-off model in each survey station were determined by minimizing the TSS between observed data and simulated ones. The numbers of data used for the St. 1, 2 and 3 calculations were 109, 488 and 280, respectively.

**Wash-off load model**

Substituting the parameter values obtained by the stormwater wash-off process model, the parameters of the wash-off load model were determined by minimizing the TSS. The numbers of data used for the St. 1, 2 and 3 calculations were 22, 43 and 8, respectively. In Equation (12), the values of \( C \) (mg/L) are given by the average value of the observed rainfall concentration data (\( n = 13 \)) for three events at St. 2 (Run 2-1: \( n = 4 \), Run 2-2: \( n = 6 \), Run 2-3: \( n = 3 \)) as shown in Table 3.

**Figure 4** shows some examples of the simulation results and Table 4 shows the parameter values obtained with the wash-off load model.

\( D_0 \) and \( k_f \) varied widely among the survey stations even if the traffic at each site was the same. The particulate organic matter varied greatly for each roadway. The typical urban gross pollutants transported by stormwater were litter such as cigarette butts, and vegetation such as leaves.

**Figure 4** | Simulation results of rainfall wash-off process. (—Estimated value; □ Observed value).
and twigs. The result of the previous study (Allison et al. 1997) reported that organic matter such as vegetation accounted for the largest proportion by mass of the collected gross pollutants. The wind speed was a loss factor for the roadway surface deposit amount, which was expressed as $k_f$ (Cowherd et al. 1997). This result suggested that $D_0$ was often affected by litter rather than atmospheric fallout amount. It was considered that the fugitive particulate depositions and losses on roadways were caused by a combination of wind speed and traffic-induced turbulence.

As phosphorus was adsorbed in soil, its particulate portion could not be washed off when the rainfall intensity was weak. Nitrogen oxides and ammonia might be involved in the formation of secondary aerosols (Tarnay et al. 2001; Hayashi 2003). Vehicular emissions of reactive nitrogen compounds such as nitric oxide (NO), nitrogen dioxide (NO$_2$), and ammonia (NH$_3$) had a substantial impact on urban air quality (Narusawa 2003; Norbert et al. 2008).

In addition, a sink surface was a hydrologically inactive surface on which reentrained particles could settle and be eliminated from the hydrological transport. It was possible that the change in $k_s$ could be the result of these influences.

The wash-off loading rates provided by the model were examined and compared with observed data and the simulated ones. These simulated data correspond reasonably well with the observed ones (Figure 5). They produced $R^2$ values of more than 0.6 for most of the water quality indices and fractions (Table 4). The simulation results for the three stations showed the effectiveness of the model, under such factors as industrial activity, roadway condition and meteorological phenomena. The model is applicable to other urban areas.

### MODEL APPLICATION TO ENTIRE URBAN ROADWAYS IN LAKE BIWA WATERSHED

#### Extension of model and verification

The model was applied to the estimation of pollutant load from the urban roadways in the Lake Biwa watershed. In this case, all the parameter values were unified to make the model applicable to roadways in the watershed, although the previous analysis adopted individual parameter values for different stations. In other words, each of the three stations was regarded as one of general urban roadways for the category of “roadway” in land use classification. Therefore, unified parameter values were newly determined to minimize the TSS for all data observed at the three stations.

In the calculation, the number of data of all the survey stations used for the stormwater wash-off model and the wash-off load model were 877 and 73, respectively.

Table 5 shows the unified parameter values for stormwater wash-off model from the roadways in the Lake Biwa watershed. The tank model was able to describe the

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**Table 2 | Parameter values of stormwater wash-off process model**

<table>
<thead>
<tr>
<th>Station</th>
<th>$h_1$ (mm)</th>
<th>$k_0$ (1/hr)</th>
<th>$k_1$ (1/hr)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. 1 \ ($n = 109$)</td>
<td>0</td>
<td>0.525</td>
<td>2.139</td>
<td>0.994</td>
</tr>
<tr>
<td>St. 2 \ ($n = 488$)</td>
<td>1.487</td>
<td>0.013</td>
<td>5.727</td>
<td>0.997</td>
</tr>
<tr>
<td>St. 3 \ ($n = 280$)</td>
<td>0.106</td>
<td>0.502</td>
<td>2.952</td>
<td>0.962</td>
</tr>
</tbody>
</table>

$R^2$ is Coefficient of Determination.

**Table 3 | Water quality concentration of rainfall**

<table>
<thead>
<tr>
<th>Water quality constituent</th>
<th>C (mg/L)</th>
<th>Particulate</th>
<th>Dissolved</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD$_{Mn}$</td>
<td>0.09</td>
<td>0.92</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>TOC</td>
<td>0.21</td>
<td>0.73</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>TN</td>
<td>0.024</td>
<td>0.356</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>TP</td>
<td>0.004</td>
<td>0.001</td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>

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**Figure 5 | Simulation results of wash-off load of P-COD$_{Mn}$**

(— Simulated; • Observed; □ Rainfall intensity) (left: St. 1, right: St. 2).
observed wash-off phenomena satisfactorily by assigning
unified parameter values with the coefficient of determi-
nation ($R^2$) of 0.986 (Figure 6). Table 6 shows the unified
parameter values of wash-off pollutant load from the
roadways in the Lake Biwa watershed. The coherence of
the parameter values reduced the estimation precision
($R^2 = 0.197 \pm 0.807$). However, the model still provided
accurate estimations especially as regards organic matter
and nitrogen (Figure 7).

The accuracy of parameter was evaluated by Root
Mean Square Errors (RMSE) of load (as percent of the
mean value). RMSE is expressed as follows:

$$
RMSE(\%) = \sqrt{n \sum_{i=1}^{n} (L_{obs} - L_{sim})^2} \times 100
$$

(13)

where $n$ is the number of data, $L_{obs}$ is the observed data,
$L_{sim}$ is the simulation results and is mean value of
the observed data. RMSE of the individual parameter
(St. 1 – St. 3), RMSE of the unified parameter and the
error increase obtained by the difference between them are
shown in Table 7.

The range of RMSE of the individual parameter of
St. 1, St. 2 and St. 3 were 9–54%, 18–82% and 7–26%,
respectively and that of the unified parameter was
19–109%. As regards the flow rate, RMSE of the unified

<table>
<thead>
<tr>
<th>Water quality constituent</th>
<th>Station</th>
<th>$D_o$ (mg/m²·hr)</th>
<th>$k_r$ (1/hr)</th>
<th>$k_s$ (1/mm)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-COD$_{Mn}$</td>
<td>St. 1</td>
<td>15.70</td>
<td>0.225</td>
<td>0.739</td>
<td>0.757</td>
</tr>
<tr>
<td></td>
<td>St. 2</td>
<td>81.14</td>
<td>0.651</td>
<td>0.065</td>
<td>0.893</td>
</tr>
<tr>
<td></td>
<td>St. 3</td>
<td>0.934</td>
<td>0.008</td>
<td>0.332</td>
<td>0.961</td>
</tr>
<tr>
<td>D-COD$_{Mn}$</td>
<td>St. 1</td>
<td>3.346</td>
<td>0.067</td>
<td>0.736</td>
<td>0.859</td>
</tr>
<tr>
<td></td>
<td>St. 2</td>
<td>0.771</td>
<td>0.007</td>
<td>14.370</td>
<td>0.629</td>
</tr>
<tr>
<td></td>
<td>St. 3</td>
<td>0.698</td>
<td>0.006</td>
<td>0.301</td>
<td>0.925</td>
</tr>
<tr>
<td>POC</td>
<td>St. 1</td>
<td>18.30</td>
<td>1.360</td>
<td>6.533</td>
<td>0.422</td>
</tr>
<tr>
<td></td>
<td>St. 2</td>
<td>4.368</td>
<td>0.027</td>
<td>0.051</td>
<td>0.890</td>
</tr>
<tr>
<td></td>
<td>St. 3</td>
<td>76.36</td>
<td>0.741</td>
<td>0.345</td>
<td>0.812</td>
</tr>
<tr>
<td>DOC</td>
<td>St. 1</td>
<td>1.050</td>
<td>0.010</td>
<td>0.805</td>
<td>0.895</td>
</tr>
<tr>
<td></td>
<td>St. 2</td>
<td>0.647</td>
<td>0.005</td>
<td>14.37</td>
<td>0.683</td>
</tr>
<tr>
<td></td>
<td>St. 3</td>
<td>0.638</td>
<td>0.006</td>
<td>0.335</td>
<td>0.884</td>
</tr>
<tr>
<td>P-TN</td>
<td>St. 1</td>
<td>1.271</td>
<td>0.676</td>
<td>4.426</td>
<td>0.678</td>
</tr>
<tr>
<td></td>
<td>St. 2</td>
<td>0.797</td>
<td>0.088</td>
<td>0.101</td>
<td>0.559</td>
</tr>
<tr>
<td></td>
<td>St. 3</td>
<td>7.851</td>
<td>1.357</td>
<td>0.866</td>
<td>0.896</td>
</tr>
<tr>
<td>D-TN</td>
<td>St. 1</td>
<td>1.272</td>
<td>0.425</td>
<td>7.293</td>
<td>0.985</td>
</tr>
<tr>
<td></td>
<td>St. 2</td>
<td>0.069</td>
<td>0.003</td>
<td>0.801</td>
<td>0.828</td>
</tr>
<tr>
<td></td>
<td>St. 3</td>
<td>0.210</td>
<td>0.006</td>
<td>0.248</td>
<td>0.957</td>
</tr>
<tr>
<td>P-TP</td>
<td>St. 1</td>
<td>0.156</td>
<td>0.397</td>
<td>6.063</td>
<td>0.636</td>
</tr>
<tr>
<td></td>
<td>St. 2</td>
<td>0.007</td>
<td>0.000</td>
<td>71.430</td>
<td>0.693</td>
</tr>
<tr>
<td></td>
<td>St. 3</td>
<td>0.013</td>
<td>0.012</td>
<td>0.336</td>
<td>0.738</td>
</tr>
<tr>
<td>D-TP</td>
<td>St. 1</td>
<td>0.002</td>
<td>0.032</td>
<td>0.450</td>
<td>0.894</td>
</tr>
<tr>
<td></td>
<td>St. 2</td>
<td>0.013</td>
<td>0.021</td>
<td>0.069</td>
<td>0.777</td>
</tr>
<tr>
<td></td>
<td>St. 3</td>
<td>0.053</td>
<td>0.010</td>
<td>0.004</td>
<td>0.844</td>
</tr>
</tbody>
</table>

P- is particulate portion and D- is dissolved portion.
parameter corresponded well with that of the individual parameter. The range of the error increase was acceptable (0–83%), so that the unified parameter was shown to be effective.

**Estimation of pollutant load from urban roadways in the Lake Biwa watershed**

The model proposed in this study is able to adequately describe the wash-off behavior of roadways and to predict their load amount. By using unified parameter values, the model is able to estimate the total pollutant loads of urban roadways in the Lake Biwa watershed.

The pollutant loads were calculated by using the precipitation data at the Omihatiman District Meteorological Observatory provided by the Japan Meteorological Agency (Japan Meteorological Agency HP). The precipitation data were available at an interval of ten minutes with a scale range of 0.5 mm. Data for all dry weather periods and all the rainfall amounts were substituted into the model, and the pollutant loads were calculated to be the average values for 10 years by the data of 1998–2007. The pollutant loads of roadways in the Lake Biwa watershed were as follows:

- P-COD\(_{\text{Mn}}\), POC, P-TN and P-TP were 15.9, 15.7, 0.88 and 0.15 kg/(km\(^2\)·d); and D-COD\(_{\text{Mn}}\), DOC, D-TN and D-TP were 14.1, 12.5, 2.62 and 0.03 kg/(km\(^2\)·d). The percentages of the particulate portions were 53, 56, 25 and 85% (Figure 8). From these results, COD\(_{\text{Mn}}\), TOC, TN and TP were calculated to be 29.9, 28.2, 3.50 and 0.18 kg/(km\(^2\)·d), respectively.

**Table 7** | RMSE of the unified parameter and the individual parameter

<table>
<thead>
<tr>
<th>Flow rate(^\ast)</th>
<th>P-COD</th>
<th>D-COD</th>
<th>POC</th>
<th>DOC</th>
<th>P-TN</th>
<th>D-TN</th>
<th>P-TP</th>
<th>D-TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual parameter(^\ast)</td>
<td>St. 1 (n = 22)</td>
<td>22</td>
<td>33</td>
<td>29</td>
<td>13</td>
<td>26</td>
<td>34</td>
<td>32</td>
</tr>
<tr>
<td>Error increase(^\dagger)</td>
<td>– 3</td>
<td>18</td>
<td>35</td>
<td>49</td>
<td>54</td>
<td>46</td>
<td>38</td>
<td>62</td>
</tr>
<tr>
<td>St. 2 (n = 43)</td>
<td>18</td>
<td>47</td>
<td>58</td>
<td>50</td>
<td>51</td>
<td>82</td>
<td>47</td>
<td>57</td>
</tr>
<tr>
<td>Error increase(^\dagger)</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>12</td>
<td>29</td>
<td>– 2</td>
<td>0</td>
<td>37</td>
</tr>
<tr>
<td>St. 3 (n = 8)</td>
<td>15</td>
<td>7</td>
<td>12</td>
<td>20</td>
<td>14</td>
<td>17</td>
<td>9</td>
<td>19</td>
</tr>
<tr>
<td>Error increase(^\dagger)</td>
<td>4</td>
<td>44</td>
<td>52</td>
<td>42</td>
<td>66</td>
<td>63</td>
<td>38</td>
<td>75</td>
</tr>
<tr>
<td>Unified parameter(^\ast)</td>
<td>All stations (n = 73)</td>
<td>19</td>
<td>51</td>
<td>64</td>
<td>62</td>
<td>80</td>
<td>80</td>
<td>47</td>
</tr>
</tbody>
</table>

\(^\dagger\)RMSE, % of Mean Load.

\(^\dagger\)Error increase of RMSE of Unified parameter to that of Individual parameter.

\(^\dagger\)Number of Flow rate data; n = 109 (St. 1), n = 488 (St. 2), n = 280 (St. 3), n = 877 (All stations).
time, typically kg/(km²·d), for various pollutants. The unit loads of roadway in the Lake Biwa Water Quality Protection Program (Shiga & Kyoto Prefectures 2007) were 14.4, 3.86 and 0.20 kg/(km²·d) for CODMn, TN and TP, respectively. The value of CODMn in this study was shown twice as much as that of the LBWQPP, and the values of TN and TP were almost the same with those of the LBWQPP (Figure 9). These values were multiplied by the total area of roadways in the watershed (98.8 km²) obtained from the Roadways Traffic Census (Ministry of Land, Infrastructure, Transport and Tourism and Shiga Prefecture 2002), and the calculated amounts of pollutant loads of roadways in the Lake Biwa watershed were 2,950 CODMn kg/d, 350 TN kg/d and 18 TP kg/d, respectively. This estimated load for CODMn was equivalent to 7.7% of the total CODMn inflowing load of Lake Biwa in 2005 (38,400 CODMn kg/day). This clearly means that measures must be taken against wash-off load from urban roadways to protect the water quality of lakes.

CONCLUSIONS

The model capable of estimating the roadways load was proposed with combination of two principal processes of deposit and wash-off. It was verified based on field survey data obtained over a 5-year period, and was applied to estimate the load from all the urban roadways in the Lake Biwa watershed. The main results obtained in this study are as follows;

(1) The analytical solutions of the model provided a sole set of parameter values in the model by minimizing the total sum of squares of differences between the observed data and the simulated ones.

(2) The effectiveness of the model was confirmed by the good agreement between observed data and simulated ones. This model is expected to be applicable to large watersheds.

(3) According to the model, P-CODMn, POC, P-TN and P-TP were calculated to be 15.9, 15.7, 0.88 and 0.15 kg/(km²·d), respectively, and D- CODMn, DOC, D-TN and D-TP were calculated to be 14.1, 12.5, 2.62 and 0.03 kg/(km²·d), respectively.

(4) From the results, the pollutant loads of CODMn, TN and TP obtained for the Lake Biwa watershed (total roadway area of 98.9 km²) were estimated to be 2,950, 350 and 18 kg/d, respectively.

(5) The estimated load for CODMn was equivalent to 7.7% of the total inflowing load of Lake Biwa.

ACKNOWLEDGEMENTS

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REFERENCES


Ministry of Land, Infrastructure, Transport and Tourism and Shiga prefecture 2002 Roadways traffic census.


