Evaluation of factors influencing diffusion of pollutant loads in urban highway runoff

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Abstract
Many studies have identified the first flush phenomenon and runoff characteristics. The purpose of this study is to elucidate which parameters influence the runoff pollutant loads. Eight runoff events during the period from May 1999 to September 2000 were investigated. From the dimensionless cumulative analysis, it was suggested that particulate substances such as suspended solids (SS), iron and total phosphorus (T-P) were inclined to be washed off in heavier rainfall condition. The cumulative curves of particulate constituents were appreciably variable in slope, while those of dissolved were approximately constant. Accordingly it was indicated that dissolved load was discharged regardless of rainfall conditions. Event mean runoff intensity and cumulative runoff height showed significant correlation with the cumulative runoff load of the constituents except for total nitrogen (T-N). On the other hand, antecedent dry weather period (ADWP) and traffic flow volume during ADWP did not show correlation with the cumulative runoff loads. Only T-N load showed correlation with those factors, consequently it was suggested that vehicular exhausts affected nitrogen load on the surface of urban highway.

Keywords
First flush; highway runoff; rainfall intensity; suspended solid

Introduction
Nonpoint source pollution resulting from stormwater runoff has been identified as one of the major causes of the deterioration of the quality of receiving waters. Line et al. (1999) reviewed several aspects of nonpoint source pollution, including policy, economics, and management issues; effects and extent of pollutants in surface and groundwater; pollution controls; and modeling and monitoring.

Especially in urban area, stormwater runoff from road surface contains significant loads of various pollutants, such as heavy metals and polycyclic aromatic hydrocarbons (PAHs) (Hoffman et al., 1984; Sansalone and Buchberger, 1997; Barrett et al., 1998). Previous study (Shinya et al., 2000) showed that the concentration of heavy metals and PAHs was highest in the initial runoff water regardless of rainfall conditions. Owing to these compounds, toxic effects were observed with urban runoff (Maltby et al., 1995; Boxall and Maltby, 1997; Marsalek et al., 1999).

Many studies have identified the first flush phenomenon as being a relatively high load of pollutants in the initial phases of runoff flow. The expression first flush effect denotes the high pollution load in the runoff water at the beginning of a rainfall event. The maximum rainfall intensity, maximum inflow, rainfall duration, and the antecedent dry weather period were found to be the most important parameters influencing the first flush load (Gupta and Saul, 1996). However, variations in the first flush load of surface runoff could not be calculated using a universal set of climate, rainfall and runoff characteristics (Deletic, 1998). Total suspended solids and organic matter indices such as BOD and COD were often used to estimate urban stormwater runoff quality. Suspended solids loading rate
was influenced by rainfall intensity and overland flow rate (Deletic and Maksimovic, 1998). Usually concerning first flush effect, dissolved compounds were disregarded from analysis since they were not subject to erosion, however, a significant impact of dissolved compounds was caused on receiving water (Krebs et al., 1999). Further studies have been required because runoff characteristics were complicated as described above.

The objective of this study is to elucidate the factors influencing diffusion of pollutant loads in urban highway runoff. A study about the factors on the basis of accurate investigation is necessary in order to develop relevant load runoff models.

**Methods**

**Study site**

Sampling site was the same as previous study (Shinya et al., 2000). The average daily traffic preceding each runoff event was approximately 62,000 vehicles. The drainage area selected for this study was 1,082 m².

**Sampling and analytical procedure**

Five different runoff events were investigated in 1999 and three events in 2000. Sampling was started at the beginning of each runoff event and stopped at the end of runoff or two hours had elapsed from the beginning, because flush peak observed within two hours elapsed. Runoff samples were collected and analyzed by the same procedure as previous study (Shinya et al., 2000). In this study, “PAHs” described below means the sum of fifteen 3- to 6-ring PAHs, includes phenanthrene, fluoranthene, pyrene and benzo[a]pyrene.

**Load runoff factors**

It is considered that runoff loads of pollutants are influenced by various factors. In this study, effects of following factors were examined. Antecedent dry weather period (ADWP) and traffic flow volume during the period are considered to be related to pollutant deposition, while cumulative runoff height and event mean runoff intensity are considered to be related to pollutant diffusion. These data observed in each event were presented in Table 1.

**Results and discussion**

**Event mean concentration**

Even though pollutant concentrations often vary by several times of magnitude during a runoff event, a single index known as event mean concentration (EMC) can be used to characterize runoff constituents (Huber, 1993). EMC represents a flow average concentration defined as the total pollutant load divided by total runoff volume, as follows:

\[
EMC = \frac{\sum C(t)Q(t)}{\sum Q(t)}
\]

(1)

**Table 1** Summary of hydrologic and traffic indices

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<tr>
<td>Runoff sampling duration [hr]</td>
<td>2.0</td>
<td>2.0</td>
<td>1.0</td>
<td>2.0</td>
<td>2.0</td>
<td>1.0</td>
<td>0.5</td>
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<tr>
<td>Precipitation [mm]</td>
<td>7.5</td>
<td>2.5</td>
<td>3.0</td>
<td>6.5</td>
<td>30.5</td>
<td>13.5</td>
<td>6.0</td>
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<tr>
<td>Cumulative runoff height [mm]</td>
<td>7.9</td>
<td>2.9</td>
<td>3.3</td>
<td>6.5</td>
<td>29.0</td>
<td>13.7</td>
<td>6.0</td>
</tr>
<tr>
<td>Event mean runoff intensity [mm hr⁻¹]</td>
<td>4.0</td>
<td>1.5</td>
<td>3.3</td>
<td>3.2</td>
<td>14.5</td>
<td>6.9</td>
<td>6.0</td>
</tr>
<tr>
<td>Antecedent dry weather period (ADWP) [day]</td>
<td>19</td>
<td>9</td>
<td>9</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>12</td>
</tr>
</tbody>
</table>
where $C(t)$ is the time variable concentration, $Q(t)$ is the time variable flow, and $t$ is the time elapsed from the start of the event. EMCs can be compared with other highway data (Barrett et al., 1998).

EMCs obtained in this study are presented in Table 2. EMC of each constituent was the same order of the value obtained in previous research (Shinya et al., 2000).

### Pollutant load and cumulative analysis

Table 2 also shows a summary of cumulative load of each constituent. Cumulative load per area of the catchment was calculated by using the following equation:

$$\text{Cumulative load} = A^{-1} \int C(t)Q(t)dt$$  \hspace{1cm} (2)

where $A$ is the drainage area, $C(t)$, $Q(t)$ and $t$ are represented in Eq. (1). For the most runoff constituents, the highest cumulative loads were shown in the event on September 8, 2000, in which the heaviest rainfall was observed, while the lowest loads in the event on June 6, 1999, in which intense rainfall was not observed. These results imply that rainfall intensity relate to cumulative runoff loads.

Figure 1 illustrates the cumulative curves of constituents for the events of July 18, 1999 and June 9, 2000. In the event on June 2000, rainfall was heavier than in the event on July 1999, while sampling duration and antecedent dry weather period (ADWP) were the same. Geiger defined a first flush as occurring when such curves have an initial slope greater than 45%, and used the point of maximum divergence from the 45 degrees slope to quantify the first flush (Geiger, 1987). In this definition, first flush was observed in both events and occurred more strongly in the June 2000 event, especially for suspended solids (SS), PAHs, iron (Fe) and total phosphorus (T-P). These substances were considered as particulate-bound. From both cumulative curves, it was suggested that these particulate constituents were inclined to be washed off in heavier rainfall condition.
Figure 1  Cumulative curves of constituents for the events of July 18, 1999 and June 9, 2000

Figure 2  Cumulative curves of: (a) SS, (b) TOC, (c) T-N, (d) T-P, (e) Fe and (f) Zn
Cumulative curves of SS, total organic carbon (TOC), total nitrogen (T-N), T-P, Fe and zinc (Zn) for all the events are shown in Figure 2. Suspended solids, T-P and Fe clearly show a strong first flush. Figure 2(a), 2(d) and 2(e) indicate that the cumulative curves of these particulate constituents are appreciably variable in slope. In the highest intense rainfall event on September 8, 2000, first flush occurred weakly, even though Korean researchers reported that first flush occurred strongly as the rainfall intensity higher (Lee and Bang, 2000). Further study will be necessary for generalization of this phenomenon.

As shown in Figure 2(c), T-N shows a weak first flush, and the cumulative curves of T-N are approximately constant in slope. Because 80% of T-N were dissolved form, whereas 50% of T-P and only 6% of iron (Shinya et al., 2002), it was suggested that dissolved load was discharged regardless of rainfall conditions. The cumulative curves of TOC and Zn indicate intermediate tendency between particulate and dissolved constituents.

**Correlation between cumulative load and load runoff factors**

Table 3 shows a summary of the square of correlation coefficients ($R^2$) between cumulative pollutant loads of each constituent and factors influencing load runoff. Event mean runoff intensity showed strong correlation with cumulative runoff loads of SS, aluminium (Al) and Fe. It also showed significant correlation with those of the other constituents except for T-N. Cumulative runoff height also correlated with cumulative runoff load of the constituents except for T-N. These factors, which are considered to be associated with transport of solids, influenced diffusion of pollutant loads in highway runoff. On the other hand, antecedent dry weather period (ADWP) and traffic flow volume during ADWP, which is considered to be associated with pollutant deposition on the road surface, did not show significant correlation with cumulative runoff loads. Only T-N load showed correlation with those factors, accordingly it was suggested that vehicular exhausts affected nitrogen load on the surface of urban highway.

**Conclusion**

Data generated from eight runoff events during the period from May 1999 to September 2000 were statistically analyzed with the aim of elucidating which parameters influence the runoff pollutant loads. The following general conclusions could be drawn.

From the dimensionless cumulative analysis, it was suggested that particulate substances such as SS, Fe and T-P were inclined to be washed off in heavier rainfall condition. The cumulative curves of particulate constituents were appreciably variable in slope, while

<table>
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<th>Constituents of pollutant</th>
<th>Factors influencing diffusion of pollutant loads in highway runoff</th>
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<tr>
<td></td>
<td>Cumulative runoff height</td>
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<tr>
<td>SS</td>
<td>0.610</td>
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<tr>
<td>TOC</td>
<td>0.429</td>
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<tr>
<td>T-N</td>
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<td>0.606</td>
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<td>Cu</td>
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<td>Fe</td>
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<td>Mn</td>
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<tr>
<td>Pb</td>
<td>0.678</td>
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<td>Zn</td>
<td>0.575</td>
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<tr>
<td>PAHs</td>
<td>0.798</td>
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</table>
those of dissolved were approximately constant. It was indicated that dissolved load was discharged regardless of rainfall conditions.

Event mean runoff intensity and cumulative runoff height showed significant correlation with the cumulative runoff load of the constituents except for T-N. On the other hand, ADWP and traffic flow volume during ADWP did not show correlation with the cumulative runoff loads. Only T-N load showed correlation with those factors, consequently it was suggested that vehicular exhausts affected nitrogen load on the surface of urban highway.

Further work is required to develop an appropriate mathematical model of runoff pollutant in order to make runoff characteristics more general.

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References