Characterization of runoff from various urban catchments at different spatial scales in Beijing, China


ABSTRACT

In order to investigate the characterization of runoff in storm sewer from various urban catchments, three monitoring systems at different spatial scales have been installed separately. They have been held since July 2010 in urban area of Beijing (China). The monitoring data revealed that chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), and NH3-N values significantly exceed the Class V surface water quality standard developed by Ministry of Environmental Protection of the People’s Republic of China (MEP). A surface solids buildup and wash off model for small watershed was adopted to analyze and discuss the process of a runoff pollutant discharge. More than a half of pollutant parameters presented a good fit to the model. However, a slightly worse-fit to the wash off model appeared in less than half of the data. Due to the influence of sewer sediments, sewer system characteristics, catchment characteristics, and other reasons, first flush was seldom observed in storm sewer runoff from these three survey areas. Meanwhile, the correlation between TSS and any other pollutant was analyzed according to cumulative load of pollutants in runoff events. An event mean concentrations (EMCs) approach was adopted to quantify the pollution of runoff. EMCs of various pollutants in storm sewer runoff between different rainfall events were slightly higher than the typical values observed in similar areas at home and abroad, according to other studies reported in literature. Based on quantitative analysis, it can be concluded that urban non-point source pollution is recognized as the major causes of quality deterioration in the receiving water bodies. This is after the point source pollution has been controlled substantially in Beijing. An integrated strategy, which combines centralized and decentralized control, along with the conditions of meteorology, hydrology, urban planning, existing drainage system, etc., will be an effective and economic approach to urban runoff pollution control.

Key words | control strategy, event mean concentration (EMC), runoff quality, storm sewer, urban runoff

INTRODUCTION

Water quality deterioration is one of the serious problems we are facing in urban environments while Chinese cities are developing rapidly. As early as about 20 years ago, point source pollution had aroused widespread concern of scientists, environmentalists, government regulators, and the public in China, especially in developed cities, such as Beijing, Shanghai, Guangzhou, etc. From 2004–2009, Beijing’s sewage collection rate increased from 59.1 to 94.3%. This has reached the level in developed countries (Beijing Water Authority 2009). Meanwhile, the proportion of water bodies inferior to the Class V surface water quality standard is generally increasing year by year. Although urban point source pollution has been substantially controlled, the problem of urban water environment has not been effectively resolved in Beijing urban areas. It is an important time to heed urban runoff pollution and put considerable emphasis on it. Investigation and relevant research should be carried out to pursue an appropriate strategy and program to reverse the present trend of water quality deterioration.

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MATERIAL AND METHODS

Study area

In order to investigate the characterization of runoff from various urban catchments at different spatial scales, three monitoring systems have been installed in the experimental catchments of urban areas in Beijing (Figure 1).

The three systems are all located in the downtown of Beijing, which are characterized by different kinds of catchment. The catchment land use of survey points A and B are road (for most part) and lawn. The catchment land use of survey point C is mixed, with road, roof, plaza, open space, parking lots, etc. There is a separated sewer system respectively in these three areas and the conditions of sampling and monitoring is easy to implement. Basic information of investigated areas is shown in Table 1.

Sample collection and testing

Three manual combined automatic monitoring stations were established at the outlets of these three catchments studied. Rain gauges were equipped to obtain rainfall intensities during storms.

Sampling in the study catchment was carried out during the period from July to October 2010. Sampling was obtained at 1–10 min intervals in the first 60 min of storm events and then 20–30 min intervals for receding flow stage. A total of 18 samples were taken during a long duration rain event; while less than 12 samples were collected from events of short duration.

The sample was calibrated to collect 500 ml in a 600 ml bottle per sample, and were recovered immediately after the rain event or very early the next morning (if rain occurred at night) and transported to the laboratory for testing total...
suspended solids (TSS), chemical oxygen demand (COD), turbidity, total nitrogen (TN), NH₃-N, total phosphorus (TP) and pH using Standard Methods (APHA 1998). The sample was well mixed manually before preparing the sample for testing. If samples were not assayed upon arrival, they would be kept in refrigerators and tested within 24 h.

**Characteristic of rainfall events monitored**

Six rainfall events were sampled during the period from July to October 2010 (Table 2).

**RESULTS AND DISCUSSION**

**Surface solids buildup and wash off model for small watershed**

Based on statistical analyses of many survey samples, which describe the relationship between pollutant concentration (COD, TSS, TN, TP, etc.) in runoff from building roof, road surface, atmosphere and the duration of storm event in urban areas in China, the following ‘first order’ flush model was derived (Che et al. 2003):

\[ C_t = C_0 e^{-kt} \]

where \( C_0 \) is pollutant concentration from catchment at the initial stage of a runoff event (mg/l) \( C_t \) is pollutant concentration at elapsed time of rainfall (mg/l) \( k \) is flush coefficient which reflects the multiple influence of flush intensity, the characteristics of catchments and pollutants etc. (min⁻¹), \( t \) is elapsed time of rainfall (min).

The analysis on the stormwater runoff from these three catchments monitored during 2010 suggests that there is a better model fitting in the catchment consisted of road (survey points A and B) than the one consisted of several kinds of catchment (survey point C). The data for TSS from the survey points A and B are taken as an example (Figure 2). Results show reasonable regression equations and degree of fit. The TSS values at the initial stage of runoff from survey points A and B range from 168.79 to 1,069.9 mg/l. The values of \( k \) range from 0.0071 to 0.0443, and \( R^2 \) varied from 0.05 to 0.85. It can be concluded that the discharge process of several pollutants in sewer runoff is similar to the process in runoff from a small watershed (building roof, road surface, parking lots, etc.). However, a much lower degree of fit for nearly half of pollutants appeared. When runoff flow into a sewer, due to the multiple influence of flush intensity, the characteristics of catchments and pollutants, and the pollutant discharged process gradually deviate from the wash off model. The simplification of catchment’s constitution and the small scale of drainage system as survey points A and B is that there is not an extremely significant influence for some pollutants appeared in the two sewer runoffs monitored.

**Table 2** | Characteristics of rainfall events and antecedent dry weather period condition

<table>
<thead>
<tr>
<th>Survey point</th>
<th>Rainfall date</th>
<th>Depth mm</th>
<th>Duration min</th>
<th>Average intensity mm/h</th>
<th>ADWP d</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2010-7-1</td>
<td>6.1</td>
<td>380</td>
<td>0.96</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>2010-7-9</td>
<td>88.9</td>
<td>345</td>
<td>15.46</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2010-8-4</td>
<td>24.0</td>
<td>125</td>
<td>11.52</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>2010-9-20</td>
<td>21.3</td>
<td>375</td>
<td>3.41</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>2010-7-9</td>
<td>47.2</td>
<td>370</td>
<td>7.65</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>2010-8-4</td>
<td>25.4</td>
<td>120</td>
<td>12.70</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>2010-8-18</td>
<td>20.1</td>
<td>470</td>
<td>2.57</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>2010-9-20</td>
<td>23.6</td>
<td>430</td>
<td>3.29</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>2010-8-30</td>
<td>20.5</td>
<td>90</td>
<td>13.80</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2010-10-1</td>
<td>7.3</td>
<td>510</td>
<td>1.20</td>
<td>9</td>
</tr>
</tbody>
</table>

ADWP: antecedent dry weather period.

**Figure 2** | TSS from urban runoff in different catchments. Left: Survey point A. Right: Survey point B.
The TSS, COD and TN have a high fit with the first flush model in most rainfall events. Meanwhile, TP and NH₃-N have a low fit with the model in most events. As a result of the influence of multiple factors apparently, a special case also existed in some rainfall event.

**First flush**

A first flush phenomenon occurs when most of the event load is transported in the initial part of the event discharged volume. Generally, plotting the normalized cumulative pollutant mass versus the normalized cumulative runoff volume (LV) curve assesses the first flush (Lee & Bang 2000; John & Chad 2004). An LV curve lying above the bisector would represent a first flush condition. An LV curve lying below the bisector represents a condition in which the majority of the pollutant load was not delivered until the later stages of the runoff event. This means that last flush occurs. The term ‘last flush’ was noted in some literature (Hager 2001) as an antonym to first flush, which is defined as the high pollutant load in the later part of stormwater runoff. The storm sewer network, different pollutant concentration in different inlets of stormwater sewer and stormwater sewer sediment are possible causes for the occurrence of last flush.

According to the definition and method discussed above, the curves of major pollutants from sewer runoff in survey point C were reproduced for two typical rainfall events respectively (Figure 3). In accordance with definition and LV curve method above, first flush of COD, TSS, TN, TP is observed in more than 60% of the monitored rainfall events in survey catchments A and B. However, first flush was seldom observed in the catchment at survey point C due to the influence of sewer sediments, sewer system characteristics, catchment characteristics, etc.

**Cumulative correlations between TSS and other pollutant parameters**

As the wide concentration varies for the constituents, it was suspected that, due to the high percentage of particulate matter and pollutants in particulate form, a connection between the individual pollutant concentrations exists. In order to assess possible relationships between parameters analyzed, a correlation analysis was performed. In some early research, by some Chinese scholars, the instantaneous concentration of a pollutant in urban runoff is the main object of correlation analysis (Ren et al. 2005). However, the variation of instantaneous concentration cannot completely represent an actual process of urban runoff pollutant emissions. Assessing possible relationships between the analyzed parameters should be integrated with the runoff volume emission process. Generally, plotting the normalized cumulative pollutant (A) mass versus the normalized cumulative pollutant (B) mass assesses the relationships between pollutant A and pollutant B.

According to the method above, correlation analysis for TSS and other pollutant parameters is illustrated in Figure 4. Correlation coefficients between TSS and other pollutant parameters is shown in Table 3.

It should be noted that the correlation coefficients reported in Table 3, calculated according to the method above, may be higher than the actual situation. There are several limitations for this analysis method. By this definition, due to both the normalized cumulative mass of TSS and other pollutants would increase from 0 to 1 during a rainfall event, the higher $R^2$ does not necessarily imply
there is an inherent correlation between them. It may imply that there is a high possibility of correlation between the two parameters. Another limitation of the analysis is that the number of rainfall events monitored is not enough to make a convincing conclusion. Therefore, further research and runoff investigations should be done to analyze the correlation between different pollutants. It may indicate that TSS could act as a representative pollutant in urban runoff (i.e. when TSS has been controlled; other pollutants would be controlled largely at the same time).

**Event mean concentrations**

The event mean concentration (EMC) of a pollutant parameter for a runoff event is defined as the flow-weighted average concentration of the pollutant that has been discharged during the event (USEPA 1983). For this study, EMCS of different pollutants were calculated. EMCS of COD in runoff range from 150 to 300 mg/l. The range of TSS, TN and TP is 200–400 mg/l, 5–20 mg/l and 0.5–2 mg/l, respectively. EMCS of pollutants are slightly lower than the value of the corresponding pollutant parameters of local sewage. Moreover, these values much exceed the Class V surface water quality standard developed by the Ministry of Environmental Protection of the People’s Republic of China (MEP). As shown in Table 4, EMCS of COD, TSS, TN and TP in Survey C are higher than the median pollutant concentration for corresponding parameters which were taken from foreign research (USEPA 1983; Burton & Pitt 2002; Pradeep 2002; ATV-DVWK 2003; Brombach et al. 2005). This includes the well-known NURP study from the United States Environmental Protection Agency and the study sponsored by the German Association for Water, Wastewater and Waste (ATV-DVWK). Through analysis and comparison between this study and relevant research reported in literature at home and aboard, it can be concluded that urban runoff pollution in Chinese developed cities (Beijing, Shanghai, etc.) is more serious than in some developed countries; a similar conclusion has been proposed by some Chinese scholars (Che et al. 2004; Li et al. 2007).

### Table 3 | Correlation coefficients ($R^2$) between TSS and other pollutant parameters

<table>
<thead>
<tr>
<th>Date</th>
<th>COD</th>
<th>TN</th>
<th>TP</th>
<th>NH3-N</th>
<th>Turbidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey point C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010-8-30</td>
<td>0.9944</td>
<td>0.9300</td>
<td>0.9865</td>
<td>0.9946</td>
<td>0.9760</td>
</tr>
<tr>
<td>2010-10-1</td>
<td>0.9833</td>
<td>0.9733</td>
<td>N/A</td>
<td>0.8739</td>
<td>0.9958</td>
</tr>
</tbody>
</table>

### Table 4 | EMCS of different pollutant parameters in survey point C

<table>
<thead>
<tr>
<th></th>
<th>COD</th>
<th>TSS</th>
<th>TN</th>
<th>TP</th>
<th>NH3-N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey point C (2010-8-31)</td>
<td>250.3</td>
<td>194.7</td>
<td>7.1</td>
<td>1.3</td>
<td>2.6</td>
</tr>
<tr>
<td>Survey point C (2010-10-1)</td>
<td>148.0</td>
<td>166.1</td>
<td>10.1</td>
<td>1.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Median pollutant concentration (ATV-DVWK 2003; Brombach et al. 2005)</td>
<td>81.0</td>
<td>141.0</td>
<td>2.4</td>
<td>0.42</td>
<td>0.8</td>
</tr>
<tr>
<td>Median pollutant concentration (USEPA 1983)</td>
<td>65</td>
<td>100</td>
<td>2.18</td>
<td>0.33</td>
<td>N/A</td>
</tr>
</tbody>
</table>
An integrated runoff control strategy

Based on the characteristics of runoff from various urban catchments above, urban runoff pollution can no longer be ignored because of serious impact on the water environment and ecosystem. If urban runoff cannot be treated and discharged to the water-body directly, it will be a huge obstacle to maintaining good urban waterscapes, designing a healthy urban water ecosystem and creating a sustainable urban water environment. An integrated strategy, which combines centralized and decentralized control, along with the conditions of meteorology, hydrology, urban planning, existing drainage system, etc., will be an effective and economic approach to urban runoff pollution control in Beijing (Figure 5). The basic principles of the integrated strategy can be demonstrated as follows.

- The control of total load amount should be paid more attention and given considerable emphasis.
- The strategy includes centralized and decentralized technologies at various spatial scales.
- According to function of urban planning for a city subdivision, specific stormwater planning and corresponding implementation which emphasize a main aspect of stormwater management, such as urban pollution control, flooding control, ecological restoration, rainwater harvesting, etc., was developed.
- Non-structural practices should be adopted into the integrated strategy to achieve the target of urban runoff pollution control and water environment restoration.

CONCLUSIONS

Based on integrated analysis results of the experiment in 2010 and research over the past 10 years, the following conclusions are made.
First flush is not a universal phenomenon in urban stormwater, especially when runoff flows into a sewer system. First flush is common and pronounced in runoff from small catchments. It can be seldom observed in an extremely large catchment when stormwater flows into a sewer. Additionally, there is an uncertainty in sewer runoff from a simple and small catchment due to the lower influence of multiple factors.

A method of correlation analysis combined the runoff volume emission process and was used to analyze the relationship between TSS and other pollutant parameters.

The preliminary analysis revealed that there may be a high possibility of correlation between TSS and other pollutants in a runoff emission process. However, further research and more runoff investigations should be done to analyze the correlation between different pollutants. It may indicate that TSS could act as a representative pollutant in urban runoff.

The EMCs of runoff are equal to, or even higher than, the median number of values in some previous research. Moreover, these values much exceed the Class V surface water quality standard developed by Ministry of Environmental Protection of the People’s Republic of China (MEP). Urban runoff pollution is a huge obstacle to maintaining good urban waterscapes, designing a healthy urban water ecosystem and creating a sustainable urban water environment.

An integrated strategy, which combines centralized and decentralized control, will be an effective and economic water environment.

ACKNOWLEDGEMENTS

These studies were financially supported by the Major Science and Technology Program for Water Pollution Control and Treatment (2010ZX07320-002) and Project of Beijing Academic Innovation Group in Urban Stormwater System and Water Environmental Eco-Technologies (PHR201106124). The authors would like to extend their appreciation to the laboratory of Beijing Drainage Group Co. Ltd for providing zealous support to analyze the samples.

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First received 11 November 2011; accepted in revised form 14 February 2012