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Pollutant Washoff Characterization of Expressway Runoff in Shanghai

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Abstract Pollutant washoff loads from an expressway in Shanghai, China were investigated during a 1-year study program. The median washoff load during an rainfall event for total solids, chemical oxygen demand, total nitrogen and total phosphorus were 4,389.8, 2,123.0, 47.6 and 1.6 mg/m^2, respectively. Through principal factor analysis, three factors that represent the influence of pollutant source availability, rainfall volume and rainfall intensity account for 89% variance of the monitoring data. The result of multiple regression analysis reveals that antecedent dry period significantly influences the washoff load, while peak rainfall intensity and runoff volume may have some influence, which correlates well with the principal factor analysis results.

Keywords Expressway runoff · Multiple regression analysis · Principal factor analysis · Pollutant washoff load

Highway storm runoff has been recognized as one of the important non-point pollution sources (Barrett et al. 1998; Lundberg et al. 1999; Flint and Davis 2007) and imposes high pressure on the urban aquatic environment (Taebi and Droste 2004; Vaze and Chiew 2004; Li et al. 2007). However, prediction of pollution loads during storm events has proven to be difficult due to the complex washoff mechanism. There has been considerable contradiction in the literature regarding the importance of factors influencing the pollutant washoff load. Some studies (Gupta and Saul 1996; Li et al. 2007) demonstrated that antecedent dry period (ADP) largely affects the washoff load and runoff quality. Whilst other studies (McLeod et al. 2006; Shinya et al. 2003) indicated that ADP is not related to the washoff load. Driver and Troutman (1989) and McLeod et al. (2006) argued that it is the total rainfall depth or runoff volume rather than the rainfall intensity controls the pollution loads, while Brezonik and Stadelmann (2002) and Shinya et al. (2003) suggested that rainfall intensity dominantly contributes to the pollutant washoff loads.

As a result of the rapid social and economic development in Shanghai, expressways have been extensively constructed in the past two decades, reaching 500 km at the end of 2007 (Fig. 1). The surface area of the expressway system corresponds to 2.5% of the downtown area and has brought about significant pollution to the ambient aquatic environment. Presently, water quality of about 87.5% of the water body in Shanghai belongs to class IV or worse of the Chinese Surface Water Quality Standard and the road runoff is regarded as one of the major sources of organic and nutrient pollution. However, the pollution load from expressway runoff has never been investigated with field sampling in the area. A 3-year research program was launched by the Shanghai Municipal Government in 2007 to understand and minimize the expressway runoff pollution. Investigation of the pollutant washoff characterization of the expressway runoff is a part of the research program and the results of the 1-year field sampling are reported in the paper. Such information will provide the basis for

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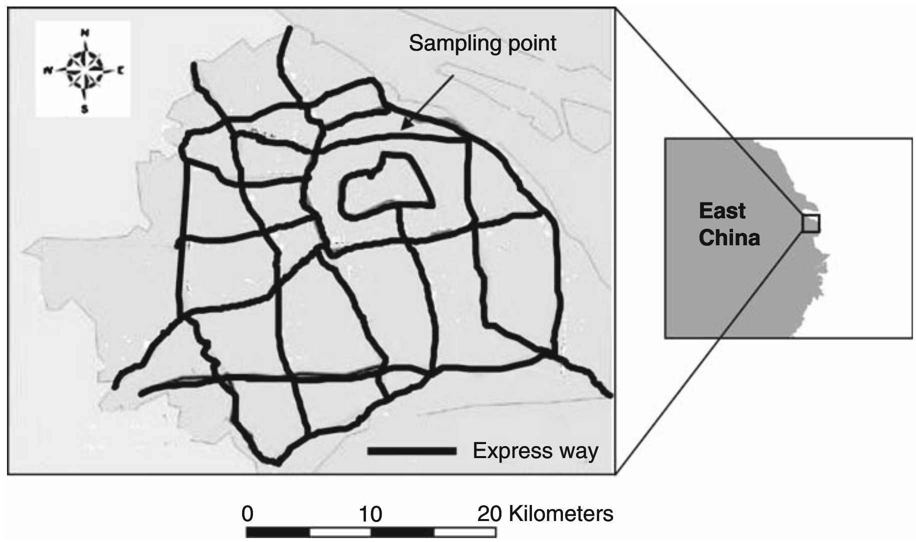

Fig. 1 Main expressway system of Shanghai and the sampling site

selecting of optimal runoff treatment process and design parameters, and will help to understand and predict the expressway runoff pollution.

Materials and Methods

The sampling site is located at Wuzhou Expressway (Fig. 1) with the average daily traffic volume of about 20,000. The road surface is asphalted and drained into two roadside gullies. The pollutants accumulated on the road surface were sampled in a way that were adopted by Zhang and Yamada (1996) and Vaze and Chiew (2002). The investigated road surface was divided into dozens of blocks of 2 m in length. Pollutant samples on the surface were collected periodically at different blocks using a vacuum cleaner. Precautions were taken in choosing the sampling surface such that the samples were collected from surfaces that had not been sampled in the previous days. These blocks are close to each other and therefore identical rainfall patterns and pollutant buildup and washoff characteristics can be assumed. Results from such sampling approach can be used for analyzing the pollutant buildup pattern in dry weathers and also the washoff loads during rainfall events which is the difference between the load collected before and after each event.

Particulate materials with diameter larger than 2,000 μm are considered difficult to be transported by rainfall-runoff and were sieved out from the samples. Total solids (TS) were measured gravimetrically and expressed as per unit area. Kjeldahl method was used for total nitrogen (TN) determination and Na_2CO_3 fusion method was used for total phosphorus (TP). Samples were digested using $K_2Cr_2O_7$–H_2SO_4, titrated with $FeSO_4$, and expressed as the chemical oxygen demand (COD) per unit area. The analytical method for the pollutant content in soil that is widely used in China was adopted for this study (Agrochemistry Commission and Soil Science Society of China 1983). Rainfall volume and the 10-min peak rainfall intensity were recorded by a rain gauge station near the site. SPSS 13.0 was applied to conduct the principal factor analysis (PFA) and multivariate regression analysis to analyze the main factors influencing the pollutant washoff loads.

Results and Discussion

Twenty one valid results were obtained during the 1-year monitoring period. Four parameters, i.e., total rainfall volume (RAINV), 10-min peak rainfall intensity (RINT), rainfall duration (RDUR) and ADP have been used to characterize the rainfall events. Detail information about these events is shown in Table 1. Pollutant loads accumulated on the expressway surface before each rainfall event are expressed as source availability (SAVAIL) and the washoff loads during each rainfall event as WASH. The statistical distribution of the measured loads is shown in Fig. 2. The average washoff loads of the investigated rainfall events for TS, COD, TN and TP were 4,389.8, 2,123.0, 47.6 and 1.6 mg/m^2, respectively with the coefficients of variation large than 0.80. Assuming a rainfall-runoff coefficient of 0.9, event mean concentrations (EMCs) were calculated for these pollutants and shown in Table 2.

Kaiser–Meyer–Olkin (KMO) and Bartlett's tests were performed to examine the suitability of these data for principal factor analysis. KMO is a measure of sampling adequacy that indicates the proportion of variance. The factor analysis is generally useful if the KMO values are

Table 1 Characteristics of the investigated rainfall events

Event number	Event date	RAINV (mm)	RINT (mm/h)	RDUR (h)	ADP (days)
1	5/29/2007	20.5	6	8.1	9
2	6/11/2007	15	4	6.3	11
3	6/21/2007	36	8	18.1	9
4	6/27/2007	31	4	17.2	5
5	7/2/2007	108	13	22.2	4
6	7/17/2007	11	3	8.5	5
7	8/3/2007	80	13.5	43.0	10
8	8/9/2007	11	9	2.0	4
9	8/26/2007	47	5	14.4	1
10	8/29/2007	6.5	5	3.7	1
11	9/16/2007	155.5	26	106.0	3
12	10/6/2007	25	30	1.45	8
13	12/14/2007	7.5	7.5	2.3	5
14	1/17/2008	40.5	15	11.1	4
15	1/24/2008	6.5	6.5	1.8	5
16	2/23/2008	34	12.4	13.5	22
17	4/13/2008	10	9	3.6	7
18	5/6/2008	44	8.6	9.7	9
19	5/16/2008	12	4	8.1	9
20	6/5/2008	11	2.5	9.5	11
21	6/11/2008	70	10.1	26.3	2

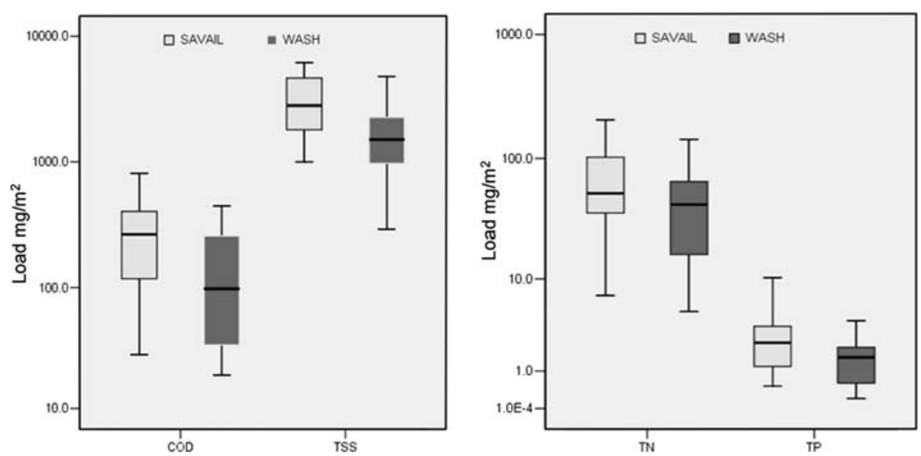

Fig. 2 *Box* plot of pollutant source load and washoff load. (Median value is indicated by the *horizontal line*. *Upper* and *lower* ends of the *box* are the quartiles while the ends of the *vertical line* represent the non-outlier data rang.)

Table 2 Summary of calculated event mean concentrations

	TS (mg/L)	COD (mg/L)	TN (mg/L)	TP (mg/L)
Minimum (mg/L)	124.5	29.8	0.41	0.01
Maximum (mg/L)	970.0	977.0	13.22	1.72
Median (mg/L)	191.8	108.0	3.11	0.13
Mean (mg/L)	277.7	176.7	4.71	0.26
C.V.	0.80	1.20	0.83	1.53

close to one, but not useful if less than 0.5 (Parinet et al. 2004). Bartlett's test of sphericity indicates whether correlation matrix is an identity matrix, which indicates that variables are unrelated. In this study, KMO values are around 0.70 and significance of Barlett's test values are less than 0.05, indicating that the data are suitable for the factor analysis.

The data shown in Table 1 and Fig. 2 were normalized to eliminate the large difference (Ouyang 2005; Zitko

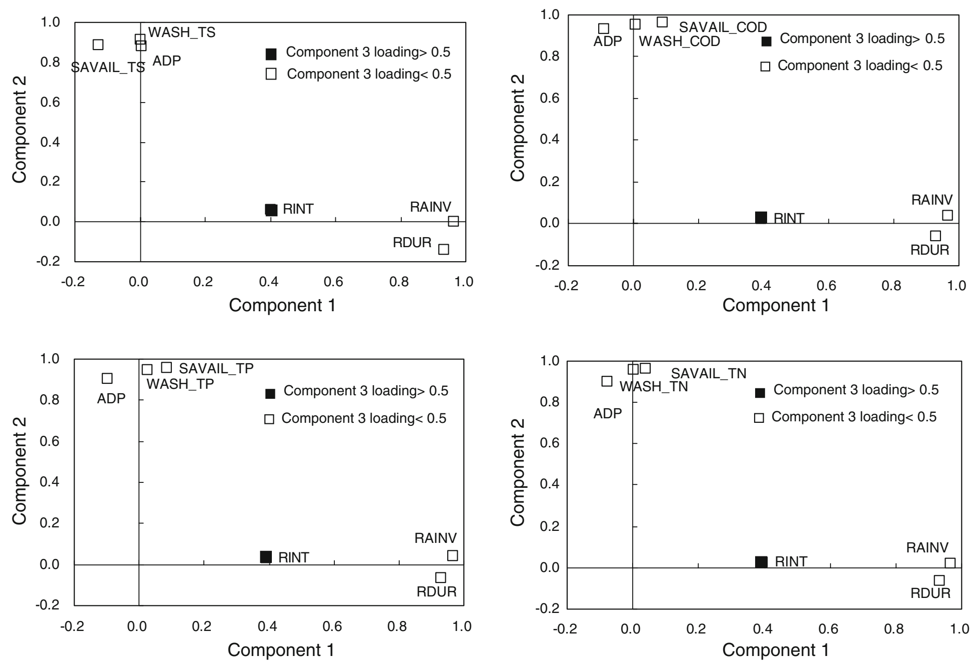

Fig. 3 Results principal factor analysis

2006). The results of the PFA are presented in Fig. 3. The first three factors account for more than 46.4%, 34.4% and 8.5% of the total variance in the data set. It is found that the first factor is significantly related to RAINV and RDUR, while the second is related to WASH, SAVAIL and ADP. The third factor is only related to RINT. Furthermore, the washoff loads of TS, COD, TN and TP (as WASH_TS, WASH_COD, WASH_TN and WASH_TP, respectively) can be expressed by the three factors, as shown in formula (1)–(4). The three factors explain 87.1%, 82.1%, 89.5% and 94.3% of the total variance of the four parameters.

$$\mathrm{WASH\_TS} = 0.001f_1 + 0.914f_2 + 0.188f_3 \quad (1)$$

$$\mathrm{WASH\_COD} = 0.091f_1 + 0.960f_2 - 0.03f_3 \quad (2)$$

$$\mathrm{WASH\_TN} = 0.004f_1 + 0.960f_2 + 0.027f_3 \quad (3)$$

$$\mathrm{WASH\_TP} = 0.027f_1 + 0.950f_2 + 0.002f_3 \quad (4)$$

Multiple regression analysis seeks to determine a relationship between a dependent variable and several independent variables by minimizing the total error between the observed data and the proposed regression relationship. The most important parts of multiple regression analysis are to choose independent variables and the function types. Three statistical indicators were used to examine the regression relationships which are adjusted determination ($\bar{R}^2$) regression significance test (*F*-test) and regression coefficients significance test (*t*-test).

From the above PFA results, it is found that three factors can explain most variance of the washoff load. These three factors represent the influence of the source availability, rainfall volume and rainfall intensity. Therefore ADP, RAINV and RINT are chosen as the initial regression parameters while stepwise method is used so they might be excluded from the equations if the results do not pass the *t*-tests.

Table 3 Multiple regression results

Function expression	$\bar{R}^2$
$\mathrm{WASH\_TS} = \mathrm{ADP}^{1.52} \times \mathrm{RINT}^{1.23}$	0.931
$\mathrm{WASH\_COD} = \mathrm{ADP}^{1.99} \times \mathrm{RAINV}^{1.24}$	0.961
$\mathrm{WASH\_TN} = \mathrm{ADP}^{0.75} \times \mathrm{RINT}^{0.99}$	0.941
$\mathrm{WASH\_TP} = 0.22 \times \mathrm{ADP}^{0.59} \times \mathrm{RINT}^{0.3}$	0.941

Power function was adopted for multiple regression analysis. The regression results and $\bar{R}^2$ are shown in Table 3. All these results have been passed *F*-test and *t*-test.

As shown in Table 3, the power functions provide a well fitness in the analysis. Pollutant source availability, which can be reflected by ADP, shows a strong influence on the pollutants washoff loads. This also correlates well with the PFA results which reveal that the second factor is related to the pollutant source availability (SAVAIL_TS, SAVAIL_COD, SAVAIL_TN and SAVAIL_TP), washoff loads (WASH_TS, WASH_COD, WASH_TN and WASH_TP) and ADP.

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