Available online at www.sciencedirect.com

ScienceDirect

Progress in Natural Science 19 (2009) 873–880

Progress in Natural Science

www.elsevier.com/locate/pnsc

Pollutants in stormwater runoff in Shanghai (China): Implications for management of urban runoff pollution

Siaka Ballo [a], Min Liu [a,*], Lijun Hou [b], Jing Chang [a]

[a] *School of Resources and Environmental Sciences, Key Laboratory of Geographical Information of the Ministry of Education, East China Normal University, Shanghai 200062, China*

[b] *State Key Laboratory of Estuarine and Coastal Research, Shanghai 200062, China*

Received 25 June 2007; received in revised form 15 July 2008; accepted 18 July 2008

Abstract

Runoff samples were collected from four functional areas (traffic, residential, commercial and industrial) and four roof types (old concrete, new concrete, old clay and new clay) in central Shanghai, China, during rain events. The event mean concentrations (EMCs) of three forms of nitrogen (NH_4^+—N,NO_3^-—N,NO_2^-—N) and the temporal variations of total phosphorus (TP) were then measured to evaluate the effects of runoff from different areas on water quality management. The results revealed that the TP levels varied significantly in the samples collected from different functional areas and roof types during rain events. In addition, although the NO_3^-—N and NO_2^-—N concentrations in runoff remained well below the fifth class values of the national surface water quality standards, the NH_4^+—N levels were 1.36, 1.17, 1.10 and 0.85 times higher than the standard value in samples collected from commercial, traffic, industrial, and residential areas, respectively. Similarly, the concentrations of NH_4^+—N in samples collected from old concrete, new concrete, old clay and new clay roofs exceeded the fifth class standard by 6.66, 5.72, 4.32 and 3.32 times, respectively. And the NO_3^-—N levels were 1.86 and 1.53 times higher than the standard values in runoff samples collected from new and old concrete roofs, respectively.

Keywords: Urban stormwater; Pollution; Management implications; Central Shanghai

1. Introduction

Growing urbanization and daily human activities are a large source of pollutants that affect the quality of urban stormwater runoff. Indeed, several studies have reported that stormwater runoff contains nitrogen in concentrations that exceed surface water quality standards [1–3]. In addition, other studies have reported high levels of pollution by nutrient elements, such as nitrogen and phosphorus, and by suspended solids in street runoff [4–7]. In addition, roof runoff is known to be a potential source of nonpoint source pollution because the compounds contained in roof materials and deposited on roof surfaces can leach into the runoff. This effect is exacerbated by the high temperatures that develop on roofs, which increase the rates of chemical reactions and organic decomposition of materials that have accumulated on rooftops [8]. However, although Forster [9] demonstrated that roof runoff was a significant source of trace pollutants, Pazwash and Boswell [10] reported that roof runoff was often nearly free of suspended matter and impurities found in runoff from other surfaces. These contradictory findings indicate that the materials used to construct the roof, as well as its age and the surrounding environment, play an important role in determining the water quality of roof runoff.

Many compounds such as nitrogen and phosphorus are often found at levels higher than the fifth class value defined in the national environmental quality standards for surface water [11]. Therefore, we evaluated the event

* Corresponding author. Tel.: +86 21 62232117; fax: +86 21 62232416.
E-mail address: mliu@geo.ecnu.edu.cn (M. Liu).

1002-0071/$ - see front matter © 2009 National Natural Science Foundation of China and Chinese Academy of Sciences. Published by Elsevier Limited and Science in China Press. All rights reserved.
doi:10.1016/j.pnsc.2008.07.021

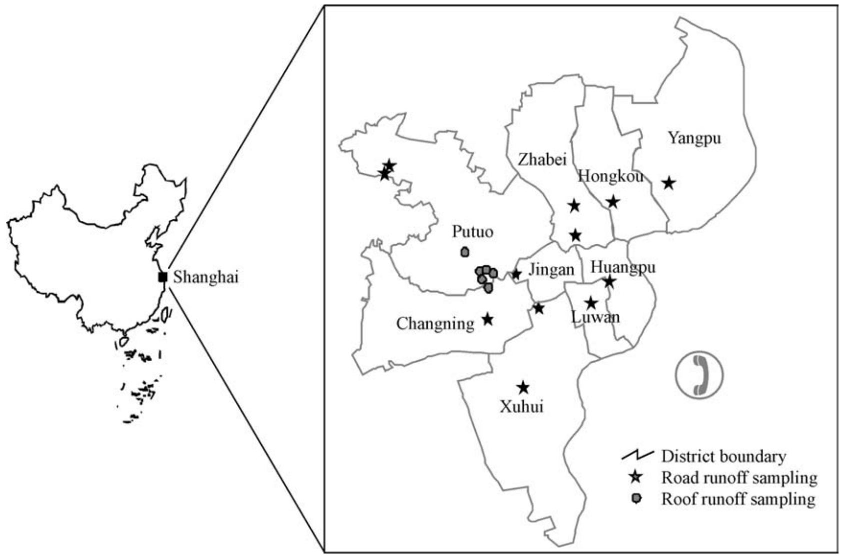

Fig. 1. Sampling locations in Shanghai.

mean concentrations (EMCs) of three forms of nitrogen in runoff and the temporal variations in total phosphorus (TP) in runoff using samples collected from different functional areas (traffic, residential, commercial, and industrial) and from different types of roofs in central Shanghai during rain events. A clear quantification of pollutant concentrations in urban runoff will facilitate development and implementation of the most effective stormwater runoff management practices.

2. Experimental method

2.1. Study area and sample collection

Shanghai is one of the ten largest municipalities in the world. In addition, central Shanghai is densely populated, with approximately 10 million people living in the built-up area surrounded by Shanghai's outer ring road. Land use in central Shanghai includes residential areas (30.5%), industrial areas (8.4%), commercial areas (13.0%), and road surfaces (15.0%). In addition, public facilities such as schools, hospitals, scientific institutions, libraries, and parks account for 10.5% of the total area, while 10.5% of the area is used for agriculture, 2.8% is used for green belts, and the remaining 9.3% is used for miscellaneous purposes [12]. Impervious ground (e.g. pavement) covers approximately 80% of the total area.

In this study, stormwater runoff samples were collected from four different functional areas (traffic, residential, commercial and industrial) and from roofs comprised of four commonly used roofing materials (new and old clay and concrete) in central Shanghai (Fig. 1). The stormwater runoff samples were collected from streets in the functional areas in March, May and June of 2004, whereas the roof runoff samples were collected in February and May of 2004, respectively. Runoff samples were collected manually using 5 L polyethylene buckets to collect the samples at 5-min intervals during each event. Descriptions of the hydrological characteristics of each rainfall event are presented in Table 1.

2.2. Measurements

The concentrations of NH_4^+—N, NO_3^-—N, NO_2^-—N and TP in the runoff samples were analyzed within 24 h according to the methods described by the State Environmental Protection Administration of China [13]. The methods used for the chemical analyses and their detection limits are shown in Table 2. All data shown are the EMC for each nitrogen parameter and the temporal variations for TP. The EMC represents a flow-weighted average concentration computed as the total pollutant mass divided by the total runoff volume for an event of duration t_r and is described by the following equation [14]:

$$\mathrm{EMC} = \frac{M}{V} = \frac{\int_0^t Q_t C_t \,\mathrm{d}t}{\int_0^t Q_t \,\mathrm{d}t} = \frac{\sum C_t Q_t \Delta f}{\sum Q_t \Delta t} \quad (1)$$

Table 1
Hydrologic description of rain events sampled in 2004.

Event (date)	Rainfall depth (mm)	Duration (min)	Mean intensity (mm/5 min)	Maximum intensity (mm/5 min)	Time since last rain (h)
2004-02-21	21.01	45	1.8	5.3	72
2004-03-21	8.84	75	0.68	2.1	25
2004-05-21	36.57	70	3.1	7.6	144
2004-06-24	27.18	50	2.6	6.2	146

Table 2
Methods of analyses used to evaluate stormwater runoff pollutants.

Pollutant	Test method (SEPAC, 2002)	Detection level
NH_4^+—N	Nessler's reagent colorimetric method	0.025–2 mg/l
NO_3^-—N	Copper-cadmium reduction method	0.02–2 mg/l
NO_2^-—N	Spectrophotometric method	0.003–0.2 mg/l
TP	Ammonium molybdate spectrophotometric method	0.01–0.6 mg/l

where M is the total mass of pollutants over the entire event duration (g); V is the total volume of flow over the entire event duration (m^3); t represents time (min); C_t is the concentration of a pollutant (mg/l); Q_t is the variable flow (m^3/min); and Δt is a discrete time interval (min). The EMC was computed for the entire runoff duration of each event.

3. Results and discussion

3.1. Variation in total phosphate concentrations of runoff during rain events

The temporal variations in the TP concentrations of runoff from different functional areas and roofs are shown in Figs. 2 and 3. The results indicated that the temporal variations in the TP concentrations during runoff events differed in samples collected from different functional areas and roofs. In addition, as shown in Fig. 2(a)–(c), the TP concentrations remained irregular throughout the duration of each rainfall event. For example, the concentrations of TP in March runoff samples collected from industrial areas were 2.58 mg/l, 1.29 mg/l and 2.25 mg/l at 5 min, 25 min and 45 min, respectively, while they were 1.15 mg/l, 3.02 mg/l and 1.22 mg/l at 2 min, 15 min and 35 min, respectively, in the samples collected from commercial areas. This variability was also reflected in the TP concentrations of runoff samples collected from traffic areas in May, with values of 1.11 mg/l, 0.47 mg/l and 1.13 mg/l observed at 2 min, 20 min and 35 min, respectively. Similar variations in TP concentrations were observed in the runoff samples collected in June as well as in the roof runoff samples (Fig. 3). However, the extent of the variation in the TP concentrations of samples collected from road and roof runoff differed during each rain event. Based on the concentrations of TP in the road and roof runoffs, it is likely that the sampling time, amount of pollutant accumulation between storm events, storm intensity and duration, and runoff volume were responsible for the differences observed in the level of pollution in samples collected during different rain events.

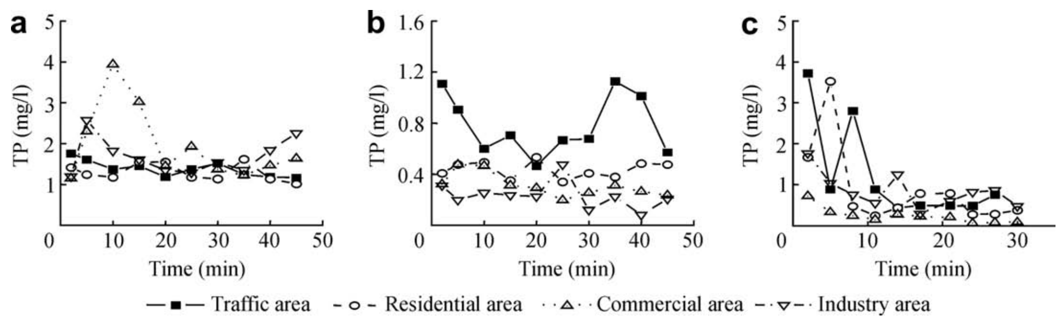

Fig. 2. Temporal variation of TP in runoff from different functional areas. (a), (b) and (c) represent March, May and June data, respectively.

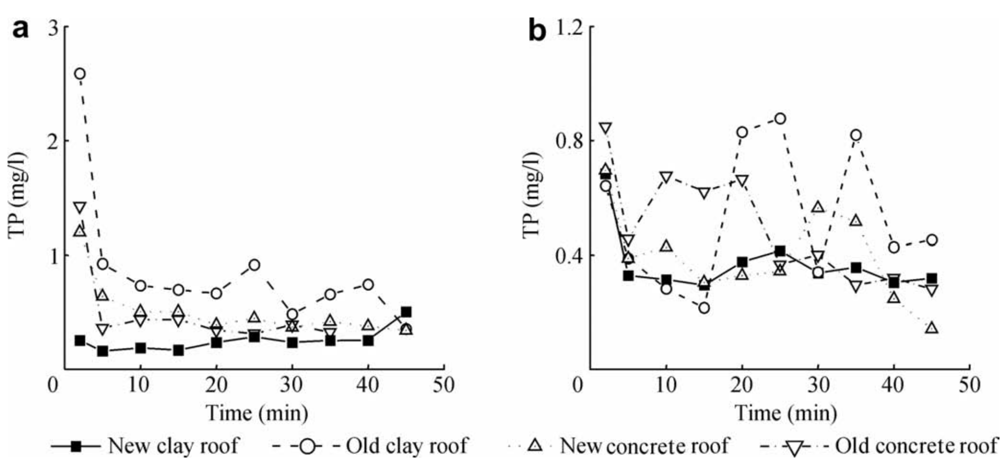

Fig. 3. Temporal variation of TP in runoff from different types of roofs. (a) and (b) represent data of March and May, 2004, respectively.

Table 3
EMC values of pollutants in runoff samples collected from different functional areas in Shanghai (mg/l).

Event date	Site	NH_4^+—N	NO_3^-—N	NO_2^-—N	TP
2004-02-21	Traffic area	2.7	0.23	0.16	0.39
	Industrial area	4.05	0.36	0.31	0.69
	Commercial area	3	0.18	0.15	1.95
	Residential area	2.38	0.37	0.15	1.3
2004-03-21	Traffic area	2.05	0.87	0.43	0.81
	Industrial area	1.04	0.25	0.09	0.26
	Commercial area	0.82	0.45	0.17	0.37
	Residential area	1.64	0.62	0.24	0.44
2004-06-24	Traffic area	2.32	0.34	0.23	1.2
	Industrial area	1.54	0.71	0.17	0.85
	Commercial area	3.34	0.34	0.05	1.37
	Residential area	1.09	0.23	0.14	0.41

3.2. EMC of pollutants in runoff from different functional areas

NH_4^+—N was consistently the most abundant form of nitrogen in stormwater runoff collected from the four functional areas. However, the NH_4^+—N concentration varied among the land-use types over time (Table 3, Fig. 4(a)). For this study, the average levels of NH_4^+—N in the four functional areas are described in terms of multiples of the fifth class standard for surface water [11]. The concentration of NH_4^+—N was 1.36, 1.17, 1.10 and 0.85 times higher than the value of the standard in runoff from commercial areas, traffic areas, industrial areas, and residential areas, respectively. These values are also higher than the values reported in several studies conducted in other countries (Table 5). For example, the concentration of NH_4^+—N in road runoff collected in this study was 2.6 times that reported in a study conducted in Germany [15]. In addition, the concentrations of NH_4^+—N observed in the present study were higher than those reported in a study of runoff in Atlanta and Washington [16].

The NO_3^-—N and NO_2^-—N pollution levels were well below the fifth class value defined by the national surface water quality standards in all samples (Table 3 and

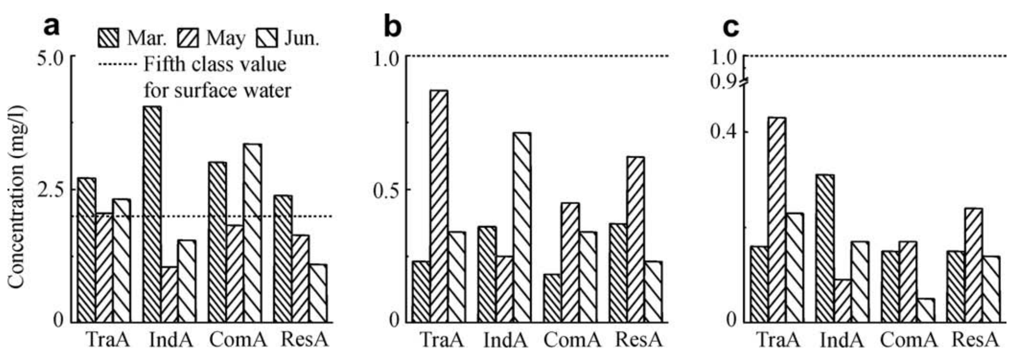

Fig. 4. EMC values for NH_4^+—N (a), NO_3^-—N (b) and NO_2^-—N (c) in runoff from different functional areas. The fifth class values of NH_4^+—N, NO_3^-—N and NO_2^-—N for surface water are 2 mg/l, 1 mg/l and 1 mg/l, respectively; TraA, traffic area; IndA, industrial area; ComA, commercial area; ResA, residential area.

Table 4
EMC values of pollutants in runoff samples collected from roofs constructed from different materials in Shanghai (mg/l).

Event date	Site	NH_4^+—N	NO_3^-—N	NO_2^-—N	TP
2004-03-21	New concrete roof	10.87	1.77	0.24	0.45
	Old concrete roof	17.61	1.41	0.31	0.4
	New clay roof	5.38	0.75	0.04	0.24
	Old clay roof	4.9	0.53	0.29	0.62
2004-05-21	New concrete roof	12.04	1.96	0.1	0.46
	Old concrete roof	9.05	1.65	0.4	0.65
	New clay roof	7.92	0.4	0.01	0.16
	Old clay roof	12.02	1.01	0.32	0.15

Table 5
Data comparison with the results of several international studies (mg/l).

Location	NH_4^+—N	NO_3^-—N	NO_2^-—N	Data sources
Shanghai	2.35	0.64	0.25	Present study
Atlanta	0.18	0.25	–	Stanley [16]
Washington	0.26	0.48	–	Stanley [16]
Germany	0.9	–	–	Geiger [15]

Fig. 4(b), (c)). However, there were differences in the concentrations of the three forms of nitrogen collected from different areas during different events. These differences may result from several reasons, including differences in the efficiency of the drainage system where the samples were collected from and the point-source inputs. In addition, the spatial distribution of impervious areas in the land-use types differs, which may have influenced the duration and velocity of surface runoff, and hence the pollutant load [17].

For these reasons, the difference in the quantities of NH_4^+—N, NO_3^-—N and NO_2^-—N in different areas may be explained by the nature of the specific activities in each area. On average, the highest concentration of NH_4^+—N was observed in the commercial areas of Shanghai, which had an average concentration of 2.39 mg/l, or 1.19 times the fifth class standard for surface water. The traffic areas, industrial areas and residential areas had concentrations of NH_4^+—N that were 1.17, 1.10 and 0.85 times greater than the fifth class standard for surface water. However, the highest concentrations of NO_3^-—N and NO_2^-—N were observed in the traffic areas. This is likely due to the number of people who use these areas and the complexity of the activities that occur in these areas. For example, the high levels of traffic in these areas create NO_x compounds, whereas waste generation by small businesses such as restaurants, shops, as well as large shopping malls in commercial areas is suspected to be an important source of nonpoint pollutants.

3.3. EMC of pollutants in runoff from different roof materials

In February, the highest EMC of NH_4^+—N in roof runoff was observed in samples collected from concrete roofs, while the lowest levels were observed in the samples collected from old clay roofs (Table 4 and Fig. 5(a)). However, in May, the highest EMC of NH_4^+—N in roof runoff was observed in samples collected from old clay roofs and the lowest level was observed in samples collected from new clay roofs (Table 4 and Fig. 5(a)). Overall, the highest concentrations were observed in samples collected from old concrete roofs, followed by roofs comprised of new concrete, new clay and old clay. In addition, the mean NH_4^+—N concentrations of samples collected from concrete and clay roofs exceeded the fifth class standard for surface water. Specifically, the mean NH_4^+—N concentration of old concrete roofs was 6.66 times the fifth class value, whereas the concentrations of samples collected from new concrete roofs, old clay roofs and new clay roofs were 5.72, 4.32 and 3.32 times greater than the standard value (Table 4 and Fig. 5(a)). Additionally, the highest EMC of NH_4^+—N differed significantly between samples collected in February and May (e.g. 17.61 mg/l versus 12.04 mg/l). These differences may have occurred due to the nature of the roofing materials and the time interval between rain events. The mean concentration of NO_3^-—N also exceeded the values of the standard in some cases. For example, the mean concentrations of runoff samples collected from new and old concrete roofs were 1.86 and 1.53 times greater than the standard value (Table 4 and Fig. 5(b)). Conversely, the NO_2^-—N concentration levels remained well below the fifth class value for surface water at all sampling times (Table 4 and Fig. 5(c)). These findings suggest that, at present, efforts to monitor this pollutant can be focused on preventive measures.

The contamination of roof stormwater runoff can occur for several reasons, including leaching of compounds present in the roofing materials and airborne pollutants and organic materials such as leaves and bird droppings [18] being deposited on roofs with subsequent contaminating runoff. In addition, the age of the roofing materials, as well as the orientation of the roof and the surrounding environment may degrade the quality of roof runoff. In the present study, roof runoff was found to contain a much higher concentration of pollutants than road runoff. This may have occurred due to differences in the sampling time and the nature of the roofs. However, further studies are necessary to better understand the reasons for these differences. In a

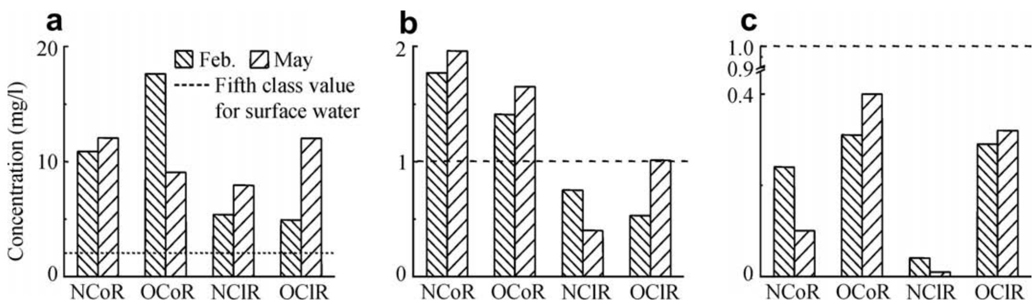

Fig. 5. EMC values for NH_4^+—N (a), NO_3^-—N (b) and NO_2^-—N (c) in runoff from different types of roofs. The fifth class values of NH_4^+—N, NO_3^-—N and NO_2^-—N for surface water are 2 mg/l, 1 mg/l and 1 mg/l, respectively; NCoR, new concrete roof; OCoR, old concrete roof; NClR, new clay roof; OClR, old clay roof.

study conducted in Australia, the concentrations of various constituents of roof runoff were reported to exceed the World Health Organization (WHO) drinking water quality standards [19]. Taken together, these findings suggest that roof runoff is a potential source of nonpoint pollution that is capable of degrading the water quality of rivers and lakes.

3.4. First flush effects

The measured EMC values of the three forms of nitrogen and the TP at various time points were converted into percentages of the total cumulative mass and total cumulative runoff volume. These values were then used to evaluate the first flush effects of pollutant levels in the runoff from different roof types and functional areas [20,21]. All sampling sites are located in small impervious surface area catchments; therefore, the runoff coefficient average is estimated to be 0.97. This phenomenon is well established in the literature and is related to saturation of the site [14,15]. The runoff volumes used in this study were then calculated as a function of total rainfall volume using the following equation:

$$\text{Runoff volume} = \text{rainfall volume(or depth)} \times \text{surface area} \times \text{runoff coefficient} \quad (2)$$

This analysis of the first flush effect was based on the relationship between the cumulative mass curve and the cumulative runoff volume curve. The percentage deviation of the curve from the diagonal ($y = x$) then serves as a reference for the strength of the first flush [20]. The magnitude of the first flush phenomenon was found to be greater for high intensity rainfall events and for some pollutants such as NO_3^-—N and TP [22,23].

Most of the pollutants evaluated here showed values greater than the diagonal, which indicates that first flush effects were impacting the levels of pollutants in the runoff from roofs. The most dramatic first flush effects for NH_4^+—N, NO_3^-—N and TP occurred on old concrete and clay roofs (Fig. 6). The magnitude of the first flush effects was weaker in road runoff, and the phenomenon was not observed for some pollutants (Fig. 7). Taken together, our data suggest that there are specific combinations of site and storm conditions that result in first flush effects. It is important to note that this phenomenon was investigated using the data collected at different times (roads in June and roofs in February). As a result, the differences in the duration and volume of rainfall reported here may have impacted the magnitude of the first flush effects.

3.5. Implications for the management of stormwater runoff

The results of the present study indicate that the pollutant concentrations in stormwater runoff from the four functional areas and from both categories of concrete roofs exceeded the fifth class value of the surface water quality standards. Furthermore, these pollutant levels were higher than those selected international results (Table 4) [16,20]. These findings clearly indicate the need for stormwater management systems that are designed to protect and improve water quality in Shanghai. Since mitigation practices can be implemented to improve stormwater quality, we will describe the mitigation plans that are most practical for Shanghai here.

The results of this study revealed an obvious first flush effect on the pollutants in the runoff, indicating that pollutant concentrations are much higher at the beginning of a

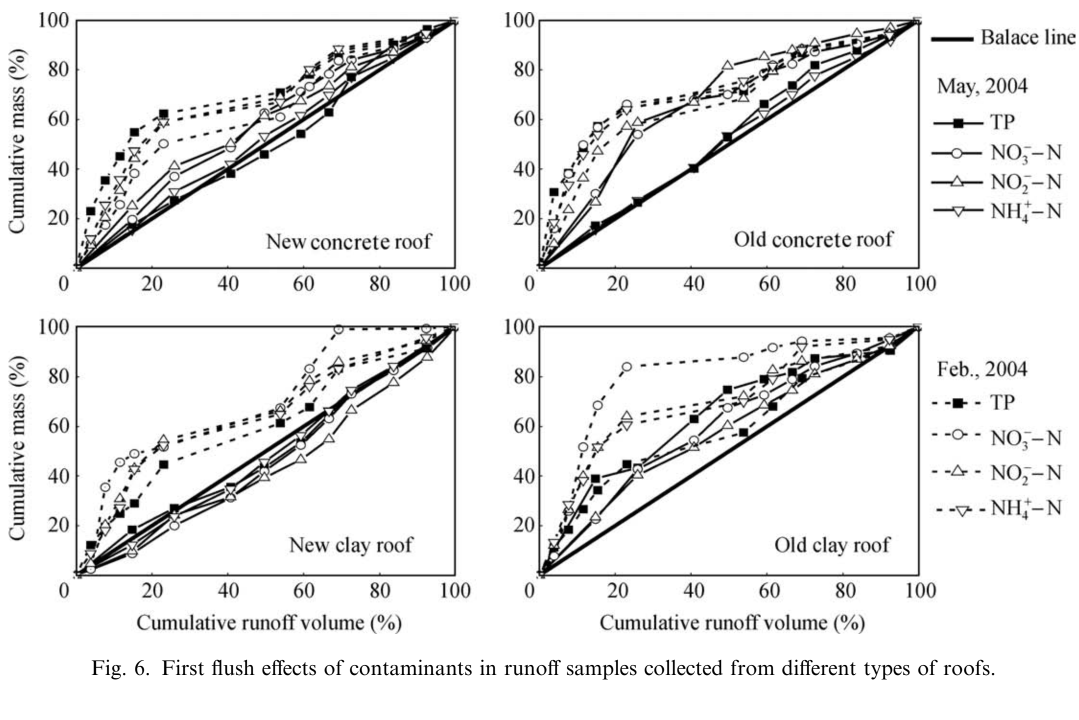

Fig. 6. First flush effects of contaminants in runoff samples collected from different types of roofs.

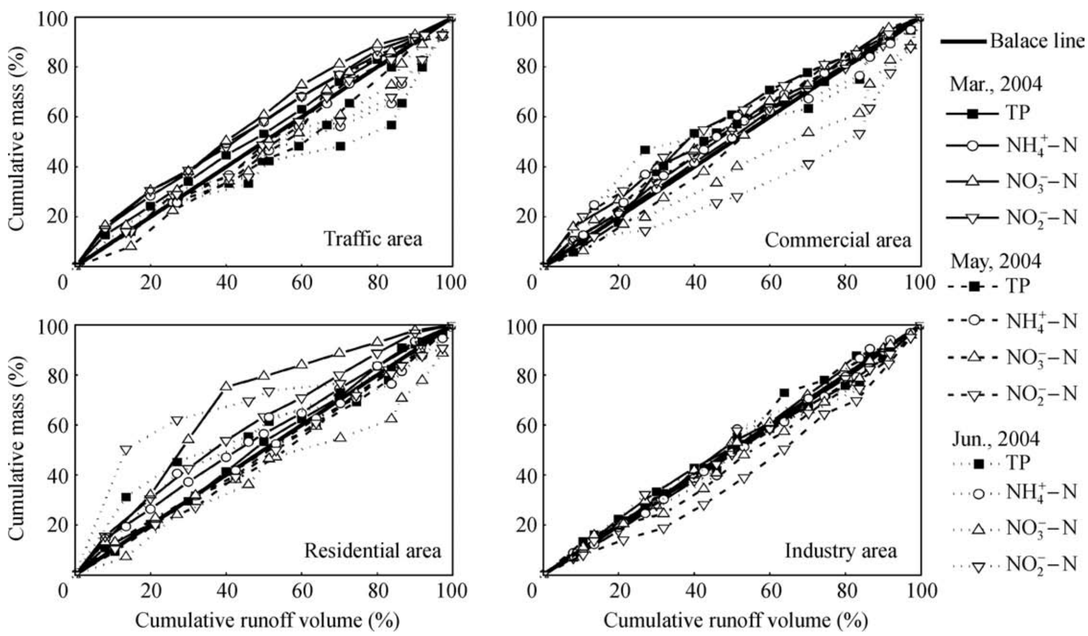

Fig. 7. First flush effects of nitrogen and TP in runoff samples collected from different functional areas.

storm event [24]. As a result, the best management practices (BMPs) for dealing with this problem must include the storage and treatment of first flush runoff water produced by rain events.

Filtering runoff water through appropriate vegetation could remove most of the nutrients from the water. In addition, soil filtration techniques can be utilized to provide both biological and chemical treatments of the runoff. Indeed in one study, the conversion of water-retention tanks into soil filtration tanks increased the system's capacity to control the quantity and pollutant concentration of discharged water [25]. In addition, the concentration of pollutants in stormwater could be reduced significantly by implementing street sweeping using vacuum devices that collect finer particles of dust from roads and parking lots. Finally, compliance with existing regulations could be improved by implementing education programs that explain the regulations designed to protect bodies of water and the rules designed to enforce such regulations to the residents of Shanghai.

4. Conclusions

The results of this study emphasize the importance of managing nonpoint-source emissions from roads and roofs in Shanghai. NH_4^+—N pollution was the most serious problem in all four urban land-use types, as well as in samples collected from all four types of roofing materials evaluated in this study. In addition, high levels of NO_3^-—N were observed in runoff from new and old concrete roofs. Furthermore, clear first flush effects existed for roof runoff. However, contaminant concentrations and the extent of first flush effects differed among land-use types and roofing materials. Taken together, our data suggest that more intensive monitoring of NH_4^+—N and TP should be conducted because both these compounds were present at levels greater than the fifth class value of the surface water quality standards. The effectiveness of various mitigation practices could then be assessed based on their ability to control the levels of these pollutants.

It is important to note that the results of the present study are based on a small sample size in terms of both the number of sampling locations and the duration of the study. Therefore, the data generated here should be considered as a means of guiding the development of a subsequent study to provide more detailed data describing the pollution in stormwater runoff in Shanghai.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant Nos. 40730526 and 40671171). The authors thank Mr. Geoff Hart and Mr. Lin Xiao for their valuable contributions to this work.

References

[1] Field R, Pitt RE, Fan C, et al. Urban wet-weather flows. Water Environ Res 1998;69(4):426–44.

[2] Chang J, Liu M, Wang H, et al. Temporal-spatial distribution and first flush effect of urban stormwater runoff pollution in Shanghai City. Geographical Res 2006;25(6):994–1002, [in Chinese].

[3] Lee JH, Bang KW. Characterization of urban stormwater runoff. Water Resources 2000;34(6):1773–80.

[4] Gromaire-Mertz MC, Garnaud S, Gonzalez A, et al. Characterisation of urban runoff pollution in Paris. Water Sci Technol 1999;39(2): 1–8.

[5] Sartor JP, Boyd G. Water pollution aspects of street surface contaminants. In: EPA-R2-72-081, US. Washington DC, USA: Environmental Protection Agency; 1972.

[6] Astruc A, Astruc M, Beguin S, et al. Qualité chimique des eaux de ruissellement d'une ville moyenne. T.S.M. L'Eau. 1979;74(2):79–85, [in French].
[7] Duncan HP. Urban stormwater quality: a statistical overview (Report 99/3). Melbourne, Australia: Cooperative Research Center for Catchment Hydrology; 1999.
[8] Chang M, Crowley CM. Preliminary observations on water quality of storm runoff from four selected residential roofs. Water Resources Bull 1993;29:777–83.
[9] Forster J. Patterns of roof runoff contamination and their potential implications on practice and regulation of treatment and local infiltration. Water Sci Technol 1996;33(6):39–48.
[10] Pazwash H, Boswell ST. Management of runoff conservation and reuse. In: Proceedings of the 24th annual water resource planning and management conference. ASCE: Houston, TX; 1997. p. 784–9.
[11] GB 3838-2002, Environmental quality standards for surface water (EQSSW), China.
[12] Renwei R, Yang Z, John M, et al. Urbanization, land use, and water quality in Shanghai 1947–1996. Environ Int 2003;29:649–59.
[13] State Environmental Protection Administration of China. Analyse methods for monitoring water and wastewater. Environmental Science Press in China; 2002. p. 836.
[14] Sansalone JJ, Buchberger SG. Partitioning and first flush of metals in urban roadway stormwater. J Environ Eng ASCE 1997;123(2):134–43.
[15] Geiger W. Flushing effects in combined sewer systems. Urban Storm Drainage, Lausanne, Switzerland 1987;4:40–6.
[16] Stanley DW. Pollutant removal by stormwater dry detention pond. Water Environ Res 1996;68(6):1076–83.
[17] Ashantha G, Evan T, Simon G, et al. Understanding the role of land use in urban stormwater quality management. J Environ Manage 2005;74:31–42.
[18] Mingteh C, Matthew W, Scott BR. Roofing as a source of nonpoint pollution. J Environ Manage 2004;73:307–15.
[19] Thomas PR, Greene GR. Rainwater quality from different roof catchments. Water Sci Technol 1993;28:291–9.
[20] Gupta K, Saul AJ. Specific relationships for the first flush load in combined sewer flows. Water Res 1996;30:1244–52.
[21] Lee JH, Bang KW, Ketchum LH, et al. First flush analysis of urban storm runoff. Sci Total Environ 2002;293:163–75.
[22] Geoff DT, Tim DF, Tony HFW, et al. Nitrogen composition in urban runoff-implication for stormwater management. Water Res 2005;39:1982–9.
[23] Deletic A. The first flush load of urban surface runoff. Water Res 1998;32(8):2462–70.
[24] Barrett ME, Zuber RD, Collins III ER, et al. A review and evaluation of literature pertaining to the quality and control of pollution from highway runoff and construction. Technical Report CRWR 239, Center for Research in Water Resources, The University of Texas at Austin; 1995.
[25] Sieker H, Klein M. Best management practices for stormwater-runoff with alternative methods. In a large urban catchment in Berlin, Germany. Water Sci Technol 1998;38(10):91–7.