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RESEARCH ARTICLE

Phosphorus loads from different urban storm runoff sources in southern China: a case study in Wenzhou City

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Abstract Storm runoff from six types of underlying surface area during five rainfall events in two urban study areas of Wenzhou City, China was investigated to measure phosphorus (P) concentrations and discharge rates. The average event mean concentrations (EMCs) of total phosphorus (TP), total dissolved phosphorus (TDP), and particulate phosphorus (PP) ranged from 0.02 to 2.5 mg·L^{-1}, 0.01 to 0.48 mg·L^{-1}, and 0.02 to 2.43 mg·L^{-1}, respectively. PP was generally the dominant component of TP in storm runoff, while the major form of P varied over time, especially in roof runoff, where TDP made up the largest portion in the latter stages of runoff events. Both TP and PP concentrations were positively correlated with pH, total suspended solids (TSS), and biochemical oxygen demand (BOD)/chemical oxygen demand (COD) concentrations ($p<0.01$), while TDP was positively correlated with BOD/COD only ($p<0.01$). In addition, the EMCs of TP and PP were negatively correlated with maximum rainfall intensity ($p<0.05$), while the EMCs of TDP positively correlated with the antecedent dry weather period ($p<0.05$). The annual TP emission fluxes from the two study areas were 367.33 and 237.85 kg, respectively. Underlying surface type determined the TP and PP loadings in storm runoff, but regional environmental conditions affected the export of TDP more significantly. Our results indicate that the removal of particles from storm runoff could be an effective measure to attenuate P loadings to receiving water bodies.

Keywords Phosphorus · Event mean concentrations (EMCs) · Composition · Storm runoff · Underlying surface · Emission flux

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Introduction

Impermeable surface area increases rapidly with urbanization, leading to many urban drainage problems, and urban storm runoff has become an important pollution source that cannot be ignored (Brezonik and Stadelmanm 2002; Taylor et al. 2005). Urban storm runoff from different underlying hard-surface types, such as roads, roofs, and parking lots, can deliver high pollutant loads, including solids, nutrients, heavy metals, oils, hydrocarbons, oxygen-demanding substances, and bacteria (Gromaire-Mertz et al. 1999; Zhao et al. 2007). In the USA, it has been reported that urban storm water had become the third largest pollution source for about 50 % of 129 major pollutants observed in urban storm runoff to national rivers and lakes (US EPA 1995). Of all pollutants, nutrients such as nitrogen (N) and phosphorus (P) have received the most attention due to their role in eutrophication (Smith et al. 1999; Conley et al. 2009). Moreover, P is regarded as more important than N in aquatic ecosystems based on Liebig's law of minimum, in relation to the limiting nutrient principal (Wetzel 2001; Lai and Lam 2009).

Total phosphorus (TP) in surface runoff can typically be divided into total dissolved phosphorus (TDP) and particulate phosphorus (PP) by filtration at 0.45 μm (Abu-Zreig et al. 2003). TDP includes orthophosphate, inorganic polyphosphates, and organic P, while PP normally includes sorbed P, organic P, and mineral P phases (McDowell and Sharpley 2001). Many

studies have reported TP concentrations in urban runoff, their variation and potential influences (Gilbert and Clausen 2006; Li et al. 2007; Roberts et al. 2009), but there is less on TP composition (Taylor et al. 2005). Moreover, different best management practices are required to treat different P compounds in urban storm runoff (Hanzlik et al. 2004; Hogan and Walbridge 2007). Thus, a clear quantification of different P compounds in urban runoff will facilitate the development and implementation of the most effective runoff management practices. The aims of this study were to (1) reveal the variations in P concentration and composition over time in urban storm runoff from different sources; (2) discuss the potential confounding influences on P concentrations; and (3) estimate the annual emission fluxes of P from different storm runoff sources.

Materials and methods

Study area description

Wenzhou (27°03′–28°36′ N, 119°37′–121°18′ E) is a typical coastal city in southern China. The land area of Wenzhou is 11,784 km^2 with an urban area of 1,187 km^2. There are three major river systems in Wenzhou, the Ou Jiang, Feiyun Jiang, and Ao Jiang. These river systems consist of more than 150 rivers and streams including the Wenruitang River, Nanxi Jiang, Qing Jiang, and Xupu Jiang, to name but a few. Wenzhou is located in the central Asian tropical monsoon climate zone, and northerly winds from the mainland prevail in winter, while southerly winds from the Pacific Ocean dominate in summer. It is, thus, cool with less rain in winter, and hot with greater rainfall in summer. On average, rain falls on nearly half the days of a year (175 days), and annual precipitation ranges from 1,225 to 2,061 mm with an average of 1,706 mm.

Two contrasting study areas were chosen in the urban district of Wenzhou city. The Jiushanwai River (JS) study area (28°0′30″–28°1′20″ N, 120°38′00″–120°39″00″ E) is in the western part of Wenzhou and has a total area of 0.3389 km^2, and the Shanxia River (SX) study area (27°59′50″–28°0′30″ N, 120°41′10″–120°42″00″ E) is on the east and has a total area of 0.3982 km^2. Monitoring sites provided samples from five underlying surface types: busy main road (M), parking lot (P), community road (C), roof (R), lawn (L), as well as the storm sewer runoff outlet (O).

Sample collection and treatment

The first flush effect of pollutants in storm runoff (Bach et al. 2010; Kus et al. 2010) can cause elevated and rapidly changing pollutant concentrations in the initial runoff response; consequently, a sampling mode with unequal intervals was adopted. Samples were taken at 5-min intervals for the first 30 min; every 10 min for the second 30 min; at 20-min interval for the second hour, and thereafter every 30 min, until runoff ceased. Five typical rainfall events were sampled during August and September 2010. Samples were mainly collected by hand using 1-L axenic polyethylene bottles at rainwater wells. Runoff volumes at each sampling interval were also measured using a 5-L measuring cup, and the extra runoff was given up after determination.

Sample pH was measured using a precision-type pH meter (pHS-3C, Shanghai Precision & Scientific Instrument Co., LTD, China; measurement accuracy 0.01). An aliquot of each sample was membrane filtered at 0.45 μm prior to analyses for TSS and TDP. Sample TSS, BOD_5, and COD_{Cr} concentrations were quantified following standard methods (APHA 1999). TP and TDP concentrations in filtered and unfiltered samples were analyzed following the ammonium molybdate spectrophotometric method (Ebina et al. 1983). PP was calculated from the mass difference of TP and TDP concentrations. Standard solutions were also tested to confirm analytical accuracy; recovery rates ranged from 96.6 to 102.2 %.

Results

P concentration variation over time and between runoff source areas

Precipitation totals for each of the five sampled events ranged between 1.6 and 48 mm (Table 1), and from light rainfall to storms, as classified by Chinese national standards for 24-h precipitation intensity.

TP, TDP, and PP concentrations in runoff from the various underlying surfaces ranged from 0.01 to 4.32 $mg \cdot L^{-1}$, ND to 0.88 $mg \cdot L^{-1}$, and ND to 4.31 $mg \cdot L^{-1}$, respectively. TP concentrations were similar to those for Xiamen City (Wei et al. 2010), and higher than from downtown Shanghai

Table 1 Characteristics of rainfall events in two study areas

Date	Study area	Dur/ min	Pre/ mm	Max int/ $mm \cdot min^{-1}$	Mean int/ $mm \cdot h^{-1}$	AWDP/ day
August 18	JS	260	4.8	0.24	1.1	7
	SX	450	6.8	2.72	0.9	7
August 30	JS	180	1.6	0.36	0.5	1
	SX	1125	7.5	0.11	0.4	1
September 01	JS	257	48	1.59	11.2	0.5
	SX	543	27.2	0.55	3.0	0.5
September 26	JS	1261	4.2	0.02	0.2	4
	SX	3022	13.6	2.40	0.3	4
September 28	JS	727	4	0.14	0.3	0.5
	SX	742	3.8	0.80	0.3	0.5

Dur duration, *Pre* precipitation, *int* intensity, *AWDP* Antecedent Dry Weather Period

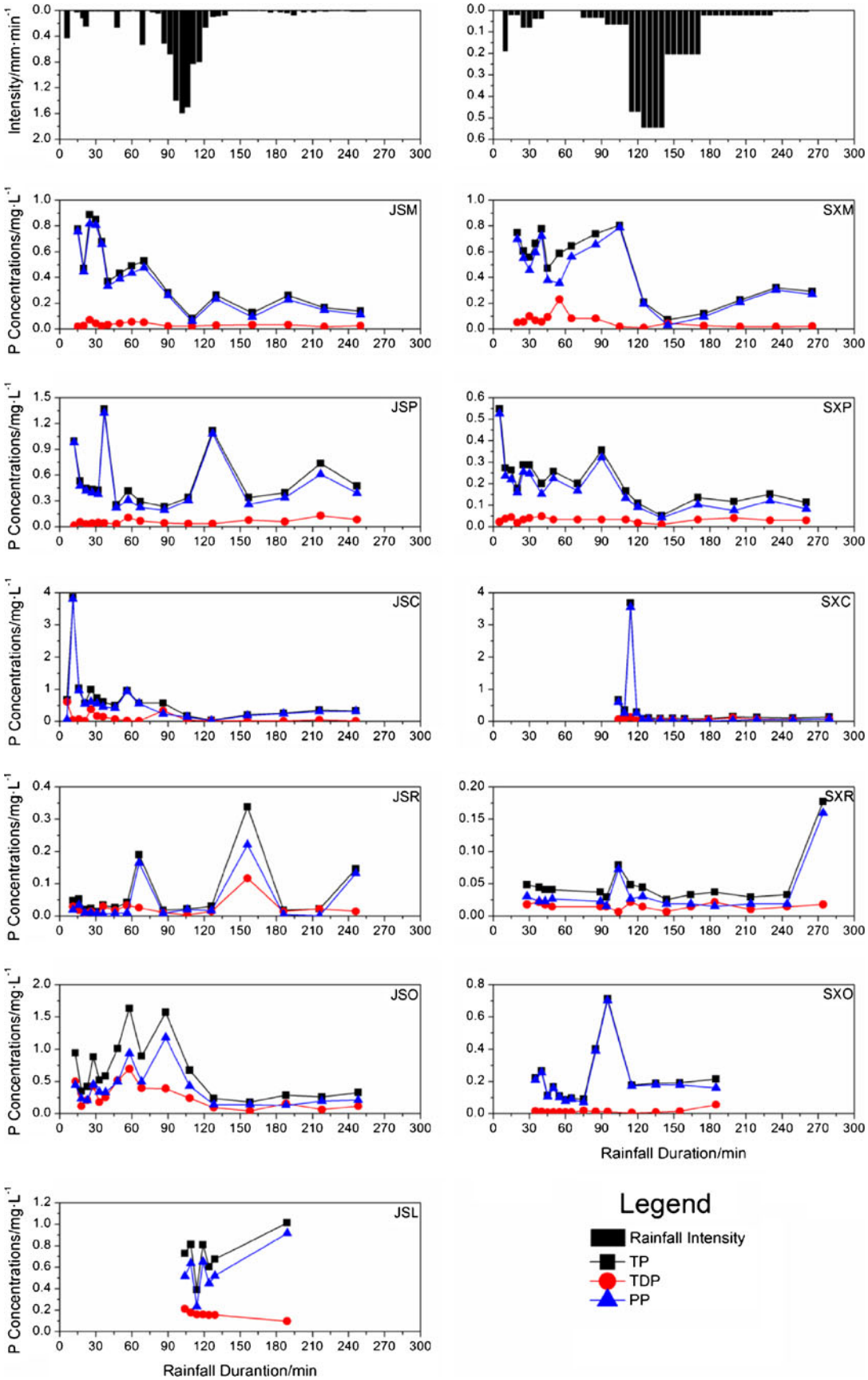

Fig. 1 Variations of TP, TDP, and PP concentrations over rainfall duration in the rainfall event which occurred in September 1, 2010

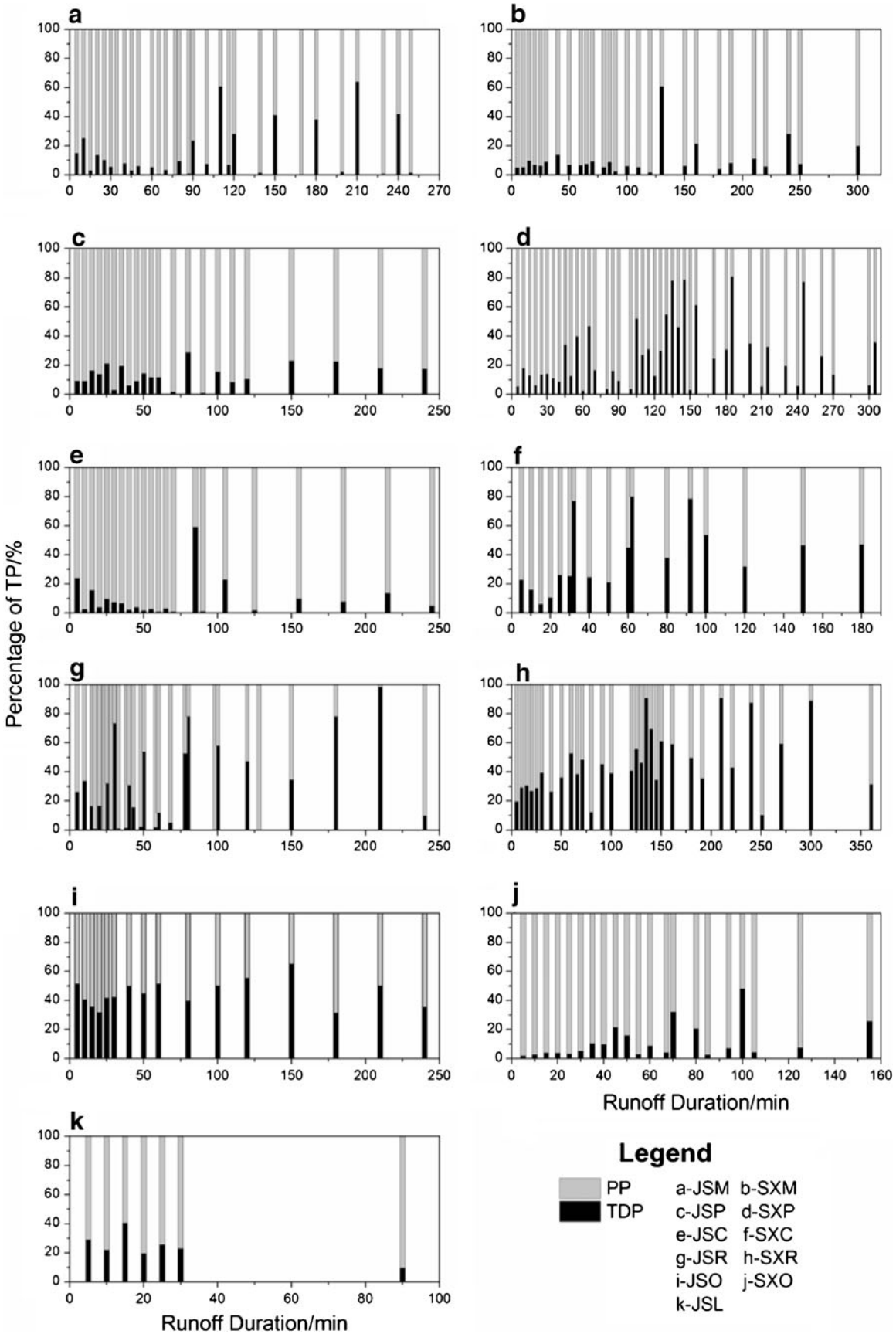

Fig. 2 Change trend of P composition over runoff duration in different urban runoff in Wenzhou

(Ballo et al. 2009), but less than residential and industrial zone runoff in Korea (Lee and Bang 2000).

From most urban runoff sources, TP and PP concentrations had significantly fluctuating declining trends over the duration of rainfall events, whereas TDP was relatively constant due to its consistently low concentration. Take the rainfall event of September 1, 2010 (Fig. 1) for example, following the onset of urban runoff, TP and PP concentrations were initially relatively high and changed sharply with time. Subsequently, their concentrations decreased; this was due to dilution, especially when the rainfall intensity reached its peak (about 100 min after the start of rainfall in the JS study area, and after 120 min in SX study area). In the latter phase of the runoff event, TP and PP concentrations increased slightly when the runoff rate had declined.

Lawn runoff was quite different in quality compared with runoff from the impermeable underlying surfaces. Lawn did not easily produce runoff; this was due to its high percolation coefficient, and only one set of lawn runoff samples was collected from the five rainfall events. When lawn runoff did occur, it took longer to accumulate enough rainwater for runoff to occur, and the duration of runoff was shorter than for the other sources (Fig. 1).

Variations in P partitioning between dissolved and particulate phases

In the initial stage of runoff (from all sources), PP was the large component of TP (average, 75.80 %), compared with TDP (Fig. 2). Generally high rainfall intensity, and the presence and wash-off of accumulated particulate pollutants, resulted in runoff carrying high sorbed and mineral P, as observed elsewhere (McDowell and Sharpley 2001).

However, the composition of TP changed in the middle and later stages of the runoff events with less PP, and more TDP, especially in roof runoff (Fig. 2g, h). The reduced availability of solids accumulations for wash-off might be a reasonable explanation for this. Compared with other source surfaces, roof is unfavorable for the accumulation of solids in dry weather due to its distance above ground. A similar situation was observed in JSO runoff (Fig. 2i). This can be explained by the special sedimentary environment found in sewers (Michelbach 1995). Flow velocity slows when runoff enters sewers, some suspended solids get deposited, and a portion of sediment adsorbed P returns to runoff as DP, especially in long sewers (Lee et al. 1989). This was not the case for SXO runoff because of its short sewer length (approximately 5 m from the water wells to the outlet).

EMC of P in different urban storm runoff

EMC was first proposed in the 1980s by the US EPA as a single index to characterize the mean pollutant concentration in a single rainfall event (Novotny and Olem 1994; Sansalone and Buchberger 1997). Essentially, EMC is the weighted average of the instantaneous pollution concentration over the whole period of runoff in a single rainfall event, which is the ratio of total pollution load and total runoff, and can be calculated using the following equation:

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

where, EMC is the event mean concentration (milligrams per liter); M is the total load of pollutant in one rainfall event (milligrams); V is the total runoff quantity in one rainfall event (liter); t represents time (minutes); C_t is the pollutant concentration at time t (milligrams per liter); Q_t is the runoff flow rate at time t (liters per minute); Δt is the interval time (minutes).

Based on the P concentrations and runoff volumes at each sampling interval, the EMCs of TP, TDP, and PP in different monitored urban runoff were calculated using Eq. 1 (Table 2). The EMCs of TP and PP in urban runoff samples (except for roof runoff) collected from the JS study area frequently exceeded the Class V (0.4 $mg \cdot L^{-1}$) of environmental quality standard (EQS) of China for TP concentration in surface water, which is the lowest quality standard, whereas low EMCs for TDP were observed in all runoff samples. Compared with the JS study area, most EMCs of TP and PP and all EMCs of TDP observed in SX study area were less than their EQS. JS study area is composed of some old communities, the buildings and roads aged seriously, and there were not regular road sweeping practices; on the other hand, SX study area is a modern region, the communities and roads were built lately, and there are regular road sweeping practices. So considering the differences between these two study areas, it seems that regional environmental factors, such as pollutant accumulation between rainfall events, human activity intensity, and road sweeping practices, would be responsible for the differences in P concentrations in urban storm runoff.

Of the storm runoff from different contributing areas, main road runoff had the most serious TP and PP EMCs with maxima of 2.50 and 2.43 $mg \cdot L^{-1}$, respectively. These were followed by community road runoff, lawn and parking lot runoff, while the lowest EMCs were observed in roof runoff. It is also important to note that the EMCs of TP and PP in lawn runoff samples exceeded their EQS despite there being less volumetric runoff.

Discussion

Effects of runoff characteristics on P concentrations

Relationships between concentrations of the various forms of P and runoff physical and chemical characteristics were

statistically analyzed using correlation analysis; the results are expressed as Pearson correlation coefficients (Table 3). The concentrations of the P forms in runoff were highly correlated ($p<0.01$). The Pearson correlation coefficient between TP and PP concentrations was greater than that between TP and TDP concentrations, confirming the dominance of PP in urban runoff. In addition, TSS concentrations were significantly correlated with other water quality parameters such as TP, TDP, BOD_5, and COD_{Cr} ($p<0.01$), indicating that these discharged pollutants were mainly associated with suspended solids in storm runoff. This finding was consistent with many other previous studies (Borst and Selvakumar 2003; Kim et al. 2005, 2007). It has been reported that surfaces of metal (Fe and Al, for example) and calcium oxides are important P adsorption sites due to the presence of multiple charge cations and high positive surface charge densities (Baker et al. 1998; Liikanen et al. 2004). These oxides were important components of TSS in runoff in our study (Zhang 2011), and contributed to the high correlation of TSS concentrations to TP and TDP (Fig. 3). P concentrations were also highly correlated with oxygen-demanding substances ($p<0.01$), which are also fine colloidal and solid particulate adsorbents of P in urban runoff (Pontier et al. 2004).

TP and PP concentrations were also positively correlated to runoff pH (Table 3) at the 0.01 level (two-tailed), which implies that increasing storm runoff pH could improve TP and PP concentrations to some extent. This finding was consistent with the study of Riley and Barber (1971), who reported that increasing of pH would decrease the P level in solution. And it was also consistent with the study of Iyamuremye et al. (1996), who found that increasing of pH benefited the adsorption of suspended solids for P in solution.

Table 2 Event mean concentrations (mean±standard deviation) of TP, TDP, and PP in different monitored urban runoff/milligrams per liter

Study area	Sampling sites	TP	TDP	PP
JS	JSM	1.24±1.03	0.08±0.11	1.16±1.06
	JSP	0.51±0.08	0.09±0.06	0.42±0.12
	JSC	1.11±0.91	0.07±0.08	1.04±0.91
	JSR	0.04±0.03	0.01±0.01	0.03±0.03
	JSL[a]	0.64	0.17	0.47
SX	SXM	0.60±0.44	0.03±0.01	0.57±0.45
	SXP	0.40±0.31	0.04±0.02	0.36±0.33
	SXC	0.35±0.16	0.11±0.07	0.23±0.14
	SXR	0.05±0.02	0.02±0.01	0.04±0.02
Environmental quality standard for surface water (Class V)		0.4		

[a] Only one set of lawn runoff samples was collected

Effects of underlying surface types on P concentrations

There were significant differences in TP, TDP, and PP concentrations in runoff samples collected from the different kinds of underlying surface ($p<0.05$). Of the various runoff sources, the highest and the most variable TP and PP concentrations were both observed in road (main road and community road) runoff, while TP and PP concentrations in roof runoff were the lowest and least variable (Figs. 4a and 5c). Similar findings were observed by many previous studies (Chang and Crowley 1993; Lee and Bang 2000; Ballo et al. 2009; Wei et al. 2010). For TDP, the highest and the most variable concentrations were observed at the sewer outlet, and not in road runoff, regardless of the fact that TDP in road runoff was quite prominent (Fig. 4b). The sewer network is where urban runoff from different contributing source areas mixes, and this mixing is one means by which high pollutant concentrations in runoff can be diluted, and variations in concentration over time are attenuated or smoothed out. In addition, a portion of the suspended load often settles out in zones of slower flow velocity during transportation within the sewer network (Michelbach 1995; Gromaire-Mertz et al. 1998, 2001; Gasperi et al. 2010). This reduction in suspended load by settlement can significantly remove TP and PP, but does not affect TDP in runoff (see Table 3 and Fig. 3). Accordingly, TDP concentrations in sewer outlet runoff were relatively high and varied greatly, and TP concentrations were not as high as in road runoff.

Effects of rainfall characteristics on EMCs of P

The EMCs of P in runoff and most rainfall characteristics showed no significant correlations (Fig. 5). However, negative relationships ($p<0.05$) were obtained between EMCs of P (excluding TDP) and event maximum rainfall intensity, which implied that that maximum rainfall intensity affects

Table 3 Pearson correlation coefficients between P concentrations and characteristics of urban runoff

	TP	TDP	PP	TSS	pH	BOD_5	COD_{Cr}
TP	1.000	0.265[a]	0.983[a]	0.769 [a]	0.218 [a]	0.536[a]	0.800[a]
TDP		1.000	0.084[b]	0.038	0.074	0.231[a]	0.200[a]
PP			1.000	0.782[a]	0.210 [a]	0.502[a]	0.788[a]
TSS				1.000	0.138 [a]	0.437[a]	0.787[a]
pH					1.000	0.093	0.102[b]
BOD_5						1.000	0.672[a]
COD_{Cr}							1.000

$N=641$

[a] Correlation is significant at the 0.01 level (two-tailed)

[b] Correlation is significant at the 0.05 level (two-tailed)

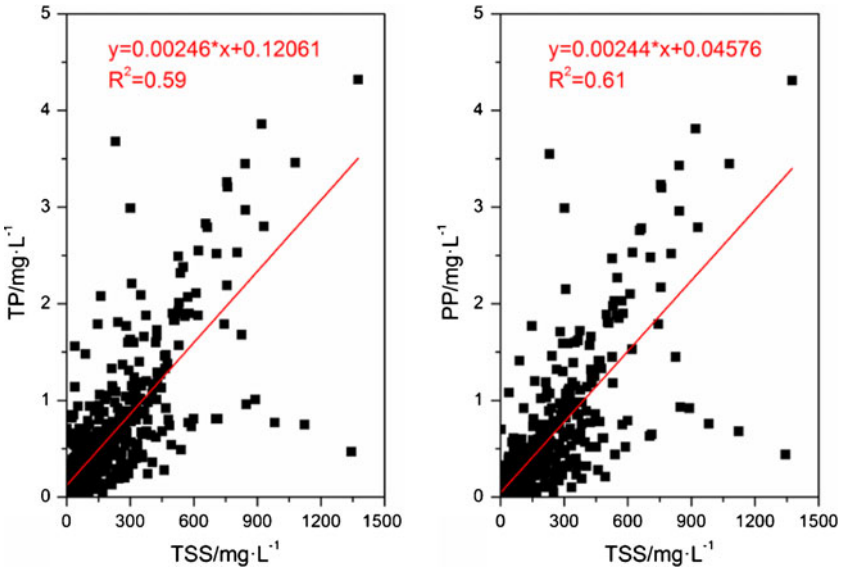

Fig. 3 Relationships between TSS and TP, PP concentrations in runoff

the transport of TSS in storm runoff markedly. TDP, conversely, was positively correlated with AWDP ($p<0.05$) implying that the accumulation of DP on the ground between rainfall events takes longer than that of TP and PP. These findings show some agreement with those of Brezonik and Stadelmanm (2002); they found that the EMCs of TP and DP were negatively correlated with rainfall duration, and positively with AWDP, and the EMC of DP was also negatively correlated with precipitation volume and positively correlated with rainfall intensity.

Estimation of P annual emission flux

Annual emission flux has been suggested as appropriate for evaluating the effects of storm runoff on receiving waters from any given area (Charbeneau and Barretti 1998). Annual emission flux of TP, TDP, and PP in specific types of urban runoff can be calculated using the following equation (Lee and Bang 2000):

$$F = K \cdot \mathrm{EMCs} \cdot \Psi \cdot A \cdot P \tag{2}$$

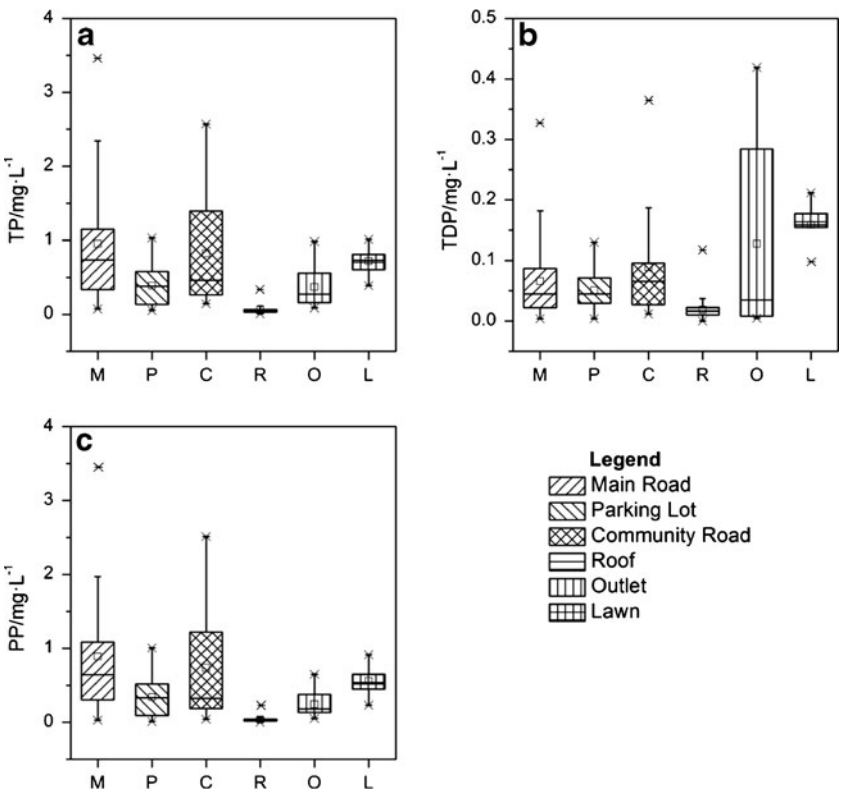

Fig. 4 Box charts of P concentrations in different urban runoff

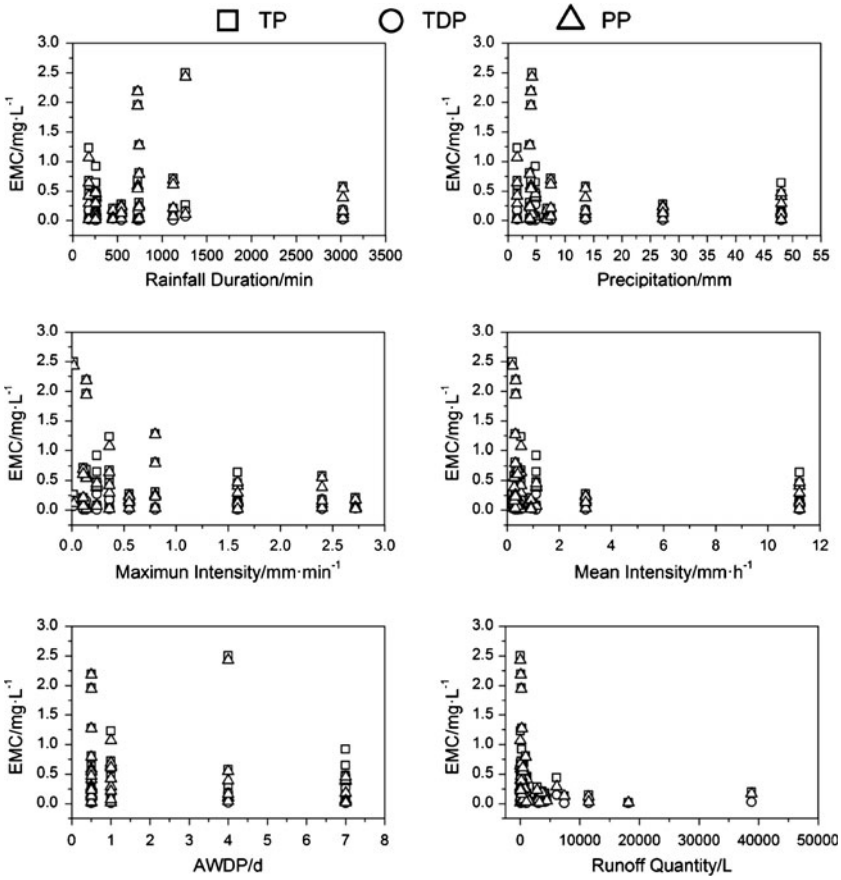

Fig. 5 Relationships between rainfall characteristics and event mean concentrations of P in runoff

where, F is the pollutant annual emission flux (kilograms); K is the conversion constant (10^{-3}); EMCs is the arithmetic average of pollutant EMC (milligrams per liter); Ψ is the average of runoff coefficient; A is the area (square kilometers); and P is the annual average precipitation (millimeters).

Table 4 Annual emission fluxes of P in different urban runoffs in study areas/kilogram

Study area	Sampling sites	TP emission flux	TDP emission flux	PP emission flux
JS	JSM	34.84	2.36	32.54
	JSP	0.55	0.09	0.45
	JSC	318.81	20.04	298.76
	JSR	6.32	1.98	4.84
	JSL	6.81	1.81	5.00
	Total	367.33	26.29	341.59
SX	SXM	61.68	2.69	59.19
	SXP	85.86	9.40	76.89
	SXC	85.76	27.97	57.17
	SXR	0.35	0.13	0.25
	SXL[a]	4.21	1.12	3.09
	Total	237.85	41.30	196.60

[a] Estimation of annual emission flux of P in SXL runoff was based on the monitor values of JSL, the same below

Due to the different runoff coefficients (ranging from 0.15 for green space to nearly 1.00 for roofs) in one urban area, Eq. (2) can be translated into the following equation:

$$F = K \cdot P \cdot \sum_{i=1}^{n} \mathrm{EMCs}i \cdot \Psi i \cdot Ai \tag{3}$$

where, EMCs_i is the pollutant EMCs of the ith type of urban runoff (milligrams per liter); Ψ_i is the runoff coefficient for the ith type of underlying surface; and A_i is the area of the ith underlying surface type (square kilometers).

Estimated annual emission fluxes for TP, TDP, and PP from the different urban runoff sources are presented in Table 4. The areas for each type of underlying surface were extracted from remote sensing data and municipal design papers from local government sources. Runoff coefficients were referenced to the design codes for building water supply and drainage (MOHURD 2003). The total annual TP emission flux from the SX study area was 237.85 kg with 17 % DP and 83 % PP, and from the JS study area, 367.33 kg (more than 1.5 times of that from SX). Only 7 % of TP from JS was DP with a total annual emission flux of 26.29 kg, while the remaining flux of 341.59 kg was PP. The difference in P fluxes between these two study areas suggests that regional environmental conditions play an

Table 5 Statistics of contribution rate of different underlying surface in Wenzhou

Sampling sites	Percentage of area (%)	TP		TDP		PP	
		Percentage (%)	*r*	Percentage (%)	*r*	Percentage (%)	*r*
JSM	5.40	9.49	**1.76**	8.98	1.66	9.53	**1.76**
JSP	0.21	0.15	0.71	0.35	**1.67**	0.13	0.62
JSC	55.03	86.79	1.58	76.24	1.39	87.46	1.59
JSR	27.09	1.72	0.06	7.55	0.28	1.42	0.05
JSL	12.28	1.85	0.15	6.88	0.56	1.46	0.12
SXM	16.93	25.93	**1.53**	6.51	0.38	30.11	**1.78**
SXP	34.93	36.10	1.03	22.75	0.65	39.11	1.12
SXC	40.66	36.06	0.89	67.71	**1.67**	29.08	0.72
SXR	1.03	0.15	0.14	0.32	0.31	0.13	0.12
SXL	6.45	1.77	0.27	2.71	0.42	1.57	0.24

The values in bold were the highest values of *r* in two study areas

important role in determining the export of pollutants, as shown elsewhere (Gromaire-Mertz et al. 2001).

In the JS study area, emission fluxes of all types of P from community road runoff were the largest; community roads comprised the largest proportion of the total urban area (55.03 %). Main road runoff provided the second largest flux, despite being just 5.4 % of the total area. Conversely, roof covering 27.09 % of the study area delivered a relatively small component of the P (especially TP and PP) emission fluxes (Table 5). These results suggest that urban roof runoff was not a significant source of P in the present study areas, which is consistent with the study by Pazwash and Boswell (1997), who reported that roof runoff was often almost free of the suspended matter and impurities found in runoff from other surfaces.

In the SX study area, although community road covered the largest proportion of the total urban area (40.66 %), parking lot runoff was the most important source of TP and PP emission fluxes. For TDP, community road runoff was the most important emission flux source. Roof runoff was also the smallest source, as found in the JS study area (Table 5).

In order to reveal the pollution capacity of each underlying surface more intuitively, a dimensionless index was calculated as follows:

$$r = \frac{\text{percentage of pollutant emission flux}}{\text{percentage of area}} \quad (4)$$

Main road runoff had the highest pollution capacity (Table 5) for TP and PP in urban runoff from both study areas (maximum of r=1.76 and 1.78, respectively). For TDP, there were significant differences in the pollution capacities of the different underlying surfaces between the two study areas. Parking lot was the most important source of TDP (r=1.67) from SX, but in JS community roads was the most predominant (r=1.67). Once again, regional environmental conditions appear to have affected the export of TDP in urban runoff significantly. Yet, roof runoff was the cleanest in both study areas for any form of P.

Conclusion

In the urban district of Wenzhou, TP, TDP, and PP concentrations in storm runoff from different contributing surfaces exhibited a significantly fluctuating and declining trend through the duration of a runoff event. PP made up the larger proportion of TP compared with TDP, while this dominance was variable with time, especially in roof runoff.

Linear relationships significant at the 0.01 level (two-tailed) were obtained between particle (TSS, BOD_5, and COD_{Cr}) concentrations and P concentrations. Based on these findings, it can be concluded that the removal of particles from urban storm runoff could be a viable measure to attenuate P loadings into receiving water bodies. In addition, pH and underlying surface type also influenced P concentrations in urban runoff markedly.

EMCs of TP and PP in both main road and community road runoff exceeded the EQS for surface water (Class V) frequently. TDP EMCs were all below the EQS. EMCs of TP and PP negatively correlated with maximum intensities of rainfall (p<0.05), but EMCs of TDP positively correlated with AWDP (p<0.05). Annual emission flux of TP from the JS study area was larger than that from the SX study area, although the former had a smaller area than the latter. This highlights the influence of regional environmental conditions on the export of pollutants. Moreover, the underlying surface type determined the pollution capacity for TP and PP from urban storm runoff, while regional environmental conditions were more important for TDP export.

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