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Total pollution effect of urban surface runoff

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Abstract

For pollution research with regard to urban surface runoff, most sampling strategies to date have focused on differences in land usage. With single land-use sampling, total surface runoff pollution effect cannot be evaluated unless every land usage spot is monitored. Through a new sampling strategy known as mixed stormwater sampling for a street community at discharge outlet adjacent to river, this study assessed the total urban surface runoff pollution effect caused by a variety of land uses and the pollutants washed off from the rain pipe system in the Futian River watershed in Shenzhen City of China. The water quality monitoring indices were COD (chemical oxygen demand), TSS (total suspend solid), TP (total phosphorus), TN (total nitrogen) and BOD (biochemical oxygen demand). The sums of total pollution loads discharged into the river for the four indices of COD, TSS, TN, and TP over all seven rainfall events were very different. The mathematical model for simulating total pollution loads was established from discharge outlet mixed stormwater sampling of total pollution loads on the basis of four parameters: rainfall intensity, total land area, impervious land area, and pervious land area. In order to treat surface runoff pollution, the values of MFF_{30} (mass first flush ratio) and FF_{30} (first 30% of runoff volume) can be considered as split-flow control criteria to obtain more effective and economical design of structural BMPs (best management practices) facilities.

Key words: total pollution effect; mixed stormwater sampling; street community; pollution loads; split-out flow control

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Introduction

Urban storm runoff has been identified as one of the leading causes of degradation in the quality of receiving waters (USEPA, 1998). Storm runoff from urban areas contains a variety of pollutants and carries a large pollutant load, thereby greatly influence the content of receiving waters (Characklis and Wiesner, 1997). The first flush is generally defined as the first portion of the runoff volume, accounting for the majority of the related pollutant load (Deletic, 1998; Bertrand-Krajewski *et al*., 1998). A review of the research on urban surface runoff shows that most sampling sites are located on surfaces identified by their different land uses, such as typical residential areas, typical commercial areas, typical industrial areas, road areas, etc. The sampling strategy focused on a particular typical runoff area, such as runoff from a road area, can adequately reflect its own surface runoff characteristics, but cannot represent the total surface runoff pollution effect when a study area includes more than two kinds of land uses.

In a given location, we cannot separately treat the stormwater runoff by BMPs (Best Management Practices) due to conditions such as the high intensity of land uses, insufficient land space, insufficient capital, etc. This sample site must be considered as an aggregate treatment object with a need for the removal of a particular pollutant due to surface runoff. Therefore, the total pollution loads at this location must be known.

Drainage systems in a modern city can be considered almost completely as isolated systems. Since their operation lasts for many years, the inner surface of pipes accumulate many pollutants. When rain water passes through these pipes, the runoff washes these pollutants out from their settled positions, and pollutants are discharged into urban rivers together with surface pollutants. Therefore, these drainage-system pollutants cannot be ignored in assessing river water quality.

This study identified the total surface runoff pollution caused by different land uses, together with the pollutants washed out from system drainage pipes, to inform the subsequent treatment of surface runoff.

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1 Materials and methods

1.1 Study area

The study area was a catchment in the Futian watershed, with an isolated, modern urban rain separate system, located in Shenzhen in the central coastal area of southern Guangdong, China. Some wastewater from sewage system often leaks into this separate rain pipe system in dry weather. This study area covers 1.192 km^2 with 6.45 km rain pipes, and is made up of 32% of resident area, 9% of communication area, 6% of industry area, 36% of green land, 16% of commerce area and less than 1% of undeveloped land (Fig. 1). The Huafu Street Community covers this study area. It was severely polluted by a large amount of urban surface runoff mixed with garbage being directly discharged into the Futian River. Most of the rain in this area occurs during April to September every year, accounting for approximately 75% of the annual rainfall.

1.2 Mixed stormwater sampling strategy for a street community at discharge outlet adjacent to river

Urban surface runoff pollution is caused primarily by rainfall, human activity, and pertinent local environmental conditions. In light of different land uses, surface runoff monitoring points have previously been chosen based mostly on the function of the area, such as industrial areas, residential areas, commercial areas, road areas, etc. In these cases, the sampling strategy was to solely sample within areas having the same type of typical runoff, thereby the results could not embody a total surface runoff pollution effect. In this study, we used a new sampling strategy, known as mixed stormwater sampling for a street community at discharge outlet adjacent to river to represent the total pollution effects of surface runoff in a city area.

The mixed stormwater sampling strategy for a street community at discharge outlet adjacent to river has five characteristics: (1) it is based on a typical urban zone and its surroundings, including the rain pipe system; (2) the range of mixed stormwater sampling strategy for a street community of discharge outlet to environment is a square or polygon that might simultaneously include the transportation on the road, the residential area, the commercial area, the industrial area, and so on; (3) it has characteristics of the different catchment functions and different land uses, and include a pollutant wash-out effect from the rain pipe system; (4) it may include one surface runoff pollution discharge outlet adjacent to the river of urban watershed; (5) a community usually is administrative district in the city, and can be considered as a whole object to be monitored for urban runoff.

This study area composed of three villages and five roads with 0.962 km^2 of impervious area and 0.23 km^2 of pervious area, and was monitored for urban runoff discharged to Futian River. The total surface runoff in this mixed area had only one exit. The sampling and monitoring point was located in the extension of the exit to the Futian River about 300 m (Fig. 1). The monitoring point captured the total pollution effect in this study area.

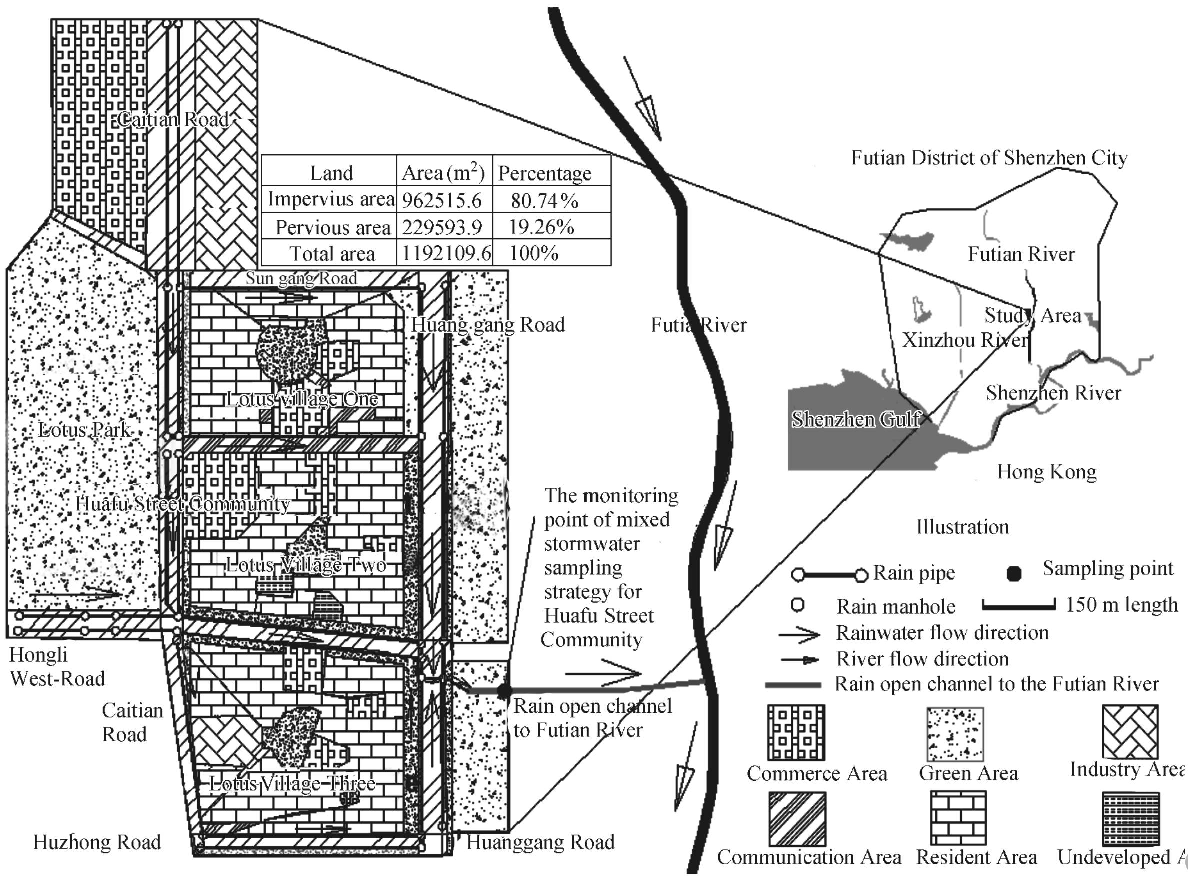

Fig. 1 Study area description.

1.3 Sampling and analyses

The samples were sampled manually using polyethylene bottles and the velocity of runoff was measured by the propeller-type current meter at the same time at monitoring point during a rainfall event. When the obvious runoff flow in this open rain channel was observed at the monitoring point after the beginning of a rainfall event, it began to sample. The sampling interval time, based on the process of urban surface runoff, was 5 min within 30 min, 10 min within 30–60 min, 20 min within 60–120 min, 30 min within 120–180 min, and 60 min beyond 180 min. The volume of runoff was calculated by Eq. (1):

$$q_t = s \times v \tag{1}$$

where, q_t (m^3/s) is the volume of runoff, s (m^2) is the average section area, v (m/s) is the average velocity of runoff.

The samples were saved, treated and analyzed in the laboratory. Total suspended solids (TSS) and chemical oxygen demand (COD) were measured according to standard methods (APHA, 1998). The unfiltered water samples were digested with $K_2S_2O_7$ solution to determine total nitrogen (TN) and total phosphorus (TP) concentrations (Ebina *et al*., 1983). The biochemical oxygen demand (BOD) was measured via respirometric methods (Zermeño *et al*., 2002). The volume of baseflow was calculated using Eq. (1) and the average volume of baseflow was 0.0055 m^3/s in dry weather. The mean concentration of COD, TSS, TN, TP and BOD_5 was 74.6 mg/L, 106 mg/L, 1.9 mg/L, 0.5 mg/L, 18.49 mg/L, respectively, at this monitoring point in dry weather. The surface runoff sampling period was from September 2007 to July 2008. Characteristics of rainfall events are shown in Table 1.

2 Results

2.1 Total pollutant effects

The pH of the surface runoff was weak acidic for all rainfall events. Combining runoff quantity and quality, each rainfall event produced a set of hydrographs and pollutographs for TSS, COD, BOD, TN, and TP. Figure 2 shows the actual flow and total effective concentrations of TSS, COD, BOD, TN, and TP during a typical rainfall event on 5/28/2008 (36 mm); it was delayed 10 min when the runoff just occurred after beginning rainfall on 5/28/2008.

The total emission mass can be calculated as the product of rainfall, catchment area, runoff coefficient, and event mean concentration (EMC). A well-structured monitoring program can yield reasonable results for EMC according to the following Eq. (2):

$$\text{EMC} = \frac{M}{V} = \int_0^T c_t \times q_t \text{d}t \Big/ \int_0^T q_t \text{d}t \approx \sum_0^{t=T} c_t \times q_t \Big/ \sum_0^{t=T} q_t \tag{2}$$

where, M (g) is the total mass of a pollutant transported during a rainfall event; V (m^3) is the total volume of runoff; c_t (mg/L) is concentration at time t. The limits of integration $t = 0$ and $t = T$ refer to the times associated with the initiation and cessation of runoff, respectively. But it is difficulty to continuously measuring in all rainfall events, therefore, Eq. (2) can be presented as Eq. (3):

$$\text{EMC} \approx \sum_{j=1}^{n} \frac{c_j + c_{j+1}}{2} \times \frac{q_j + q_{j+1}}{2} \times \Delta t \Big/ \sum_{j=1}^{n} \frac{q_j + q_{j+1}}{2} \times \Delta t \tag{3}$$

where, n is the total sampling and measurement times; j (1, 2,..., n) is the sampling and measurement sequence number in a rainfall event; c_j (mg/L) is pollutant concentration at j in a rainfall event; q_j (m^3/s) is the discharged runoff flow rate at time t; Δt is the interval time between the adjacent sampling and adjacent volumes measurement of runoff in a rainfall event.

Because of the existing baseflow, the value of EMC is expressed in Eq. (4) based on continuity principle (Conservation of Mass).

$$\text{EMC} = \frac{M - c_\text{b} q_\text{b} T}{V - q_\text{b} T} \tag{4}$$

where, c_b (mg/L) is concentration of baseflow, q_b (m^3/s) is the volume of baseflow, T is considered as the total monitored time shown in Table 1. The observation volume of runoff shown in Table 1 includes the volume of baseflow. Based on Eq. (4), EMCs of total pollution effects in the study area are summarized in Table 2.

2.2 Total pollution load distribution and discharge

Based on Eq. (4), the total pollution load can be calculated. Table 2 presents the total pollution load distributions of COD, TSS, TN, and TP for seven rainfall events. All pollution discharge loads to the Futian River from different rainfall events can be calculated according to the data

Table 1 Characteristics of rainfall events in study area

Date	Rainfall length (h)	Rainfall depth (mm)	Max rainfall intensity (mm/h)	Antecedent dry days (d)	Total monitored time (min)	Observed volume (m^3)
10/30/2007	2.42	2.3	6	20	200	957.5
3/22/2008	2.5	12.9	66	56	240	5414.9
4/19/2008	2.33	3.9	12	22	180	1547.2
5/19/2008	45.3	55	18	9.32	2880	50835.7
5/28/2008	1.25	36	96	7.67	200	19399.7
6/6/2008	2.25	8.5	12	2.44	180	7302.5
6/25/2008	2.42	67.5	66	5.67	200	18726.0

Table 2 EMCs and pollution load of surface runoff at rainfall events

	Parameter	10/30/2007	3/22/2008	4/19/2008	5/19/2008	5/28/2008	6/6/2008	6/25/2008
COD	Pollution load (kg)	268.18	2669.88	436.98	6059.08	3243.18	1372.18	1094.28
	EMC (mg/L)	300.81	500.20	294.04	120.14	167.75	189.51	58.64
TSS	Pollution load (kg)	230.20	10597.80	607.70	10446.40	8460.70	3208.90	4977.70
	EMC (mg/L)	258.22	1985.94	408.93	207.53	437.61	443.13	266.76
BOD	Pollution load (kg)	156.30	1497.10	–	–	1937.80	1303.60	538.10
	EMC (mg/L)	175.32	280.46	–	–	100.23	180.02	28.84
TN	Pollution load (kg)	7.47	13.07	8.77	111.27	50.87	18.17	38.27
	EMC(mg/L)	8.38	2.45	5.91	2.20	2.63	2.51	2.05
TP	Pollution Load(g)	0.87	68.87	0.87	60.07	3.97	2.87	0.47
	EMC(mg/L)	0.97	12.91	0.58	1.20	0.21	0.40	0.03

The measure apparatus of BOD was not work on 5/19/2008 and 4/19/2008, thereby the value of BOD was not occur in these two rainfall events.
COD: chemical oxygen demand; TSS: total suspend solid; BOD: biochemical oxygen demand; TN: total nitrogen; TP: total phosphorus.

presented in Table 2. The biggest total pollution load to this river was from the rainfall event on 5/19/2008. The main indices of total pollution loads are TSS and COD, for which the biggest discharge levels to the river in a simple rainfall event were 10.6 and 6.06 tons, respectively.

3 Discussion

3.1 EMCs of the total pollution effect

The wide distributions of EMCs depended on the total rainfall, ADD (antecedent dry days), and rainfall intensity due to the dilution effect during a rainfall storm. In this study, only TSS and COD were well correlated with EMC and ADD; the linear correlativity coefficient between TSS and ADD was 0.8084; between COD and ADD was 0.8519. Because long ADD periods caused the accumulation of more atmospheric dust and TSS is the main carrier of pollutants in surface runoff, a longer ADD resulted in higher EMCs of TSS and COD. Usually, EMC is low with heavy rainfall or short ADD; however, heavy rainfall after a long ADD reduces EMC due to the dilution effect.

It is obvious that EMCs of TSS, TN in Futian watershed are much higher than some developed countries, especially in Canada and America (Stanley, 1996). The mean value of EMC for TSS (572.6 mg/L) about 2.7 times that in Cincinnati (210 mg/L), Ohio, in America. The smallest value of EMC for TSS (207.5 mg/L) is about eight times that in Washington DC (26 mg/L). The biggest value of EMC for TSS (1985.9 mg/L) is about five times that in Topeka, Kansas (395 mg/L). The EMC of TP is very close to Canada and America, the mean EMC of TP is little higher than that in twelve cities but the biggest EMC of TP (12.91 mg/L) is about 9 times that in Roseville, Minnesoda, (1.44 mg/L) in America (Stanley, 1996).

3.2 Total variation of pollution across runoff events

Hydrographs and pollutographs of these five pollutants were different. Li *et al*. (2007) showed a relationship between the pollutant concentration peak and the flow peak. The pollutant concentration peak preceded the flow peak. As shown in Fig. 2, with the exception of TN, the pollutant concentration decreased rapidly after the peak. The rain pattern influenced the interval between the pollution peak and flow peak; the times between the pollution peak and flow peak for TSS and COD were 25–30 min during the event (6/25/2008), 35–40 min during the event (5/28/2008), and 20 min during the event (5/19/2008). However, the interval between the pollution peak and flow peak during the event (5/19/2008) was 100 min for TSS and 20 min for TN. This phenomenon also occurred for other monitored rainfall events. The time interval was shorter in the rainfalls with higher intensity during the initial period of the rainfall event. The concentrations of TSS, COD are very close to Wuhan City in central China (Li *et al*., 2007). However, it is much higher than developed counties such as American, Holland (Zhao, 2002).

3.3 Runoff coefficient

The runoff coefficient is expressed in following Eq. (5):

$$\Psi = \frac{Q}{q \times A \times 0.001} \quad (5)$$

where, Q (m^3) is the total surface runoff volume caused by rain, q (mm) is the rainfall depth, and A (m^2) is the land surface area. The land uses in study area was made of resident area, communication, industry, commerce, green and undeveloped area. Based on the rainfall intensity data and observation volume of runoff (Table 1), the calculated results of average runoff coefficients were 0.43 for these seven rainfall events. Based on empirical reference of runoff coefficient, the runoff coefficient of pervious area and impervious area is 0.9 and 0.3, respectively. The weighting runoff coefficient is equal to the percentage of pervious area and impervious area in study area, and an integrated runoff coefficient of 0.75 was also calculated by weighting the coefficients. It is obvious that the runoff coefficient calculated by Eq. (5) was less than the value calculated by weighting the coefficients; this possible reason is that the average time of observed runoff volume was not more than 3 h, so that the observation volume of runoff was small. The integrated runoff coefficient in study area was continually monitored in next research work. These runoff coefficients showed that higher land-development intensity usually results in a higher runoff coefficient, and these runoff coefficients can be used in calculating runoff volume.

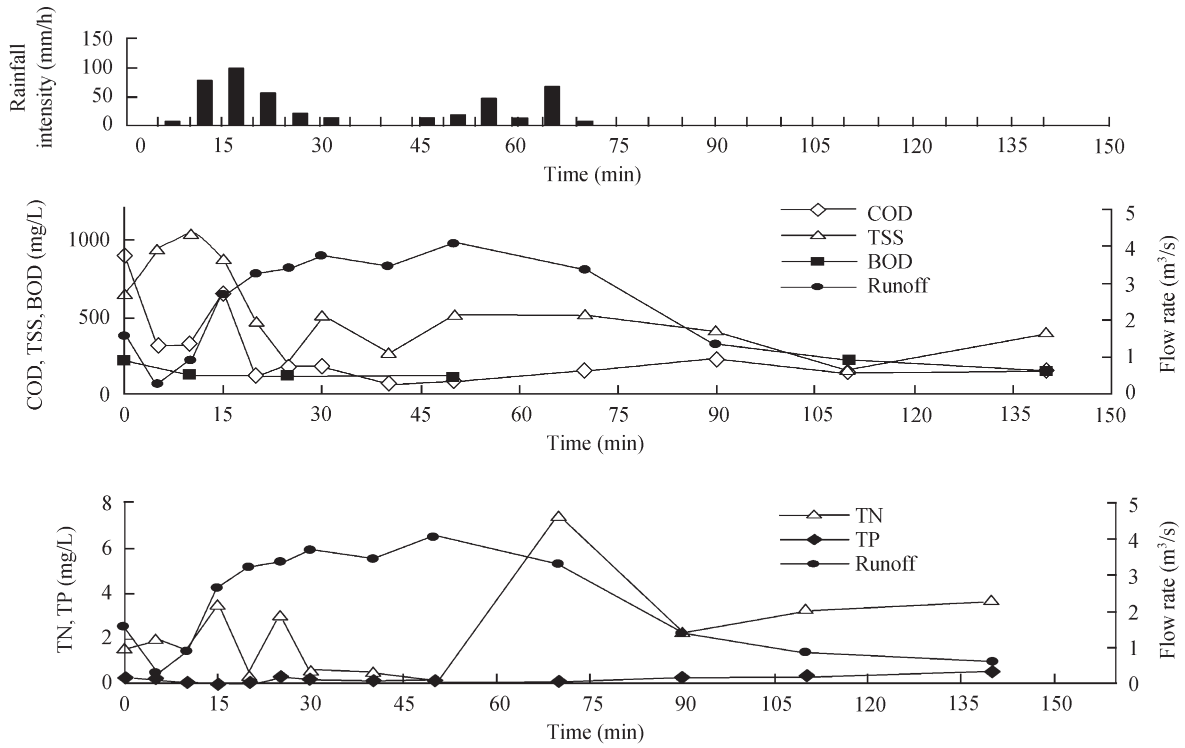

Fig. 2 Process of flow and total concentrations (5/28/2008).

3.4 Total pollutant loads in surface runoff

3.4.1 Total pollution loads distribution

Pollution load delivery was not proportional to the runoff volume from urban runoff processes. A high pollution load delivery occurred during the early portion of storm runoff, as shown by the cumulative pollutant load distribution throughout the rainfall runoff. The pollutograph of total pollution loads showed the main mass pollutants in different rainfall events to be TSS and COD in this study area.

Since the main pollution load of COD and TSS for normalized accumulated mass for each event was around 30% of the normalized accumulated flow (Fig. 3), the pollution load transported by the first 30% of runoff volume (FF_{30}) was used as an indicator to evaluate the first flush magnitude for different rainfall events. For example, the values of FF_{30} for COD, TSS, TN, and TP were 54.0%, 69.6%, 24.6%, and 25.5%, respectively, in event of 3/22/2008; were 51.9%, 44.6%, 41.0%, and 60.8%, respectively, in event of 4/19/2008; were 43.6%, 34.7%, 17.1%, and 24.4%, respectively, in event of 5/28/2008. The FF_{30} values were widely distributed, but the FF_{30} time durations were as well. For event (3/22/2008), it was 17.4 min long, the event (4/19/2008) lasted 49 min and the event (5/28/2008) lasted 38.8 min; this phenomenon depended on differences in factors such as rainfall duration, rainfall intensity, and maximum rainfall intensity. It can be concluded that solids and organic matter are the main pollutants in runoff discharges within this study area.

The land in Futian watershed in study area is typical urban land use which composes of resident area, communication, industry, commerce, green and undeveloped areas. The sampling point can capture the total pollution effect from these land uses. Because the surface runoff was not treated and discharged into the Futian River within the chosen study area, the quality of river water was mainly influenced by surface runoff. Total discharged pollution loads to the Futian River in this study area were found to be very high, indicating that the runoff pollution must be treated as soon as possible.

3.4.2 Calculation of total pollution loads

The Futian watershed in Shenzhen City covers an area of 78.8 km^2, with an impervious area about 56.6 km^2 (71.83%) and a pervious area about 22.2 km^2 (28.17%). The primary data used for our calculations are the information summarized in Tables 1 and 2, and the impervious land area, pervious land area, and the watershed area. The mathematical models were build up according the Levenberg-Marquardt (LM) nonlinear regression method, which is expressed as the following Eq. (6):

$$W = c_1 \times \text{Tangent}\,(c_2 \times I + c_3) + c_4 \times I^{c_5} \times (A_T - A_I)^{c_6} \times A_I^{c_7} + c_8 \tag{6}$$

where, W (kg) is total the pollution load of COD, TSS, or TN; I (mm) is rainfall intensity; A_T (m^2) is the total land surface area; A_I (m^2) is the area impervious to surface runoff; and c_1,..., c_8 are the different constants.

The total pollution loads were calculated by Eq. (6). Figure 4 presents that the simulated value of COD was continuously oscillated with low-middle rainfall intensity and the pollution load tendency was low with high rainfall intensity. It was obvious that the maximum pollution loads occurred with a light rainfall intensity during the early period of the rain event. The simulations of TSS and TN had similar respective tendencies for the study area and

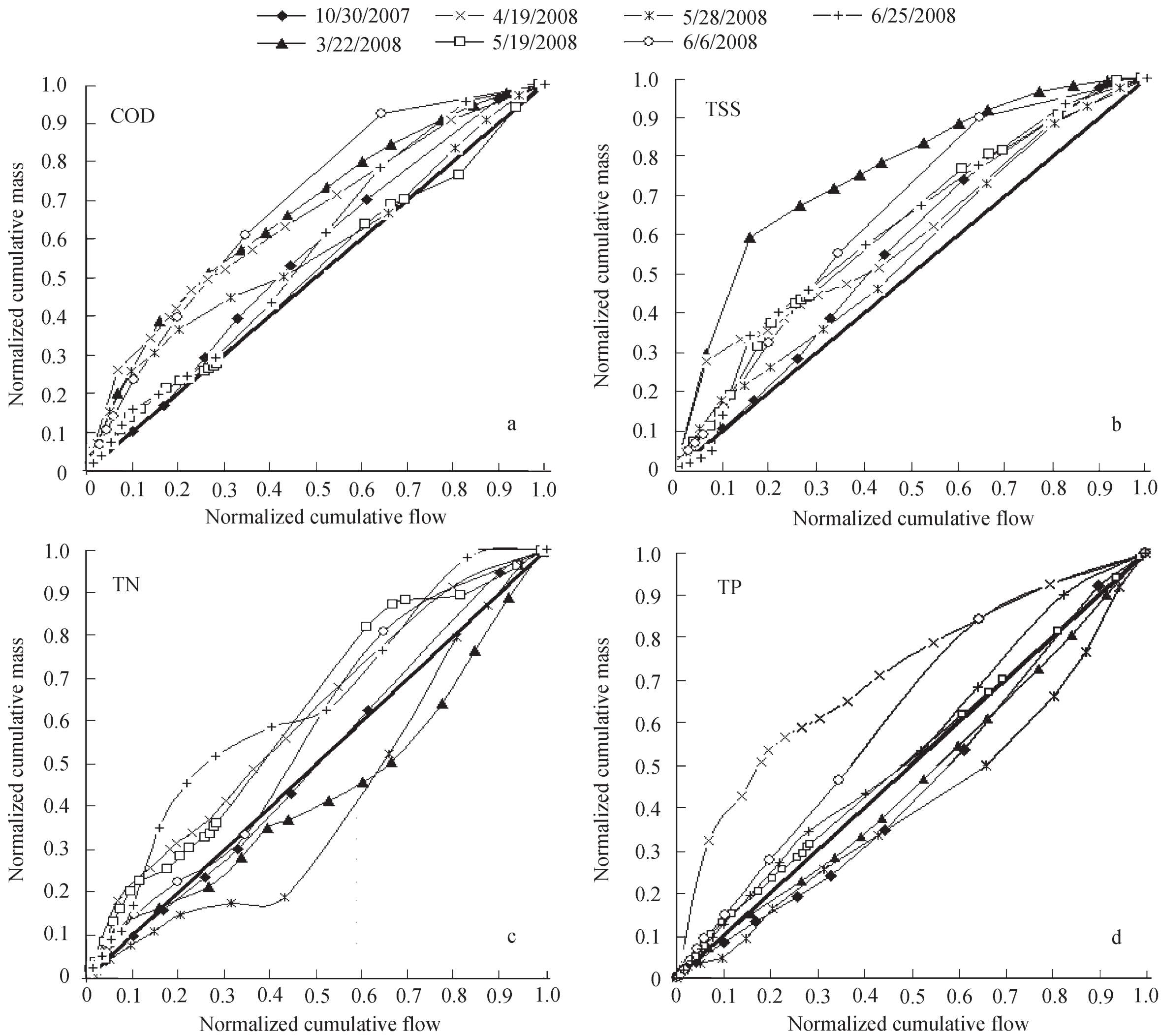

Fig. 3 Normalized cumulative curves for TSS, COD, TN, BOD, and TP.

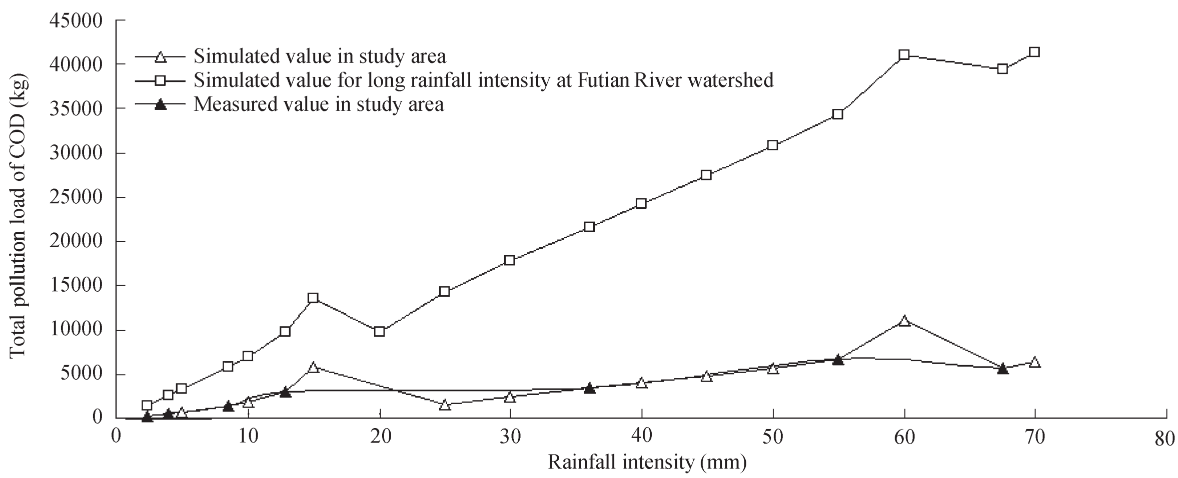

Fig. 4 Total pollution load simulation of COD.

the Futian watershed; the total pollution loads depend on the rainfall intensity and surface area, including the impervious area.

By simulating total pollution loads for the mixed stormwater sampling strategy for a street community at discharge outlet adjacent to river with all seven rainfall events together, total pollution loads were forecasted by this mathematical calculation model. The simulation results showed that the main pollutants in the Futian watershed were TSS and COD. Furthermore, it was obvious that total pollution loads of surface runoff in this modern watershed were very heavy.

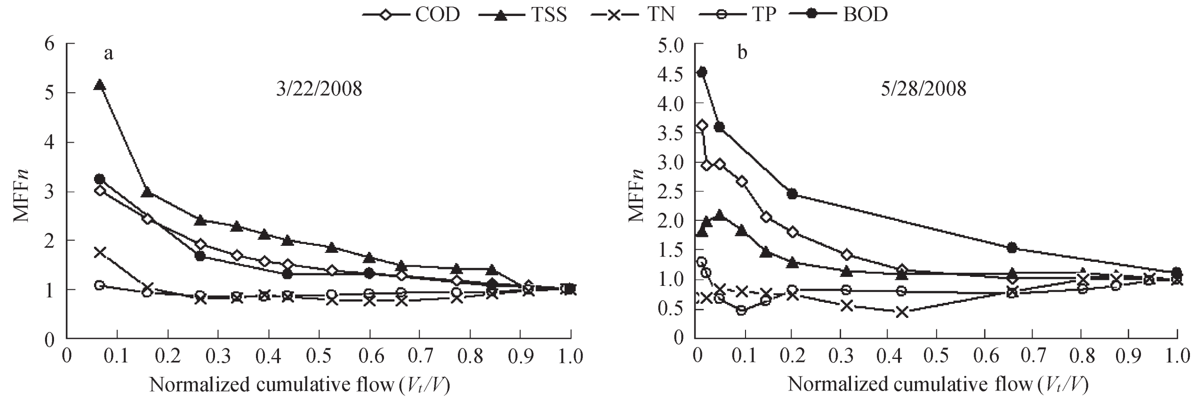

Fig. 5 Values of MFF_n in two typical rainfall events.

3.5 Analyses of split-flow control of total pollution effect

3.5.1 Split-flow quantification of surface runoff

MFF ratios (MFF_n) can be considered as split-flow quantification of surface runoff and can be calculated by following Eq. (7) (Ma *et al*., 2002; Han *et al*., 2006):

$$MFF_n = \frac{\int_0^t c_t q_t \mathrm{d}t/M}{\int_0^t q_t \mathrm{d}t/V} \tag{7}$$

where, MFF_n is mass first flush ratio at a cumulative flow volume corresponding to $n\%$ of total flow volume, t is lapsed flow time corresponding to $n\%$ of total flow volume. For example, if MFF_{20} is equal to 2.8, the pollutant mass ratio is 56% in the first 20% of the runoff volume. If the split-flow ratio is 44%, the MFF_{20} is quantified as the first 20% of runoff volume, for which the intercepting runoff volume is 56%.

When the value of MFF_n is equal to or greater than 1, the first flush occurs. The study area showed a strong first flush for five pollutants for seven rainfall events. For example, Fig. 5 shows that COD, TSS and BOD had a strong first flush, but TN and TP did not exhibit a first flush. Figure 3 also indicates whether a first flush occurred (Geiger, 1987), concluding the same results as the MFF_n calculation. For example, Figs. 3b and 5b showed a strong first flush for COD, TSS and BOD on 3/22/2008, but no first flush for TN on 10/30/2007, on 3/22/2008, on 4/19/2008, nor for TP on 10/30/2007, on 3/22/2008, on 4/19/2008, on 6/25/2008. Figure 3 clearly showed that the COD, TSS and BOD exhibited first flush in all most rainfall events except the event 5/19/2008 for COD. The maximum rainfall intensity appeared earlier during that event, causing a more distinctive first flush for COD, BOD and TSS; on the contrary, this maximum rainfall intensity caused a relatively weak first flush for TN and TP because there were enough of these two pollutants available for continued wash-out. Therefore, for event 5/28/2008 (Figs. 3 and 5b), wherein maximum rainfall intensity appeared early in the rainfall, COD, TSS and BOD had a strong first flush, but no first flush occurred for TN and TP.

3.5.2 Analyses of surface runoff pollution removal

When a first flush occurs, the FF_n can be considered as the split-flow control criteria; when there is no first flush, MFF_n can be considered the split-flow control criteria. The value of n was chosen by the appropriate BMPs.

In this study, FF_{30} in Fig. 5 was considered the split-flow control criteria, implying that the pollution loads transported by the first 30% of runoff volume (FF_{30}) can be treated by appropriate BMPs and the remaining runoff volume (70%) can be released to the Futian River. Figure 5 presents the value of MFF_n for two typical events and four pollutants; the average value of MFF_{20} for the two main pollutants COD and TSS was 1.53 and 2.43, respectively, with first flush mass ratios of 30.6% and 48.6%, respectively. The average value of MFF_{30} for COD and TSS was 1.31 and 2.06, and their first flush mass ratio was 39.3% and 60.18%, respectively. Thus, the value of MFF_{30} was chosen as the removal criterion based on the first 30% of runoff volume in this study area.

By using the value of FF_{30} or MFF_{30} in this study, split-flow control criteria are provided and can be used in the economic design of structural BMP facilities. Intercepting the early part of runoff volume (i.e., less than 30%) is more effective and economical than attempting to treat the entire volume.

4 Conclusions

1. The mixed stormwater sampling strategy of discharge outlet adjacent to river is a new sampling countermeasure. The study area, a 1.192 km^2 modern urban area with a separate drainage system, showed a strong first flush for five pollutants over seven rainfall events. Parts of the pollutant concentration peaks preceded the flow peaks, but a few were opposite because of the different rainfall intensities at different points within the various rainfall events.

2. There was a wide range of EMCs in the total pollution effect measurements; these wide EMC distributions depended on the total rainfall, rainfall intensity, and the dilution effect during rainfall events.

3. The main indices of total pollution loads were TSS and COD. The fractions of total pollution loads transported by the first 30% of runoff volume (FF_{30}) were 34.7%–69.6% for TSS, 43.6%–54.0% for COD, 17.1%–41.0% for TN, and 24.4%–60.8% for TP. The durations of FF_{30} across the unique rainfall events were very different.

4. By using the mixed stormwater sampling strategy of discharge outlet adjacent to river, mathematical models were established to calculate total pollution loads for COD, TSS and TN. The simulation of the mixed area and Futian watershed showed that surface runoff pollution discharge to river was very serious in Shezhen City.

5. The values of MFF_{30} or FF_{30} can be considered as split-flow control criteria that can be used in the economic design of structural BMP facilities, as intercepting the early part of runoff volume (i.e., less than 30%) which is more effective and economical than treating the entire volume. Follow up work from this study will be the design and treatment of the surface runoff.

Acknowledgments

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