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Pollution characterization and source analysis of the wet weather discharges in storm drainages

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ABSTRACT

For storm drainages interconnected with inappropriate or illicit sewers, urban wet weather discharges (UWWD) is one of the major factors that affect the receiving water environment. In this study, the UWWD pollutants of SS, COD, TN, TP and NH_4^+–N, as well as mass first flush ratio (MFF) at Caohejing storm drainages in Shanghai, China, were characterized. The results indicate that the first flush effect of runoff pollution was only observed in the events with the large rainfall intensity, early peak rainfall and low initial pollutant concentrations. Deposited pipe sediments and interconnected wastewater had larger contribution to the pollutant variations than runoff pollution. The decreasing trends of the pollutant concentrations were less obvious in smaller rainfall events. The cumulative rainfall amounts before the downward inflection points of UWWD were different in most moderate and heavy rainfall events ranging from 12.1 to 65.7 mm. MFF analysis shows that the total rainfall volume is the key factor affecting MFF, and the events with an early peak rainfall, less antecedent volume discharged, or a long interval time between two discharges had more obvious first flush effects. The data presented in this study will help the decision makers to better intercept pollutants in different types of rainfall and antecedent discharges. It also serves as a reference for UWWD research in similar drainage systems.

Keywords: Urban wet weather discharges (UWWD); Pollutant concentration variations; Mass first flush ratio (MFF); Discharge load analysis

1. Introduction

Due to various reasons, increasing concern has been addressed to the wet weather discharges of the separate storm drainages interconnected with inappropriate or illicit sewers [1,2]. Though in some regions pumps are installed at the outlet of such separate storm drainages to intercept inappropriate or illicit sewers to wastewater treatment plants (WWTPs), some excess wastewater is still discharged into the receiving waters due to the limited capacity of the intercepting pumps in the dry weather period [1,3]. Then, during the wet weather period, the intercepting pumps are usually closed to reduce the pressure of peak flow at WWTPs. Under this condition, therefore, stormwater and wastewater are mixed and hence discharged by rainwater pumps into the receiving waters, which is usually itemed as urban wet weather discharges (UWWD).

Usually, there are three main pollution sources of UWWD in such a system including: point source pollution from sanitary and industrial emissions, non-point source pollution from urban surface runoff, and the deposited sediments due to the complex in-sewer processes [5–9].

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These pollutants would contribute a variety of pathogenic microorganisms, nutrients (nitrogen and phosphorus), toxics and other substances to UWWD [10,11], and eventually lead to the deterioration of the urban water environment [12–16].

Furthermore, many studies showed that the characteristics of UWWD were affected by many factors, such as, catchment area, land use type, percentage of the impervious area, meteorology, interconnected wastewater, rainfall characteristic and so on [17–19]. Among these influencing factors, rainfall plays an important role on the temporal pollutant load in UWWD. More explicit, the rainfall characteristics govern the total load and event mean concentration (EMC) of UWWD [4,20]. It also reported that the first flush loads in UWWD were usually rainfall dependent [21–24]. Therefore, to assist the optimization of the UWWD interception strategy to capture the discharge with higher pollutant concentrations, a better understanding on the temporal variations of pollutants in the process of UWWD under different rainfall conditions is essential.

Consequently, in this study, nine rainfall events were surveyed in Caohejing drainage system, Shanghai in the summer of 2011. The rainfall characteristics and the pollutant concentrations in discharges were analyzed to assess the factors that affect the variations of the pollutants as well as the first flush effects. The primary objective of this study were: (1) to characterize the contributions of different sources to the pollutants in UWWD; (2) to identify the downward inflection points of the dynamic changes of the temporal pollutant loads in UWWD; and (3) to identify the first flush effect using mass first flush ratio (MFF) and discharge load distribution.

2. Materials and methods

2.1. Study area

The study was conducted in Caohejing catchment (374 ha) in Xuhui District, Shanghai city, China (Fig. 1). The catchment is a high population density area (approximately 270 population/ha) consisting of residential (41%), commercial, physical, institutional facilities (27%), industrial (25%), and green space (7%). The percentage of impervious area is 72% and the Puhui River receives the discharges from

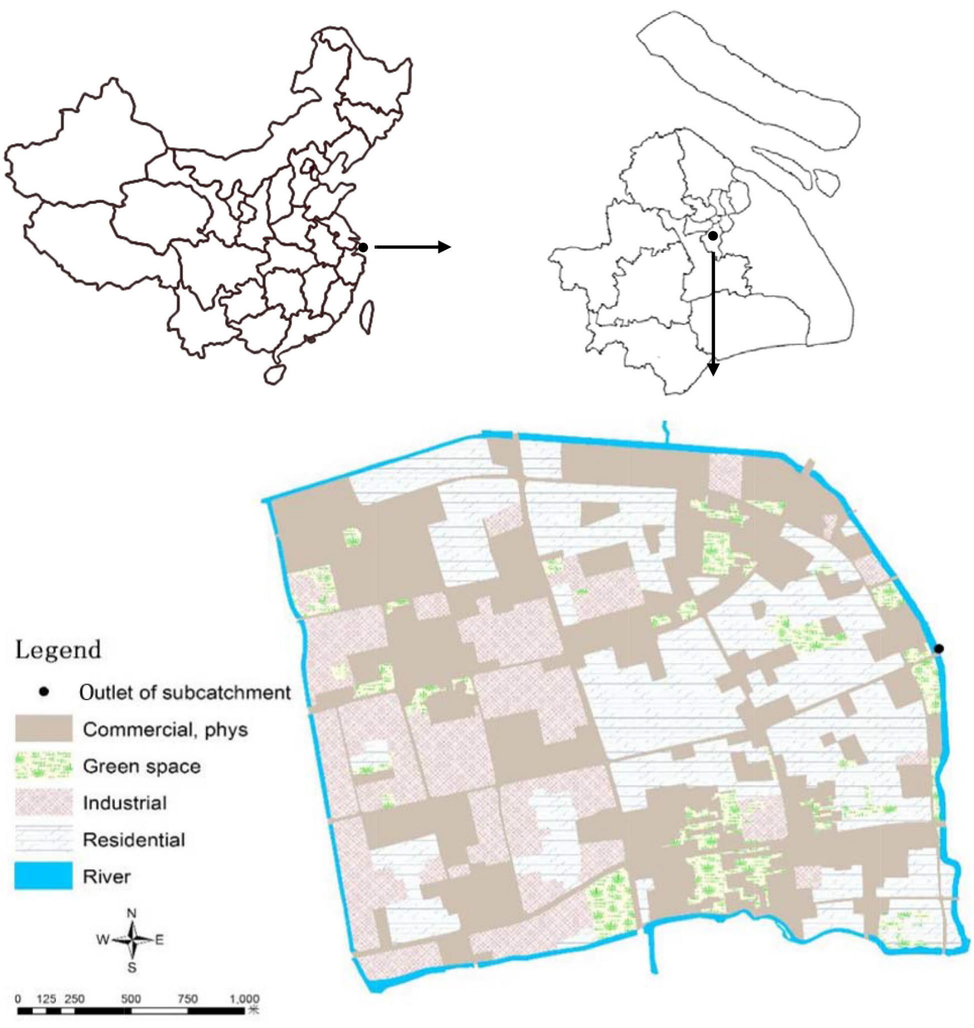

Fig. 1. Location of the Caohejing catchment and the land use.

the Caohejing catchment. This catchment has a flood control pumping station equipped with six axial flow pumps (2.3 m^3/s per pump, maximum pumping discharge of 13.8 m^3/s) to drain the surface runoff into the Puhui River on wet-weather days.

According to the previous study [1–3,25,26], inappropriate or illicit connections to storm drains is a challenging issue in this area. It reported that inappropriate sewage discharge and groundwater seepage into storm-drains were approximately 17860 m^3/d and 3624 m^3/d, respectively (i.e., up to 51% of the total sewage flow in the catchment) [1]. Therefore, in order to intercept the inappropriate or illicit connected sewers to the WWTP during dry weather periods, flood control pumping station was equipped with two additional wastewater interception pumps (0.25 m^3/s per pump, usually one pump in operation). More detailed schematic diagram can be found elsewhere [1].

2.2. Rainfall events

The rainfall occurs mostly in summer and fall seasons when southeast monsoon carries moisture into Shanghai. This study covered the time period from May to December of 2011 in the study area. The rain gauge was located in the pump station of Caohejing. Precipitation and discharges data were obtained from the online drainage comprehensive application system of Shanghai Municipal Sewerage Company Ltd (www.smsc.sh.cn/oa_index). A total amount of 235 rainfall events from 2009 to 2011 was monitored. Among the monitored events, 10% has a total rainfall amount less than 0.2 mm; 59% between 0.2 and 11.2 mm; and 30% between 11.2 and 77 mm. Only 1% of the rainfall events exceed 77 mm. Meanwhile, due to the rainfall initial loss and storage capacity of pipes, the wet-weather discharge occurs when the total rainfall was up to 5 mm.

In order to better describe the characteristics of the discharged pollutants in wet weather, nine typical rainfall events in 2011 were selected (two events ≤ 11.2 mm, seven events between 11.2 and 77 mm, and one event > 77 mm), and only one event smaller than 5 mm. These rainfall events were characterized by five variables of rainfall duration, total rainfall, mean rainfall intensity, peak rainfall (the highest rainfall during an hour in a storm), and antecedent dry weather period. Furthermore, the discharge pollution is not only related to the total rainfall but also the deposited pipe sediments due to the sanitary and industrial sewage inputs during the dry weather periods [1,27]. Therefore, the pollutant concentrations at the beginning of the studied discharge event (i.e., initial concentrations and pollutant concentrations of the first sample) is important to access the influence of the deposited sediment.

More explicit, previous discharge carries certain part of the sediments, and then decreases the amount of sediment present during the next rainfall event. More sediment will accumulate if the interval period between the rainfall events is longer. Therefore, another three discharge variables of volume discharged, antecedent volume discharged, and the interval time between two adjacent discharges (i.e., from the end point of the antecedent discharge in dry or wet time to the starting point of the studied discharge) were also considered to study the discharge pollution on wet weather. Consequently, in total, eight variables were selected and listed in Table 1.

In addition, the number of pumps in operation is related to the peak rainfall and is an important factor to affect the pollutant concentrations. Based on the peak rainfall and pump operation mode, therefore, the selected nine rainfall events can be divided into three groups as given in Table 1. In the first and second groups, the peak rainfall were less than 8.5 mm and the total rainfall were less than 30 mm, which can be further divided into two groups based on the number of pumps in operation. In the third group, the peak rainfall and total rainfall were larger, and the number of pumps in operation were more than two.

Table 1
Rainfall and discharge characteristic of 9 events

Event No.	Date (m/d)	Rainfall variables					Discharged variables			Sample number	Group	Pumps operating mode
		TR (mm)	RD (h)	MRI (mm/h)	PR (mm/h)	DAT (h)	VD (m^3)	AVD (m^3)	ITBTD (h)			
E1	10/20	0.5	3.8	0.13	0.3	157.3	28980	12420	41	11	Group 1	1[a]
E2	10/24	11.2	11.8	0.95	2.2	70.3	66240	28980	72	23		1[a]
E3	9/29	15.3	19.8	0.77	8.5	208.0	45540	24840	264	17		1[a]
E4	5/23	28.8	30.0	0.96	5.3	18.3	68300	2070	84	26		1[a]
E5	12/6	28.7	41.5	0.69	2.2	134.8	91080	44140	12	34		1[a]
E6	6/4	19.1	20.5	0.93	6.9	270.3	60030	2070	96	20	Group 2	1-2-1[b]
E7	11/2	21.8	14.5	1.50	5.3	75.8	99360	24840	108	24		1-2-1[b]
E8	6/10	46.0	49.3	0.93	27.7	8.5	190440	45540	12	24	Group 3	2-6-5-4-2-1[c]
E9	6/17	158.3	49.8	3.18	34.5	29.0	892170	53820	8	57		5-6-4-5-4-3-2-1[d]

Abbreviation: RD: rainfall duration; TR: total rainfall; MRI: mean rainfall intensity; PR: Peak rainfall; DAT: dry antecedent time; VD: volume discharged; AVD: antecedent volume discharged; ITBTD: the interval time between two adjacent discharges;
[a]"1": only one pump was in operation during the whole rainfall event;
[b]"1-2-1": firstly one pump was in operation; then two pumps were in operation; finally only one pump was in operation again;
[c]"2-6-5-4-2-1": the order of pump in operation is 2, 6, 5, 4, 2, and 1 during the whole rainfall event;
[d]"5-6-4-5-4-3-2-1": the order of pump in operation is 5, 6, 4, 5, 4, 3, 2, and 1 during the whole rainfall event.

2.3. Water samples and analysis

The water samples were collected using an automatic portable sampler (6712, Teledyne Isco) at the pumping station forebay located at the outlet of the drainage system. The automatic sampler was connected to a data-logger to record every 15 min. More specifically, the sampling started when the flow pumps started and ended when the discharge was completed. If the discharge was larger than the automatic sampler capacity (i.e., 24×1-L bottle), sample bottles were changed to ensure continuous sampling. All the observed samples were transported and stored at 4°C to the laboratory, and analyzed within 8 h after the collection. Total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), ammonia nitrogen (NH_4^+–N), and total phosphorus (TP) were determined.

Since COD and TP are strongly correlated to TSS in UWWD and regarded as indicators of organic pollution and eutrophication in water bodies [4], both of them were measured in all the rainfall events, while TSS was only measured in the selected events. NH_4^+–N is soluble and mainly from the inappropriate or illicit connected non-stormwater [5,26,28]. In order to analyze the contributions of these non-stormwater to UWWD, NH_4^+–N was analyzed in all the rainfall events. All the parameters were tested in triplicate to ensure precision and accuracy. The limits of detection (LOD), limit of quantitation (LOQ) and detail determination protocol were in accordance with the Chinese standard methods.

2.4. Mass first flush ratio

MFF describes the effect of first flush in each event [29]. It is a useful index and can be used to calculate the proportion of the cumulative load of a given pollutant to the cumulative discharge at any time [21,22]. The equations were shown as follows:

$$MFFn = \frac{\sum_{t=0}^{k} C_t Q_t \Delta t / M}{\sum_{t=0}^{k} Q_t \Delta t / VD} \tag{1}$$

$$FFn = \sum_{t=0}^{k} Q_t \Delta t / VD \tag{2}$$

where C_t (mg/l) is the pollutant concentration at time t; Q_t (m^3/s) is the discharge flow rate at time t; Δt (min) is the interval time between two samples; M (g) is the total load of discharge in an event; VD (m^3) is the total discharged volume in an event; n is the point in a discharge corresponding to the percentage of the discharge; and FFn is the ratio of cumulative volume discharged for the n to VD; and k is the time corresponding to n. The values of MFF of the pollutants were calculated to describe the characteristics of the discharge. If MFF is greater than one, then the first flush effect exists. A greater MFF value indicates a stronger first flush effect. Previous studies demonstrated that MFF_{30} is a suitable index to characterize the first flush effect [21,30].

2.5. Declining ratio

To better compare the influences of different rainfall and antecedent discharge on pollutant concentrations, the declining ratio (r_i) of each pollutant was obtained using the following formula:

$$r_i = \frac{C_{i,initial} - C_{i,end}}{C_{i,initial}} \times 100\% \tag{3}$$

where i is the pollutant types; r_i (percentage) is the declining ratio of the given pollutant; $C_{i,end}$ (mg/l) is the final concentrations in an event (i.e., the pollutant concentrations of the last sample); and $C_{i,initial}$ (mg/l) is the initial concentrations of an event.

3. Results and discussions

3.1. Pollutant concentration characteristics

As shown in Table 2, except NH_4^+–N in event E1, generally all the concentrations show downward trends. The total rainfall in E1 was only 0.5 mm; therefore, most of the precipitation seeps into the ground and produce almost no surface runoff. In other words, NH_4^+–N concentration was mainly correlated with the interconnected wastewater and there is no stormwater dilution effect in which NH_4^+–N concentration decreases. The occurrences of COD, TP and TN were affected not only by the sediments but also by the interconnected wastewater. The decreasing concentration of them were mainly due to the sediments discharged out by the overflow.

Generally, the declining ratios of main pollutants were proportional to the volume discharged, except the COD and TP in E2 and E5. The plausible explanation might be that their initial concentrations were the lowest in all nine events, though their discharged volume were larger than E1 and E3. Therefore, the declining ratios of COD and TP were not only related to the volume discharged but also the initial concentrations.

3.2. Contribution of different sources in the process of discharge

Fig. 2 shows the pollutant concentration variation of nine rainfall events. Generally the discharge occurs immediately or shortly after the peak rainfall. NH_4^+–N and TN had the same changing tendency; TP was relatively stable; and COD fluctuated continuously. More explicit, as shown in Fig. 2a, E2 had an early peak rainfall with the rainfall of 2.2 mm in an hour. The initial concentrations of COD, TP, NH_4^+–N and TN were 235 mg/l, 3.58 mg/l, 26.7 mg/l and 29.9 mg/l, respectively. During the period of 13:40–14:00, there were small peaks of COD, but not for TP, TN and NH_4^+–N.

The previous observation of the surface runoff in Shanghai shows that COD and TSS were the main pollutant sources. For example, Jing et al. (2006) measured the EMC of TSS, COD, TP, NH_4^+–N and TN with the values of 431–1731 mg/l, 150–749 mg/l, 0.425–1.005 mg/l, 0.865–2.185 mg/l and 1.5–3.2 mg/l in the city center of Shanghai, respectively [31]. Ji et al. (2012) also reported similar results in the city center of Shanghai [32]. Consequently, the results indicate that the concentration fluctuations of COD in discharge were affected by the runoff pollution in the event with the early peak rainfall and low initial concentrations. However, the concentrations of TP, NH_4^+–N and TN were not signifi-

Table 2
The three groups and declining ratios of pollutants each event

Group	Event number	Pumps operating mode	Declining ratios				
			TSS	COD	NH_4^+–N	TP	TN
Group 1	E1	1[a]	–	28%	–10%	28%	4%
	E2	1[a]	–	13%	31%	27%	30%
	E3	1[a]	–	49%	33%	26%	39%
	E4	1[a]	84%	82%	62%	78%	–
	E5	1[a]	–	39%	52%	10%	52%
Group 2	E6	1-2-1[b]	73%	63%	35%	57%	–
	E7	1-2-1[b]	–	93%	59%	66%	54%
Group 3	E8	2-6-5-4-2-1[c]	93%	86%	79%	74%	–
	E9	5-6-4-5-4-3-2-1[d]	–	87%	95%	73%	–

"–": parameter was not tested.
[a]"1": only one pump was in operation during the whole rainfall event;
[b]"1-2-1": firstly one pump was in operation; then two pumps were in operation; finally only one pump was in operation again;
[c]"2-6-5-4-2-1": the order of pump in operation is 2, 6, 5, 4, 2, and 1 during the whole rainfall event;
[d]"5-6-4-5-4-3-2-1": the order of pump in operation is 5, 6, 4, 5, 4, 3, 2, and 1 during the whole rainfall event.

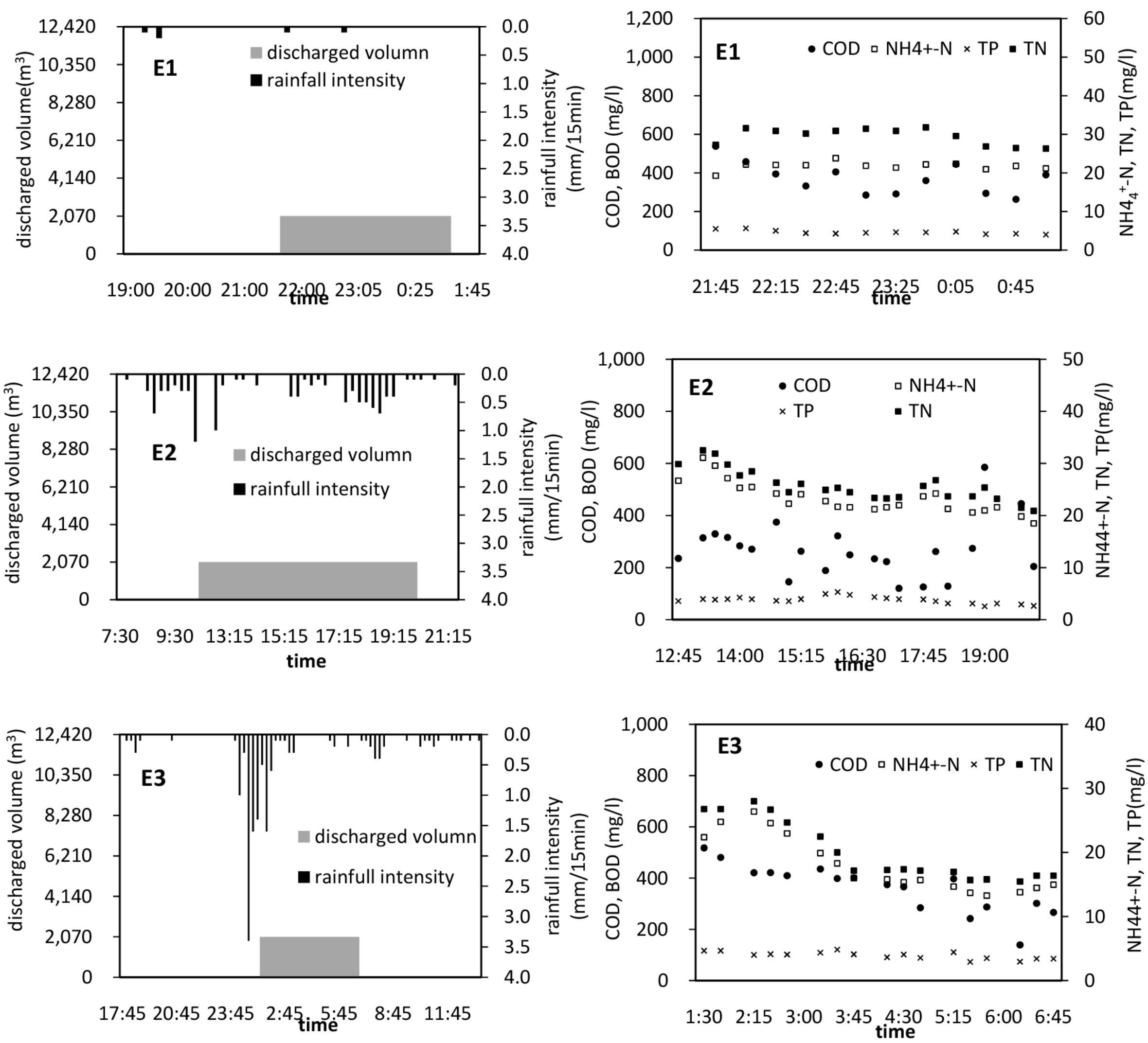

Fig. 2(a). The variation of pollutant concentrations in nine events (a) Pollutant concentrations variation for five rainfall events in group 1.

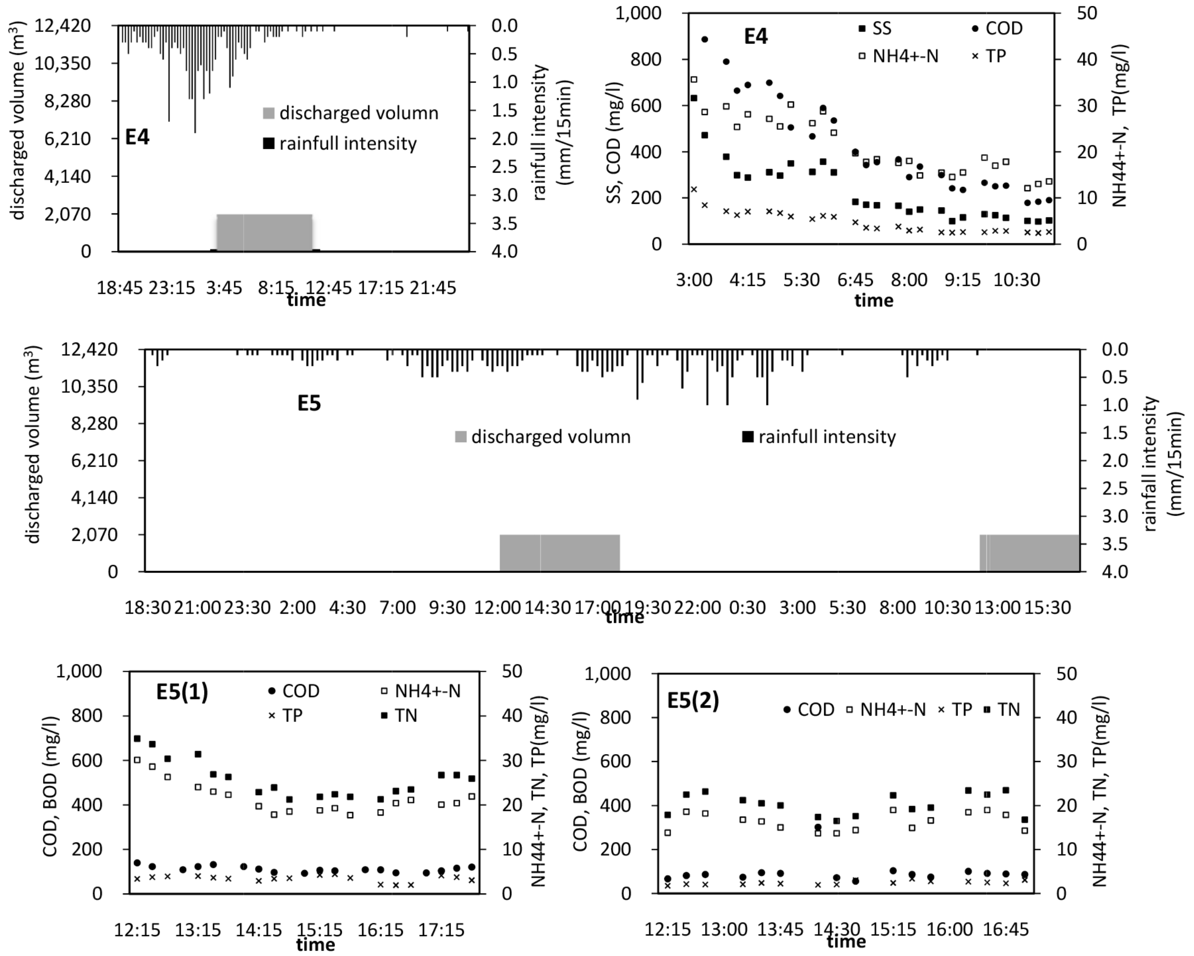

Fig. 2(a). The variation of pollutant concentrations in nine events (a) Pollutant concentrations variation for five rainfall events in group 1.

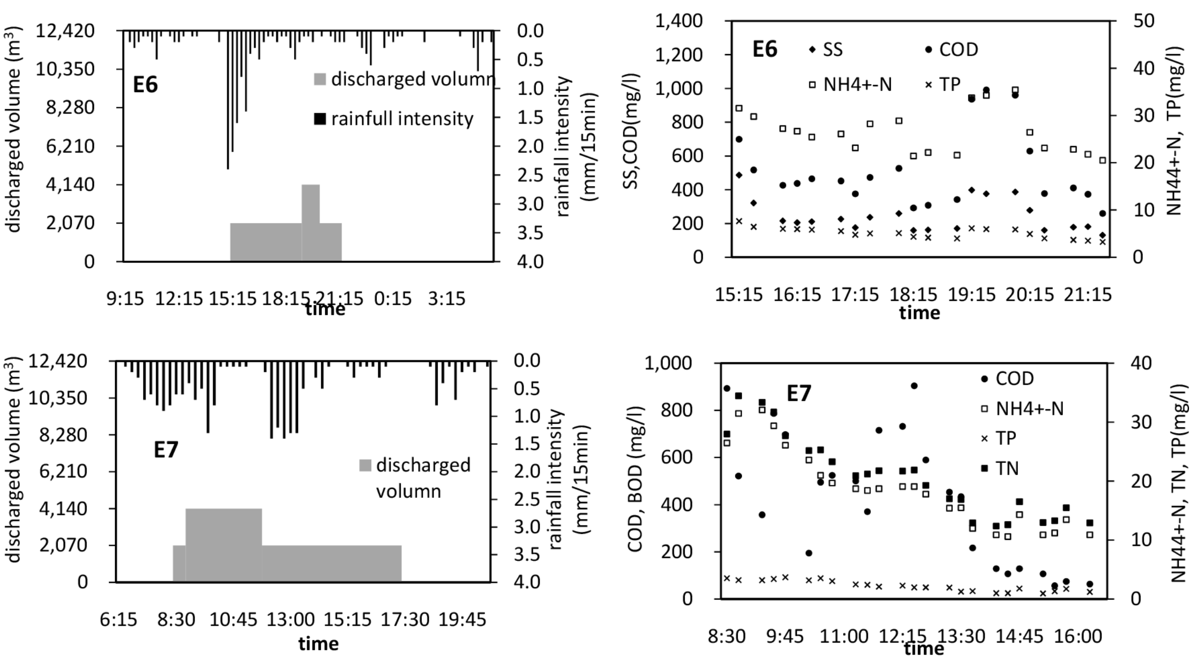

Fig. 2 (b). The variation of pollutant concentrations in nine events (b) Pollutant concentrations variation for two rainfall events in group 2.

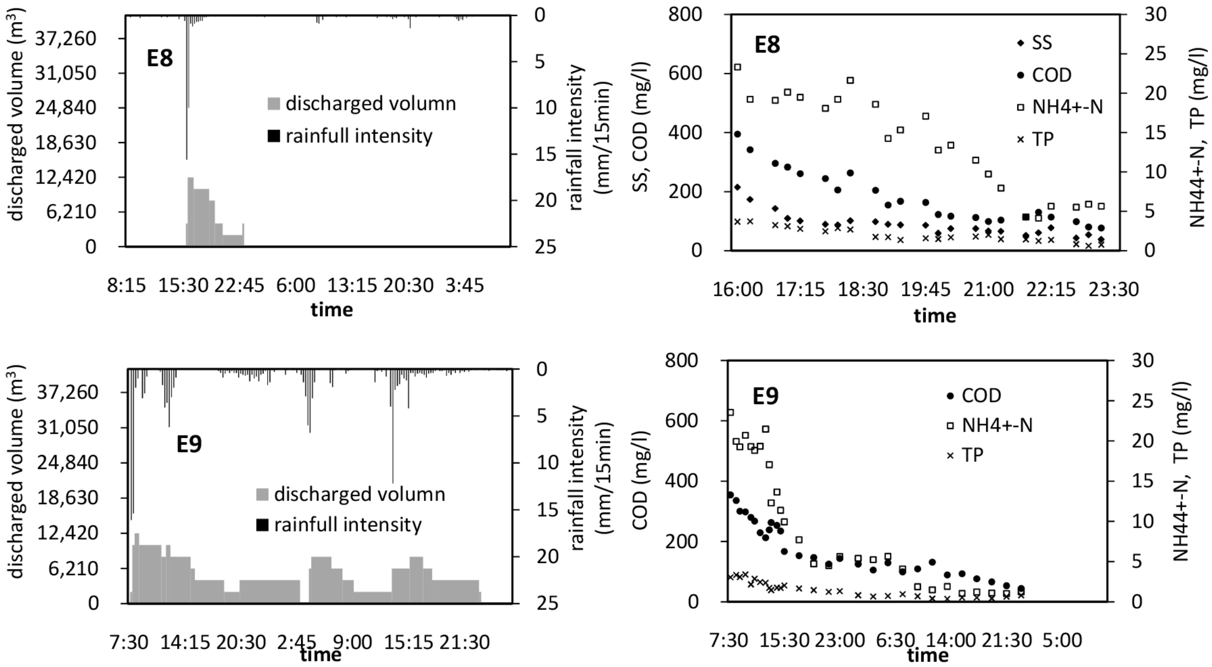

Fig. 2 (c). The variation of pollutant concentrations in nine events (c) Pollutant concentrations variation for two rainfall events in group 3.

cantly affected by the runoff pollution, because their concentrations in the runoff were much lower than the initial concentrations in the discharge. NH_4^+–N and TN had peaks from 18:00 to 19:00 mainly due to the wastewater produced by human activities in the evening.

In terms of E3 with COD initial concentrations of 518 mg/l as shown in Fig. 2a, there was no COD peak in the early discharge, which could be affected by the due to the strong influences of the discharged sediment and interconnected wastewater. In the later period (5:15–6:45), the pollutants concentration in runoff was, however a COD peak appeared. The possible reason could be the primary contribution of by the interconnected wastewater produced by the human activities. The results indicate that the COD peak in E3 might be caused by the interconnected wastewater rather than the stormwater surface runoff.

As for E4 with the highest COD initial concentrations of 1076 mg/l as shown in Fig. 2a, there was a COD peak between 4:15 and 5:15; however, the SS concentration was the low in the same time. It has been reported that of a strong positive correlation was usually found between SS and COD in stormwater surface runoff [32,33]. Therefore, similar to E3, the COD peak in E4 might be caused by the interconnected wastewater and sediments rather than the stormwater surface runoff.

E5 was a low mean intensity rainfall event (0.69 mm/h) with a long duration (41 h). The initial COD concentration of 140 mg/L was the lowest in the nine events. TP concentration of 3.4 mg/L was the second lowest in the nine events. This result suggests that the in sewer process of sediment (re-suspension and transport) had limited effects on the pollutants concentrations. In addition, two discharges during the event were observed. The first discharge was observed from 12:15 to 17:45, 18 h after the start of the rainfall. At 15:15, the concentrations of COD, TP, NH_4^+–N and TN decreased rapidly (the declining ratios of COD, TP, NH_4^+–N and TN were 34%, 44%, 39% and 39% respectively) because of the initial discharge of the pre-stored wastewater within 3 h. After 15:15, the concentrations of pollutants increased due to the less runoff volume (low rainfall intensity) and the contribution of the interconnected wastewater (the increasing ratios are 30%, 39%, 18% and 22%, respectively). The second discharge occurred 15 min after the end of the rainfall. The concentrations of COD, TP, NH_4^+–N and TN stayed stable. It is because the minor contributions from the surface runoff and sediment. However, the interconnected wastewater became the most influencing factor.

In E6 and E7 as shown in Fig. 2b, the pollutants increased quickly when the two pumps were in operation. It is due to the increased flow that transported more sediments into river. In other words, more pumps are in operation, the flow velocity in the sewer system are higher, and then more deposits accumulated inside the sewer system would be re-suspended by the rapid increase of the flow. The plausible explanation is that when the peak rainfall is higher, more than two pumps will be in operation, which will increase the flow velocity in the sewer system. Then more deposits accumulated inside the sewer system would be re-suspended by the rapid increase of the flow. The fluctuation related to the pumps in operation is consistent with a study reported by Li et al. (2013) that a pump lift drainage system in Shanghai [26].

As shown in Fig. 2c, the initial COD and TP concentrations in E8 and E9 were lower than their concentration in the other events (except for E2 and E5). In both events, the sediment effect was minimum. In E8, there were small peak concentrations of COD and TP (at 18:15) after 135 min of the peak rainfall. During this time period, the operating pumps were always five, indicating that there was no influence from the operating pump change. Due to the large stormwater volume induced dilution effect, it does not produce a corresponded concentration peak in subsequent discharge. NH_4^+–N concentration was stable before 18:15. However, it declined rapidly afterward. These results indicate that a large volume of stormwater reached the outlet after 18:15, and the discharge before 18:15 was from the earlier runoff including non-point pollution that produced small peaks of COD and TP.

In E9, the first peak of COD in discharge appeared at 13:05–13:45 (290 min after the first peak rainfall). The second peak appeared at 9:30–11:30 on the next day (275 min after the third peak rainfall). Then the COD concentration decreased continuously. Previous studies reported that if hourly rainfall is more than 12.7 mm the stormwater can wash away more than 90% of the pollutants from the surface [34]. In E9, the first, second, and third peaks of rainfalls were 34.5 mm/h, 18.5 mm/h and 11.9 mm/h, which were sufficient to wash the surface pollutants away. Therefore, the pollution in the runoff generated from the fourth peak was quite less and there was no COD peak caused by the runoff pollution in the subsequent discharge. NH_4^+–N declined significantly after 280 min of the rainfall, indicating that most runoff was transported to the outlet after 280 min.

In nine events, overall, the influences from surface pollutants were not obvious on the discharges except for E8, E9 and E2. Sediments and interconnected wastewater were the most significant impact factors on the pollutant concentrations.

3.3. Downward inflection points of discharge concentration

As shown in Table 1, the nine events had different characteristics. There were little correlation between the time of the rainfall peak and the time of the COD peak concentrations in the discharge. In E1, E2 and E6, the pollutants had no obvious downward inflection points. In E3, E5, E4, E7, E8 and E9, the downward inflection points were encountered when the cumulative rainfall reached 12.1 mm at 3.5 h, 13.2 mm at 4.5 h, 27.4 mm at 6 h, 17.1 mm at 6.5 h, 34.3 mm at 2.3 h, and 65.7 mm at 14 h, respectively. These results suggest that the downward inflection points were not notable in the small rainfall events and the inflection time varied in moderate and heavy rainfalls. In Caohejing drainage system, consequently, in order to achieve the cost-effective discharge control measures, the optimizing interception engineering should be considered in accordance with the specific characteristics of different events.

3.4. First flush effect analysis using MFF

3.4.1. Correlations between the rainfall variables, initial concentrations, and MFF30

The correlations between the rainfall variables, initial concentrations, and MFF_{30} were shown in Fig. 3. Generally, a positive correlation exists between total rainfall, rainfall duration, mean rainfall intensity and MFF30, which represents the local rainfall characteristics. More explicit, the local rainfall characteristics is that a rainfall event with a higher total rainfall usually caused by a longer duration time with a higher mean rainfall intensity. Among these variables, the total rainfall has a great influence on the first flush load. The plausible explanation is that when the total rainfall is higher, more than two pumps will be in operation, which will increase the flow velocity in the sewer system. Then more deposits accumulated inside the sewer system would be re-suspended by the rapid increase of the flow that leads to a higher value of MFF30.

However, a negative correlation was found between antecedent dry weather period and MFF30. The plausible explanation could be that in this study the rainfall event with a longer antecedent dry weather period always has a lower total rainfall. Under the most small total rainfall conditions, only one pump was in operation. Therefore, less deposited sediment would be transported and discharged, which finally lead to a low value of MFF30.

The plausible explanation is that when the total rainfall is higher, more than two pumps will be in operation, which will increase the flow velocity in the sewer system. Then more deposits accumulated inside the sewer system would be re-suspended by the rapid increase of the flow that leads to a higher value of MFF30. Furthermore, an obviously correlations between MFF30 and the initial concentrations of COD, TP, and NH_4^+–N were not found. More insight research was needed to further access the effect the rainfall variables on the first flush effect with more database.

3.4.2. Inter-event MFF variability

The first flush effects of all the parameters were studied by plotting the MFF against the cumulative runoff volume as shown in Fig. 4. When the total rainfall was less than 20 mm as shown in Fig. 4a, the first flush ratio of the pollutants was relatively smaller than the events with total rainfall more than 20 mm as shown in Fig. 4b. In addition, for similar initial concentrations, a larger volume discharged produces a larger MFF_{30}. For instance, E8 and E9 had similar initial concentrations of COD, NH_4^+–N and TP, and the volume discharged of E9 was 4.7 times more than E8. MFF_{30} of the observed COD, NH_4^+–N, and TP concentrations in E9 ranged from 1.7–2.3 and E8 ranged from 1.2–1.5. For the similar total rainfalls, the first flush effect was positively correlated to the initial concentrations, i.e. sediment in pipe. For instance, the initial concentrations of COD, NH_4^+–N, TP in E4 were 669%, 19% and 249% that were higher than them in E5. MFF_{30} in E4 ranged from 1.55 to 1.65 except for NH_4^+–N (1.3), which were greater than MFF_{30} in E5 with a range of 1.1–1.2.

In the events with the similar total rainfalls, initial concentrations and pump operating mode, more pumps in operation in the initial rainfall event have more clear first flush effect than them in operation in the late rainfall event. For example, E6 and E7 had 19.1 mm and 21.8 mm of total rainfall, and their initial concentrations of COD and NH_4^+–N were similar. They also had the same "1-2-1" pump-operating mode. The differences between the two events were that two pumps were in operation 0.5 h after the overflow occurred; however, two pumps were in operation 4 h after the overflow occurred. The MFF_{30} of COD, NH_4^+–N, and TP of E7 ranged from 1.3 to 1.5, which were larger than the MFF_{30} of E6 ranged from 0.8 to 1.15.

3.4.3. Inter-pollutant MFF variability in an event

For different pollutants, the first flush effects were different in all nine events. In E1 with 0.5 mm total rainfall and

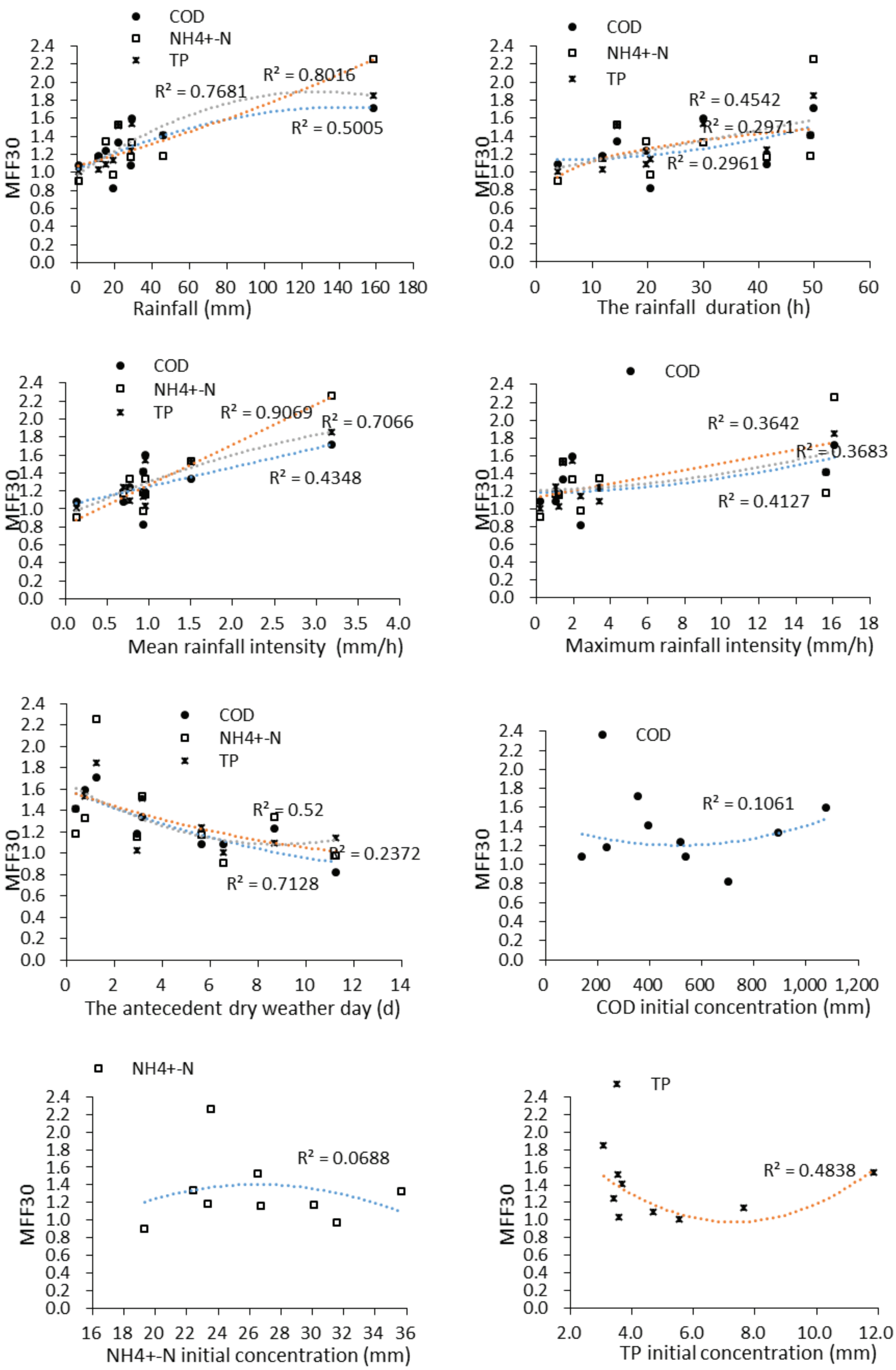

Fig. 3. Correlations between the rainfall variables, initial concentrations, and MFF_{30}.

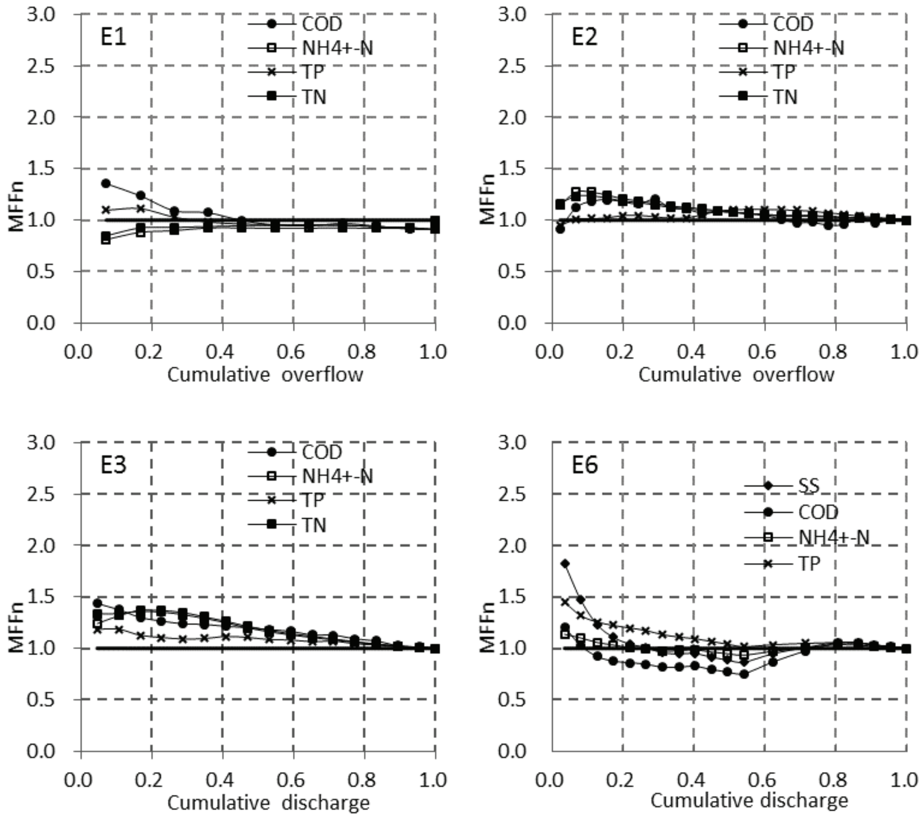

Fig. 4(a). MFF values of COD, NH_4^+–N, TP and cumulative discharge in the study area (a) Total rainfall less than 20 mm.

no surface runoff, COD and TP were mainly related to the deposited pipe sediments that accumulated due to the sanitary and industrial sewage inputs during the dry periods, and the first flush effects were expected. NH_4^+–N and TN were mainly related to the interconnected wastewater and first flush effects were not significant. When the total rainfall was small, such as E2 (11.2 mm) and E3 (15.3 mm), the first flush effects of COD, NH_4^+–N and TN were greater than the first flush effect of TP. When total rainfall was larger, the MFF of different pollutants in an event was related to their initial concentrations. To compare the impacts of initial concentrations of different pollutants to the corresponded Inter-event averaged concentrations in the discharge, an averaged value for each event relative to the all nine events is needed to represent the overall pollutant discharge:

$$\varphi_{j,i} = \frac{C_{j,i,initial}}{\frac{\sum_{j=1}^{9} EMC_{j,i}}{9}} \tag{4}$$

$$EMC_{j,i} = \frac{M_{j,i}}{VD_{j,i}} \tag{5}$$

where i is the pollutant type; j is the event number; $\varphi_{j,i}$ is the ratio of i^{th} pollutant in j^{th} event to the averaged EMC of the same pollutant in all 9 events; $C_{j,i,initial}$ (mg/l) is the initial concentration of i^{th} pollutant in j^{th} event; and $EMC_{j,i}$ (mg/l) is the event mean concentration for i^{th} pollutant in j^{th} event.

In an event (j) with the total rainfall larger than 19 mm, and if the $\varphi_{j,i}$ is larger, the first flush effect of this pollutant (i) is more obvious than the other pollutants, and vice versa. For example, in E5, such ratios ($\varphi_{4,i}$) of COD, NH_4^+–N, TP and TN were 0.4, 1.6, 1.0 and 1.5, respectively. Then the MFF of these four pollutants were in the order of TN≈ NH_4^+–N > TP > COD. In E4, the ratios of TSS, COD, NH_4^+–N and TP were 3.4, 3.4, 1.9 and 3.5, respectively. MFF of these four pollutants were in the order of COD ≈ TSS ≈ TP > NH_4^+–N. If the ratios of different pollutants in a rainfall event were close to each other, then the order of MFF varies. For example, the ratios of TSS, COD, NH_4^+–N and TP in E8 were 1.1, 1.3, 1.2 and 1.1, respectively; the ratios of COD, NH_4^+–N and TP in E9 were 1.1, 1.2 and 0.9, respectively. The MFF orders of pollutants in these two events were COD ≈ TSS > TP > NH_4^+–N (E8) and NH_4^+–N > TP > COD (E9), which were inconsistent with the orders in E8 and E9.

3.5. Discharge load distributions

Table 3 calculated the discharge loads of FF30, FF40, FF50, FF60 and FF70 (corresponding to the ratio of cumulative volume discharged for the 30%, 40%, 50%, 60%, 70% to total volume discharged in an event) for the main pollutants (COD, NH_4^+–N and TP) in all nine events. An average of 39% of the pollutant load was discharged into the receiving waters in the first 30% of the discharged volume. An average of 78% the pollutant load was discharged in the first 70% of the volume discharged. The results show the

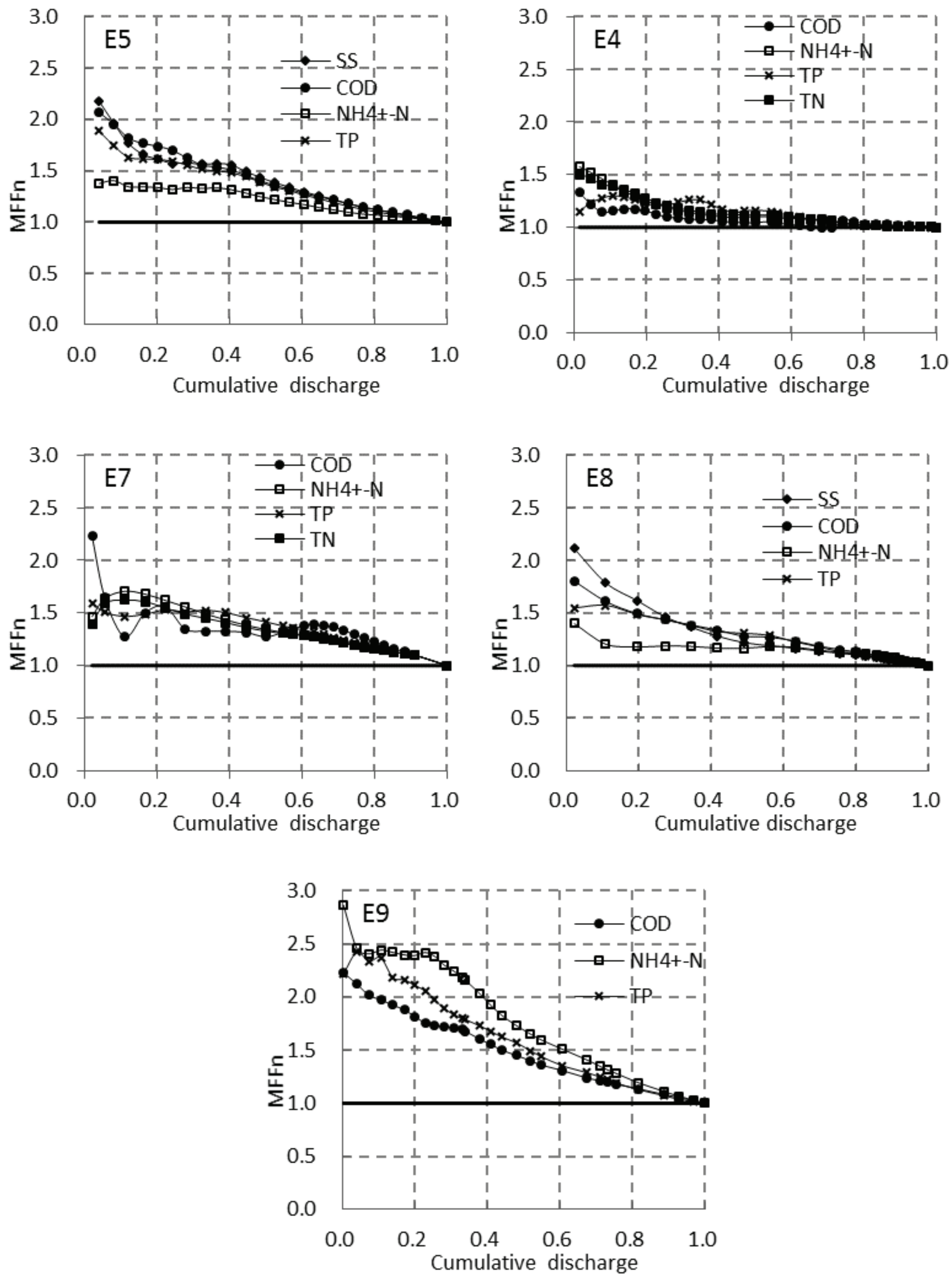

Fig. 4(b). MFF values of COD, NH_4^+–N, TP and cumulative discharge in the study area (b) Total rainfall larger than 20 mm.

first flush effects in our study site is smaller to the founding of Park et al. (2010). for the combined sewer discharges [21] and Li et al. (2015) for a rapidly industrialized City [35], and is similar to the results from Bertrand et al. (1998) for 12 separate and combined sewer systems [36] and Lee et al. (2014) for urban stormwater discharges [23]. In general, every 10% increase in the cumulative discharge removed an average of 10% more pollutants. However, in each specific event, the cumulative loads of the main pollutants for FF30, FF40, FF50, FF60 and FF70 varied because of the different impact factors. If 30% of the discharge were intercepted, then E9 would intercept the most pollution: 52% COD, 69% NH_4^+–N, and 56% TP. The least intercepted pollution, however, were in different events: 25% COD in E6, 27% NH_4^+–N in E1, and 30% TP in E2.

3.6. Treatment suggestion

In a small rainfall event, if the initial concentration of a certain pollutant was high, the concentration of this pollutant remained high in the whole discharge. Therefore, it is essential to intercept the whole discharge. In a moderate to heavy rainfall event, it is important to choose an intercepting point to capture more pollution with less volume discharged. This result can be used to establish a reliable method to design the treatment facilities. Based on the

Table 3
Statistical discharge load of FF30, FF40, FF50, FF60 and FF70 for COD, NH_4^+–N and TP

Events	COD					NH_4^+–N					TP				
	FF30	FF40	FF50	FF60	FF70	FF30	FF40	FF50	FF60	FF70	FF30	FF40	FF50	FF60	FF70
E1	33%	41%	49%	56%	66%	27%*	37%*	46%*	55%*	64%*	30%	39%	47%	56%	66%
E2	35%	44%	55%	63%	67%*	34%*	46%*	55%*	63%*	73%*	30%*	43%	56%	66%	76%
E3	36%	50%	61%	69%	80%	39%*	52%*	58%*	67%*	78%*	31%	46%	55%	64%	76%
E4	48%	61%	70%	77%	83%*	40%	53%*	62%*	71%*	77%*	46%	60%	70%	77%	82%*
E5	33%*	43%*	52%*	61%*	70%*	35%*	46%*	56%*	66%*	75%*	37%	48%*	58%	66%	74%
E6	25%	33%	39%	53%	69%	30%	40%*	47%*	60%	72%	35%	44%	52%	62%	75%
E7	39%	53%	64%	84%	94%	46%*	57%*	67%*	78%*	86%*	45%	59%*	71%*	81%*	87%*
E8	41%*	54%*	63%*	75%*	82%*	34%*	47%*	57%*	71%*	80%*	41%	53%*	64%*	75%*	82%*
E9	52%	63%*	72%*	79%*	86%*	69%*	79%*	85%*	91%*	96%*	56%*	68%*	76%*	82%*	89%*
Mean	38%	49%	58%	69%	77%	39%	51%	59%	69%	78%	39%	51%	61%	70%	79%
Maximum	52%	63%	72%	84%	94%	69%	79%	85%	91%	96%	56%	68%	76%	82%	89%
Minimum	25%	33%	39%	53%	66%	27%	37%	46%	55%	64%	30%	39%	47%	56%	66%
Standard deviation	0.08	0.10	0.11	0.11	0.10	0.12	0.12	0.12	0.11	0.09	0.09	0.10	0.10	0.09	0.07

*indicates under this interception ration, the discharged flow quality was accepted within the national standard regulation (COD ≤ 150 mg/l, NH_4^+–N ≤ 25 mg/l, TP ≤ 3 mg/l).

analysis of the discharge load distributions, 60% COD load could be removed by intercepting the initial 40% of the discharge in E4 and E9, initial 50% of the discharge in E3, E8 and E7, and initial 60% of the discharge in E5.

TP shows the similar results to COD. For NH_4^+–N, 60% could be captured by intercepting the initial 50% of the discharge in E4 and E7, and 60% of the discharge in the rest four events. These results indicate that the MFF of COD and TP were higher than the MFF of NH_4^+–N for the same MFF. For COD and TP, that event with a larger total rainfall (E8 and E9) or higher initial concentration (E4) may intercept more pollutants by intercepting the same discharge volume for some MFF.

In nine events, as shown in Table 1 and Fig. 2, if the interval time between the two adjacent discharges were shorter and the antecedent discharged volumes were larger, the initial concentrations were lower (E5, E8 and E9). Accordingly if the total rainfall was larger, the concentrations during the later stage of the discharge were lower, which was accepted within discharge regulation (Table 3). For E5, COD concentration in the second discharge was less than 150 mg/l and met a specified water pollutant discharge standard (GB8978-1996, GB18918-2002). The discharge also accounts for 92% of the total discharge. For E8 and E9, the COD and TP concentrations during later stage of the discharge were less than 150 mg/l and 3 mg/l. The discharges meeting the required standard for COD and TP accounting for 86% and 69% of the total discharge for E8, and accounting for 61% and 88% of the total discharge for E9, respectively. In the three events (E5, E8, E9), the influence of the pollution during the later stage of the discharge on the receiving waters was low and therefore the flow can be discharged directly.

For the events with long interval time between two adjacent wet discharges and small antecedent volume discharged, even if the antecedent dry weather period was short and total rainfall was moderate, the initial concentrations of the pollutant were still high, and the concentrations remained at a relatively high level in the whole discharge (i.e., E4, SS: 633–102 mg/l, COD: 1077–191 mg/l, NH_4^+–N: 35.7–13.6 mg/l, TP: 11.9–2.7 mg/l). In these cases, the whole discharge needs to be intercepted.

4. Conclusion

In a storm drainage interconnected with inappropriate or illicit sewers, major pollutants in nine wet weather discharges were analyzed to identify the main influencing factors on the pollutant concentration variations. Results show that compared to the surface runoff source contribution, accumulated sediments and interconnected wastewater in storm drainage were the main sources of pollutants in UWWD in Caohejing catchment. Rainfall variables, discharged variables and the pump operation modes were also the important factors on the pollution loads.

MFF analysis shows that when total rainfall was small, the first flush effect was relatively weak (E1, E2, E3); when total rainfall was moderate, the first flush effect was more clear and followed by obvious decline trends for all the pollutants (E4 and E7). However, if there were more operating pumps and the volume discharged was low, there was no first flush effect (E6). For the event with lower initial concentrations, the first flush effect was small (E5). When total rainfall was large (> 50 mm), the first flush effect of main pollutants was obvious (E8, E9). In each event, the cumulative loads of main pollutants for MFF were different due to the different influencing factors. If the rainfall was heavier or the initial concentration was higher, the first flush effects were more obvious, and more pollutants can be intercepted with less percentage of discharge interception.

Consequently, different interception suggestions can be considered based upon the different rainfall types. The discharges of these events with small total rainfall or little antecedent volume discharged will affect the receiving water environment, which is the main control objective. For moderate to heavy rainfall, the water quality at the end of the discharge was normally acceptable, and thus one may consider allowing later discharge into the receiving water according to the rule of first flush effect and concentration variations.

Disclosure statement

No potential conflict of interest was reported by the authors.

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