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RESEARCH ARTICLE

Characteristics of the overflow pollution of storm drains with inappropriate sewage entry

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Abstract To probe the overflow pollution of separate storm drains with inappropriate sewage entries, in terms of the relationship between sewage entries and the corresponding dry-weather and wet-weather overflow, the monitoring activities were conducted in a storm drainage system in the Shanghai downtown area (374 ha). In this study site, samples from inappropriately entered dry-weather sewage and the overflow due to storm pumps operation on dry-weather and wet-weather days were collected and then monitored for six water quality constituents. It was found that overflow concentrations of dry-weather period could be higher than those of wet-weather period; under wet-weather period, the overflow concentrations of storm drains were close to or even higher than that of combined sewers. Relatively strong first flush mostly occurred under heavy rain that satisfied critical rainfall amount, maximum rainfall intensity, and maximum pumping discharge, while almost no first flush effect or only weak first flush effect was found for the other rainfall events. Such phenomenon was attributed to lower in-line pipe storage as compared to that of the combined sewers, and serious sediment accumulation within the storm pipes due to sewage entry. For this kind of system, treating a continuous overflow rate is a better strategy than treating the maximum amount of early part of the overflow. Correcting the key inappropriate sewage entries into storm drains should also be focused.

Keywords Storm drains · Overflow pollution · Illicit cross-connection · First flush · Pumping discharge

Introduction

A storm drain system is designed to prevent the accumulation and retention of urban storm water runoff on city surfaces and to discharge accumulated waters into receiving waters. On dry-weather days, however, non-storm water discharges also find their way into storm water drainage systems; this phenomenon can be defined as storm drains with inappropriate entries, which may originate from illicit connections of unintended sewer cross-connections that connect foul water outlets from residential or industrial premises to the storm drainage system, and extraneous water intrusion into storm drains (Deffontis et al. 2013; Field et al. 1994; US EPA 2004; Xu et al. 2014). If this situation occurs, the overflow pollutants from the storm drains on dry-weather days as well as wet-weather days could severely deteriorate the receiving water quality, e.g., the occurrence of a black river and a foul stench. Therefore, it is necessary to study the overflow pollution characteristics of storm drains with inappropriate sewage entry, providing strategies for the overflow control of such drainage systems.

Since the 1970s, numerous studies have emphasized the importance of pollutant loads conveyed by combined wet weather discharges and their adverse impacts on receiving waters (Becouze-Lareure et al. 2016; Brombach et al. 2005; Chebbo 1992; Chebbo et al. 2001; Even et al. 2004; Gasperi et al. 2012; Kafi et al. 2008; Madoux-Humery et al. 2013; Rouff et al. 2013; Saget 1994; Seidl et al. 1998; Yu et al. 2013). As a

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result, databases such as QASTOR (a database covering the Paris region of France) and ATV-DVWK Datenpool 2001 (a database sponsored by the German Association for Water) for combined wet-weather overflows on urban catchments were presented. There are also literatures concerning storm water monitoring programs to identify high-risk discharges, and therefore to assist in the development of total maximum daily loads (e.g., Lee et al. 2007; US EPA 1983). For the storm water runoff and combined sewers overflow, the first flush phenomenon has been a subject of numerous discussions as well (Barco et al. 2008; Bertrand-Krajewski et al. 1998; Deletic 1998; Geiger 1987; Gikas and Tsihrintzis 2012; Lee et al. 2002; Lee et al. 2004; Li et al. 2007; Obermann et al. 2009; Park et al. 2010; Shen et al. 2016; Zushi and Masunaga 2009).

The combined sewers are mainly employed in the city's old urban area; by comparison, in the newly developed areas, the storm water is usually collected in an independent network, i.e., a separate storm and sewer system. The pollution of separate storm drains can be from different sources: rainwater quality, urban runoff from roofs/roads, illicit connections, illegal dumping, discharges from authorized companies, and so on. For separate storm drains, while studies have already been made on storm water characterization, concerning overall wet-weather pollution parameters (Pitt et al. 2003; Hathaway and Hunt 2011; Peng et al. 2015; Zgheib et al. 2011; Zgheib et al. 2012), and pollution characteristics comparisons with combined sewers (Brombach et al. 2005; Carleton 1990; De Toffol et al. 2007; Mannina and Viviani 2009), much less work on discussing the overflow pollution characteristics of separate storm drains with inappropriate sewage entry has been published so far, especially in terms of the relationship between dry-weather sewage entries and the corresponding dry/wet weather overflow pollution.

The present study was thus carried out in order to characterize the overflow pollution of water discharge from separate storm drains with inappropriate sewage entry. To this end, one separate storm drainage system in downtown area of Shanghai, which exhibited serious sewage connections to the storm pipes and was listed as one of the urban drainage systems to be corrected in first priority in Shanghai, was selected as the study site. The monitoring activities were conducted for the discharge flows on dry-weather days and wet-weather days in this site. Such a study will lead to a better knowledge of the phenomena of overflow pollution from a malfunctioned separate storm drainage system. It would then be possible to propose overflow pollution control strategies for such a kind of drainage system.

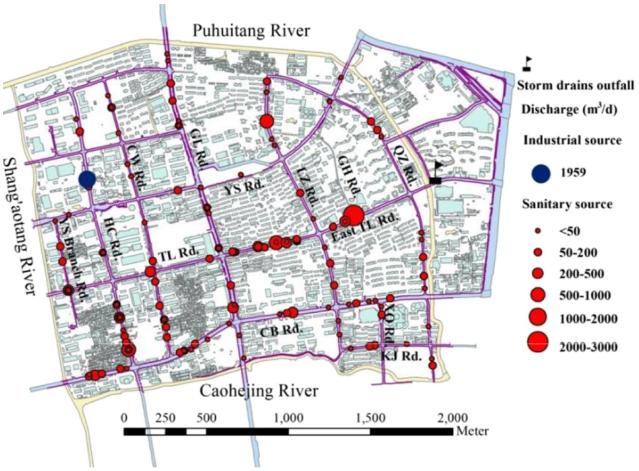
Materials and methods

Site description and outflow characteristics

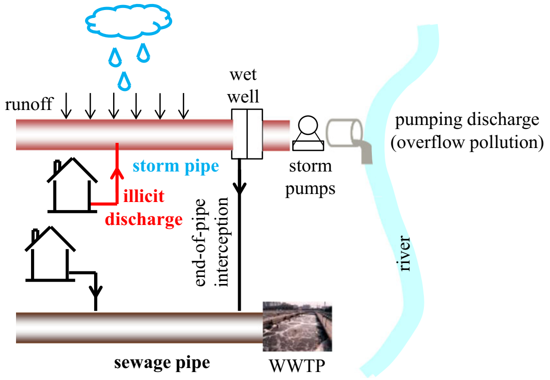
Our study site is typical of high-density urbanized catchment (approximately 270 inhabitants/ha) in Shanghai's downtown area, that is surrounded by three rivers (the Puhuitang, Shang'aotang, and Caohejing Rivers) (Fig. 1a). Completed in 1986, it is an area served by a separate sewer and storm drainage system covering 374 ha. However, non-storm water sources also find their way into storm drains and discharge in an untreated state into local watercourses, resulting in the receiving water bodies' blackness and stench.

As shown in Fig. 1b, there is one outfall for flows in the storm drainage system, where storm pumping station was set up. Flows discharged from the storm drains can be classified into three scenarios:

> *Dry-weather discharge under gravity flow.* According to the onsite investigation and non-storm water flow balance within the storm drains, the sewage with inappropriate entries into storm drains was approximately 18,000 m^3/day, accounting for 46% of the total sewage output in the



(a) Study site featuring inappropriate sewage outfall connections to the storm drains.



(b) Schematic diagram showing the end-of-storm pipe interception treatment for dry-weather flow entries into the storm drains.

Fig. 1 Depiction of the study sites. **a** Study site featuring inappropriate sewage outfall connections to the storm drains. **b** Schematic diagram showing the end-of-storm pipe interception treatment for dry-weather flow entries into the storm drains study site (Xu et al. 2014). Additionally, there was groundwater that infiltrated into the storm drains, with a total flow quantity of about 3484 m^3/day (Xu et al. 2014). Therefore, the sewage mixed with infiltrated groundwater flows from the storm drains on dry-weather days. The sewage outflow was collected by end-of-storm pipe interception sewers and ultimately transported to the nearby wastewater treatment plant (see Fig. 1b).

Dry-weather discharge under storm pump operation. On dry-weather days, when terminal wet well level was higher than the alarm level of 2.60 m in this site, the storm pump was triggered to drain the sewage within the storm drains. The storm pump operation was stopped as the terminal wet well level fell to 1.0 m. Usually, only one storm pump was started for this scenario, and the outfall discharge under each pumping event was 28,593 m^3 on average within duration of about 180 min. Under this circumstance, the pumped non-storm water was discharged into the receiving watercourse, that is, storm drains overflow on dry-weather days.

Wet-weather discharge under storm pumps operation. On wet-weather days, the storm pumps are started to prevent the runoff from accumulating on the surface road and to drain the surface runoff into the nearby watercourse. In this study site, the storm pumps were started when the wet well level reached 2.60 m and were stopped when the wet well level dropped to −1.26 m to empty the in-line storage of the storm pipes. Usually, with an increase of rainfall intensity, the number of storm pumps put into operation increases. At a maximum, six storm pumps can work concurrently, corresponding to a maximum pumping discharge of 13.8 m^3/s.

Water quality monitoring campaigns

As shown in Fig. 1b, to monitor the water quality of the outfall discharge from the storm pipe network, samples were collected from the terminal wet well using an automatic vacuometric sampler (ISCO 6712, Teledyne, Lincoln, Nebraska, USA). For the dry-weather discharge under gravity flow, a total of 10 monitoring activities were conducted during the period March 28, 2011, to May 7, 2012. Each monitoring activity lasted 18~23 h, with a fixed sampling time interval of 1 or 2 h. For the dry-weather discharge under storm pump operation, i.e., storm pipe network overflow on dry-weather days, a total of 10 monitoring activities were conducted during the period May 4, 2011, to March 27, 2012, with a sampling time interval of 20 min for each campaign. For the wet-weather discharge under storm pumps operation, i.e., storm pipe network overflow on wet-weather days, a total of 23 rainfall events were monitored during the period August 18, 2008, to March 1, 2012, with a sampling time interval of 10–20 min for each campaign. In more detail, characteristics of each monitored discharge event under dry-weather and wet-weather conditions are listed in Tables 1 and 2, respectively.

Analytical methods

For the collected water samples, the selected water quality parameters were suspended solids (SS), chemical oxygen demand (COD), 5-day biochemical oxygen demand (BOD_5), ammonia nitrogen (NH_3-N), total nitrogen (TN), and total phosphorus (TP). These parameters were measured in accordance with standard Chinese methods. Specifically, SS was measured by gravimetric method (GB11901–89), COD was measured by dichromate method (GB11914–89), BOD_5 was measured by dilution and seeding method (GB7488–87), NH_3-N was measured by Nessler's reagent spectrophotometry method (GB7479–89), TN was measured by alkaline potassium persulfate digestion-UV spectrophotometric method (GB11894–89), and TP was measured by ammonium molybdate spectrophotometric method (GB11893–89).

Results and discussions

Event mean concentrations of storm drains outfall discharge

For the three kinds of storm drains discharge scenarios, i.e., dry-weather discharge under gravity flow, dry-weather discharge under storm pump operation, and wet-weather discharge under storm pumps operation, statistics of outfall pollutant concentrations is summarized in Table 3. In this table, the event mean concentration (EMC) was presented using the following equation:

$$\mathrm{EMC} = \frac{\int_0^T C(t)Q(t)dt}{\int_0^T Q(t)dt} = \frac{\sum_{i=1}^{m} C_i Q_i \Delta t_i}{\sum_{i=1}^{m} Q_i \Delta t_i} \tag{1}$$

where T is the duration of each pumping discharge event, m is the number of samples collected for each pumping discharge event, $C(t)$ and $Q(t)$ are the pollutant concentration and outfall flow as functions of time, and C_i and Q_i are the monitored pollutant concentration and outfall flow at each time interval Δt_i. Based on Table 3, the following discussions can be presented.

1. For the pollutant indicators of SS, COD, BOD_5, their general concentrations of pumping discharge were higher than those of gravity discharge. The EMCs of pumping discharge on dry-weather days were higher than those on wet-weather days. This phenomenon was related to the

Table 1 Characteristics of monitored dry-weather discharges in the study site

Event no.	Date (day/month/year)	Monitoring duration (h)	Flow capacity (m^3/s)	Antecedent dry weather period (day)	Number of samples collected
(a) Monitored dry-weather discharge events under gravity flow					
1	3/28/2011	23	0.25	4.1	24
2	4/14/2011	23	0.25	21.1	24
3	9/4/2011	23	0.25	0.35	24
4	10/19/2011	17	0.25	2.5	18
5	11/27/2011	23	0.25	9.7	24
6	12/26/2011	22	0.25	2.8	12
7	1/9/2012	22	0.25	1.6	12
8	3/11/2012	22	0.25	0.15	12
9	4/4/2012	22	0.25	1.5	12
10	5/7/2012	22	0.25	2.9	12
Event no.	Date (day/month/year)	Pumping discharge duration (min)	Pumping flow capacity (m^3/s)	Antecedent dry weather period (day)	Number of samples collected
(b) Monitored dry-weather discharge events under storm pump operation					
1	5/4/2011	200	2.3	12.3	11
2	10/20/2011	200	2.3	4	11
3	10/26/2011	180	2.3	1.8	9
4	10/28/2011	160	2.3	2	9
5	11/29/2011	180	2.3	12.1	10
6	12/11/2011	160	2.3	3	9
7	12/13/2011	200	2.3	1.8	11
8	12/15/2011	180	2.3	1.9	10
9	3/26/2012	160	2.3	1.92	9
10	3/27/2012	160	2.3	1	9

illicit sewage cross-connection, and the corresponding sediment deposition and erosion within the storm drains. Usually, storm drains need to be larger to accommodate storm flow, which means that they are often oversized for inappropriately entered sewage flow with low velocities that allow sediments to accumulate. For example, in this study site, the storm drains dimensions range from 0.6 m in diameter to 3.0 m by 2.4-m culvert as the pipe invert becomes deeper; by contrast, the sewers dimensions range from 0.6 to 1.2 m in diameter. When the storm pumps start on dry-weather days or wet-weather days, sediments retained in the storm drains flush out, leading to an increased SS associated with pollutants. Therefore, pollutant concentration of dry-weather discharge under gravity flow is determined by sewage within the storm drains, while pollutant concentration of dry-weather discharge under storm pumps operation is determined by sewage as well as sediment erosion within the storm pipes.

2. We further compared the storm drains' overflow concentrations on wet-weather days with the overflow concentrations of two combined sewer systems (i.e., Jiangxibei and Chengdubei system) in the old downtown areas of Shanghai (Li 2006). It showed that (1) the overflow concentration of SS, COD, and BOD_5 in the study site was close to that of the combined sewers of the old downtown areas of Shanghai. This is related to significant sewage entry into storm drains and the resulting sediment erosion when starting the storm pumps and (2) the overflow concentration of NH_3-N in the study site, however, was significantly higher than that of the combined sewers of the old downtown areas of Shanghai. This phenomenon is attributed to the difference of in-line storage between storm pipes and combined sewers.

The combined sewers are designed to intercept the sewage as well as the surface runoff, at certain times the average dry-weather sewage flows (i.e., the dry-weather flows multiplied by the interception ratio) and take it into the wastewater treatment plant. The larger the interception ratio, the larger the in-line storage capacity of combined sewers will be. In Shanghai's old downtown area, the interception ratio of combined sewers is usually designed to be 3.0. By contrast, theoretically, the storm drains are only designed to accommodate the surface runoff and directly discharge the surface runoff into nearby receiving waters. Therefore, the in-line storage of the combined sewer system is larger than that of the storm drainage system.

Table 2 Characteristics of monitored wet-weather discharges under storm pumps operation in the study site

Event no.	Date (day/month/year)	Rainfall duration (min)	Rainfall depth (mm)	Maximum rainfall intensity (mm/h)	Pumping discharge duration (min)	Maximum pumping flow (m^3/s)	Antecedent dry weather period (day)	Number of samples collected
(a) Monitored wet-weather discharge events under storm pumps operation								
1	18/08/2008	680	37.9	26.4	865	11.5	2	17
2	05/09/2008	550	28.9	6.8	450	6.9	4	24
3	14/09/2008	405	26.8	10.7	365	9.2	0	12
4	05/10/2008	460	6.5	2.9	235	4.6	8	14
5	23/10/2008	560	2.9	1.2	300	2.3	1	11
6	29/10/2008	680	3.2	0.7	305	4.6	3	7
7	30/10/2008	645	2.4	1.0	335	4.6	0	12
8	17/08/2010	300	39.0	36.7	265	9.2	1	14
9	18/08/2010	210	42.4	39.1	200	11.5	0	6
10	25/08/2010	125	31.0	28.4	220	11.5	6	11
11	26/08/2010	270	28.3	14.0	375	6.9	0	24
12	21/04/2011	485	12.9	3.9	320	2.3	14	17
13	22/05/2011	785	27.0	5.7	500	2.3	0	26
14	04/06/2011	1220	19.1	7.5	370	4.6	11	20
15	10/06/2011	1065	35.1	27.7	450	11.5	0	24
16	17/06/2011	2910	157.1	34.4	2370	13.8	0	29
17	29/09/2011	1175	15.3	7.1	325	2.3	8	17
18	24/10/2011	790	11.2	2.2	460	4.6	3	23
19	02/11/2011	755	18.2	5.2	540	4.6	3	24
20	07/12/2011	1275	22.1	2.4	355	2.3	0	18
21	08/12/2011	235	2.2	1.1	300	2.3	0	16
22	29/02/2012	760	15.0	3.1	435	4.6	0	22
23	01/03/2012	630	14.9	5.7	295	4.6	0	15

Statistical parameter	Rainfall duration (min)	Rainfall depth (mm)	Maximum rainfall intensity (mm/h)	Pumping discharge duration (min)	Maximum pumping flow (m^3/s)	Antecedent dry weather period (day)
(b) Statistics of monitored wet-weather discharge events under storm pumps operation						
Minimum	125	2.2	0.7	200	2.3	0
Maximum	2910	157.1	39.1	2370	13.8	14
Median	645	17.2	5.7	355	4.6	1.0

Table 3 Event mean concentrations (EMCs) of the study site and some combined sewers in Shanghai

Discharge scenario	Statistical parameters	SS	COD	BOD_5	NH_3-N	TN	TP
Dry-weather discharge under gravity flow	EMC range	61~175	117~284	40~85	20.3~29.0	24.8~32.4	2.8~4.7
	EMC averaged	135	188	61	25.6	29.4	3.76
	SD	31.4	47.2	13	2.86	2.40	0.56
	CV	0.23	0.25	0.1	0.11	0.08	0.15
Dry-weather discharge under pumping flow	EMC range	117~319	195~807	82~145	18.9~29.3	27.6~37.2	2.08~10.3
	EMC averaged	194	327	110	24.8	31.0	4.64
	SD	91.7	175	25.7	3.41	3.02	2.42
	CV	0.47	0.54	0.23	0.14	0.10	0.48
Wet-weather discharge under pumping flow	EMC range	80~336	47~714	16~126	1.4~33.6	5.9~42.2	0.60~8.16
	EMC averaged	172	290	96	15.0	20.8	3.32
	SD	81.2	169	35.1	8.05	7.64	1.67
	CV	0.47	0.58	0.53	0.54	0.37	0.50
Combined sewer overflows (Li 2006)	EMC range	30~140	113~436	40~184	6.4~14.1		
	EMC averaged	110	268	101	9.5		
	SD	39.6	131	56.6	3.14		
	CV	0.36	0.49	0.56	0.33		

SD standard deviation, *CV* coefficient of variation

According to the relationship between wet-weather overflow and rainfall events for the combined sewer system, wet-weather overflow usually occurs when the accumulated rainfall was up to 10~20 mm in the combined sewers of Shanghai's old urban area (Li 2006; Li and Li 2009). However, in the study site, the wet-weather overflow did occur when the accumulated rainfall was up to 5 mm, due to pipe storage being occupied by inappropriately entered sewage. As a result, the percentage of surface runoff retained in the combined sewers is larger than that in the storm drainage system. Higher flow dilution by means of surface runoff in the combined sewers resulted in lower NH_3-N concentrations from combined sewer overflow than from storm drains overflow. Therefore, for separate storm drains with seriously inappropriate sewage entry, their original design to abate wet-weather overflow pollution is questionable; it may be even worse than combined sewers from the perspective of overflow pollution control.

First flush effect and pollutant mass distribution

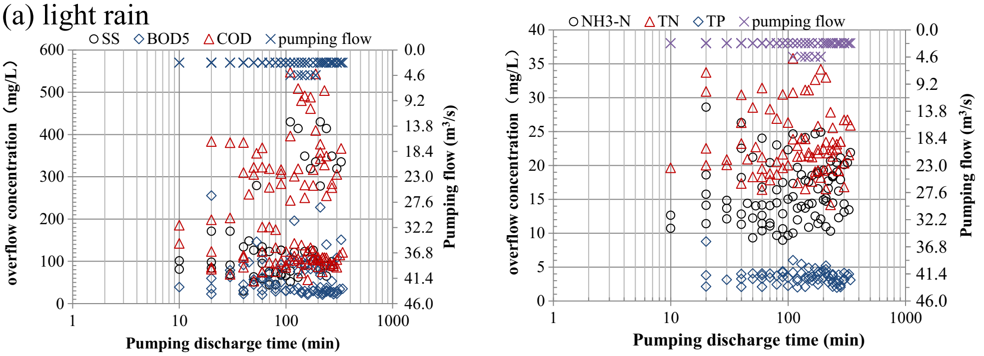
Time-series pollution and M(v) curves

The time-series overflow concentration over the course of wet-weather pumping discharge is shown in Fig. 2. Furthermore, the normalized pollutant mass as a function of normalized flow for each pumping discharge event (i.e., M(v) curve) is presented in Fig. 3. Generally, the first flush can be defined as occurring when the slope of normalized cumulative pollutant mass plotted against normalized cumulative flow volume is greater than 45°, i.e., positive gap between the M(v) curve and the bisector (Geiger 1987). Based on the figures, it can be concluded as the following.

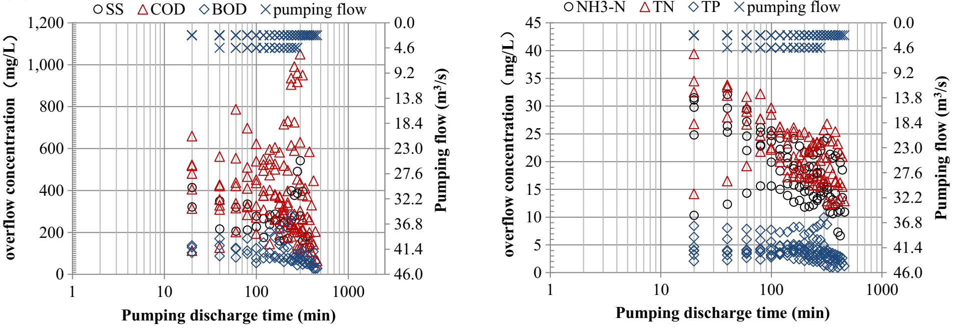
1. For the pumping discharge under light rain, the slope of the mass emission line was almost identical to the bisector line in most cases (Fig. 3a). The reason was that under light rain, majority of pumping discharge flow was from the water stored within the storm drains. The latter increased pumping discharge flow would even give rise to pollutant constituent (Fig. 2a), and accordingly even negative gap between the M(v) curve and the bisector occurred.
2. For the medium rain event, the slope of mass emission line exceeded the diagonal of 45° in some circumstances (Fig. 3b), fitting the definition of first flush. The reason was that at later medium rain, flow dilution by means of relatively clear surface runoff induced lower overflow concentrations. However, no indispensable first flush phenomenon was observed, and increased pumping discharge flow with the duration of rainfall would also give rise to pollutant constituent peak in the middle or later stage of overflow (Fig. 2b).
3. For the storm pumping discharge under heavy rain, the slope of the mass emission line exceeded the diagonal of 45° in most cases (Fig. 3c). Some cumulative load curves exhibited relatively strong first flush effect, which was more likely to be associated with large and intense event. The relatively highest first flush corresponded to a rainfall event with precipitation of 157.1 mm (i.e., on June 17, 2011). During this event, the pumping discharge

Fig. 2 Monitored water quality data sets plotted with pumping discharge duration. **a** Light rain. **b** Medium rain. **c** Heavy rain

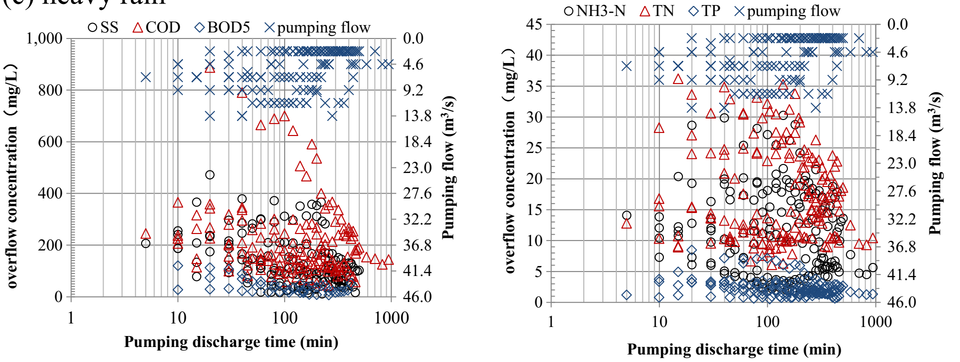
(a) light rain



(b) medium rain



(c) heavy rain



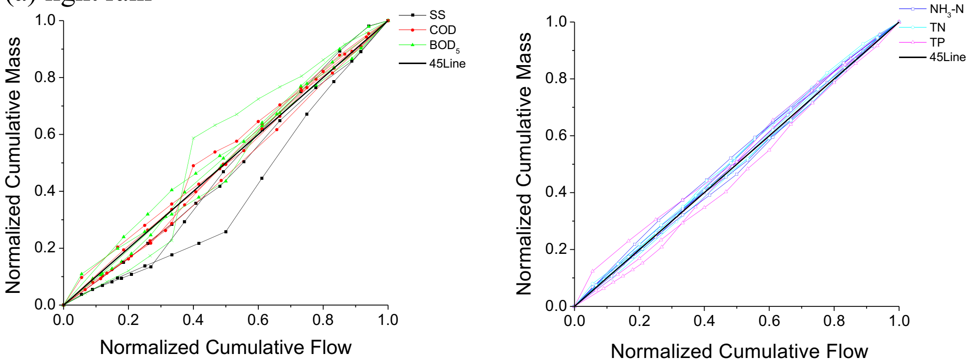
increased significantly from 2.3 to 13.8 m^3/s after starting the storm pumps for 40 min, inducing a much more incipient in-pipe sediments erosion, while overlapping early runoff that contained large amounts of anthropogenic pollutants as well as naturally occurring materials such as soil erosion. At the later stage of rainfall, the accumulated pollutants on the surface roads as well as within the storm drains had been flushed out to a large extent; therefore, an obvious decline in overflow concentration was observed.

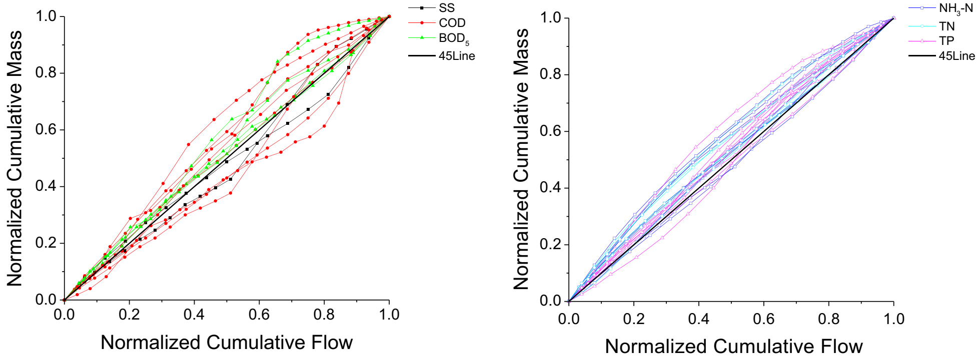
To further discriminate the scenarios that first flush occur, the fitted M(v) curve parameters (i.e., parameter *b*) as a function of rainfall, maximum rainfall intensity, maximum pumping discharge flow, and antecedent dry weather days are presented in Fig. 4. In this figure, the parameter *b* was fitted approximately by a power function (Bertrand-Krajewski et al. 1998; Sansalone and Cristina 2004)

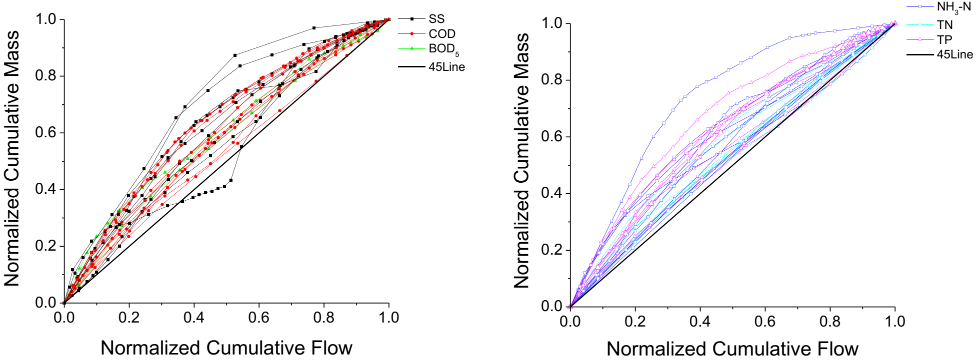
$$F(X) = X^b \tag{2}$$

where X is the normalized cumulative flow, $X \in [0, 1]$, and $F(X)$ is the normalized cumulative mass. The value of the parameter b characterizes the gap between the M(v) curve and the bisector. $b < 1$ indicates positive gap between M(v) curve and the bisector; the lower the value of b, the more pronounced is the first flush proven by the fact that the main proportion of total pollutant load is transported in the first proportion of the total volume. It was presented that $0 < b \leq 0.185$, $0.185 < b \leq 0.862$, and $0.862 < b \leq 1.0$ indicated high, medium, and negligible first flush effect, respectively (Bertrand-Krajewski et al. 1998).

Fig. 3 M(v) curves for different water pollutant indicators during wet-weather pumping discharge. **a** Light rain. **b** Medium rain. **c** Heavy rain


(a) light rain


(b) medium rain


(c) heavy rain

From Fig. 4, it was seen that with the increase of rainfall, maximum rainfall intensity, and maximum pumping discharge flow, the first flush effect tended to be intensified. Under the scenarios of rainfall greater than 30 mm, maximum rainfall intensity greater than 26.3 mm/h, and maximum pumping discharge flow greater than 9.2 m^3/s, the medium first flush was most likely to occur (i.e., $0.185 < b \leq 0.862$), which usually corresponded to the pumping discharge under heavy rain. However, no high first flush effect was observed using the criteria of $0 < b \leq 0.185$.

Another phenomenon was that with the increase of antecedent dry weather period, the first flush effect tended to be weakened. On condition that the antecedent dry weather period was above 8 days, the first flush did not occur. In the reported literatures, Saget (1994) and Chebbo (1992) found that low values of b tended to occur more frequently when longer antecedent dry weather periods and high rainfall intensities occurred simultaneously, but no clear relationship was established between the duration of antecedent dry weather period and first flush based on the 12 sites from the QASTOR database of combined sewers (Bertrand-Krajewski et al. 1998). In our study site, the diameter of sediment particles flushed out of the storm drains due to storm pumps operation was also measured. Typically in the collected water samples from two pumping discharge events (dry-weather pumping discharge on May 4, 2011 with antecedent dry-weather period of 12.3 days and wet-weather pumping discharge on April 21, 2011 with antecedent dry-weather period of 14.0 days), the

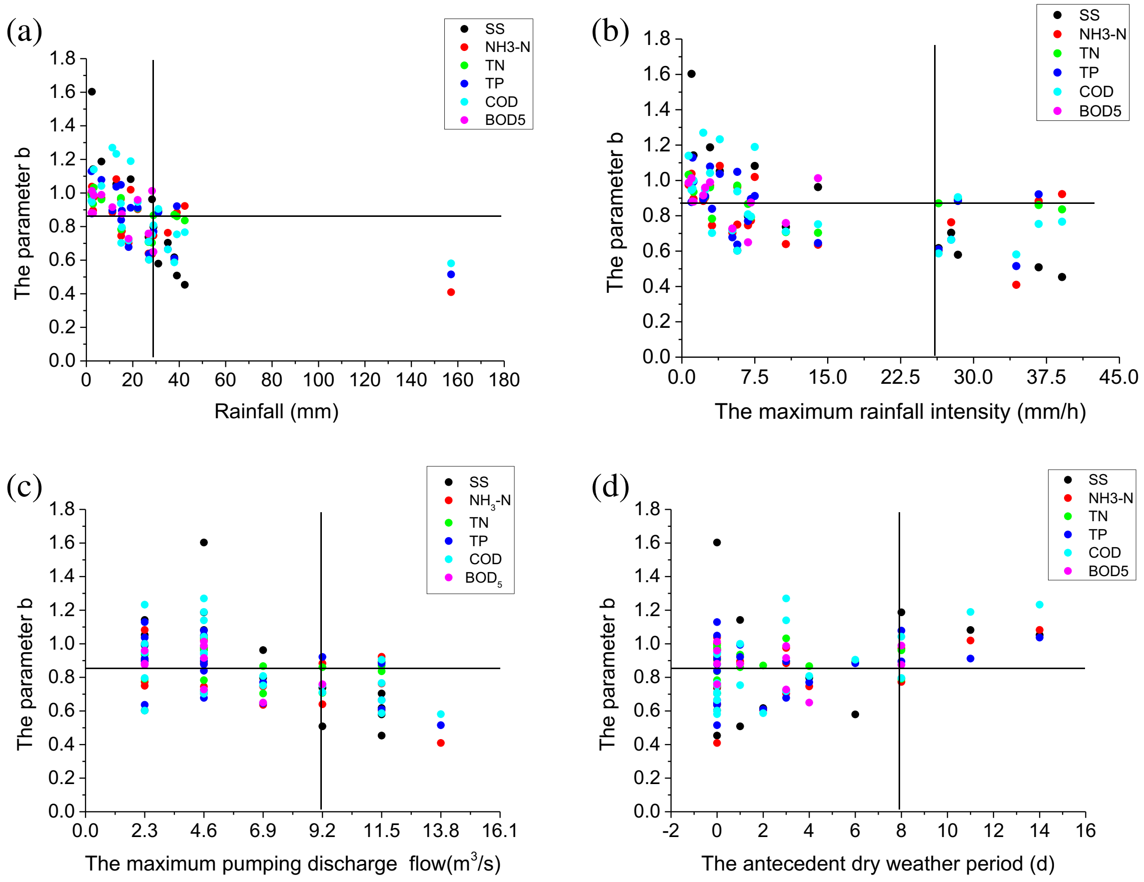


Fig. 4 Parameter *b* as a function of **a** rainfall, **b** maximum rainfall intensity, **c** maximum pumping discharge, and **d** antecedent dry weather period

time-series diameters of sediments were measured using a laser particle size analyzer (Ankersmid Ltd., Netherlands), as shown in Fig. 5. Figure 5 was presented based on the particle volume percentage under 50 and 90% (d50 and d90 percentiles). Take measured d50 diameter as an example, under dry-weather pumping discharge event, the range of d50 was 77.2~114.1 μm, with average value and coefficient of variation (COV) being 97.8 μm and 0.10, respectively; in contrast, under the wet-weather pumping discharge event, the range of d50 was 41.3~118.4 μm, with average value and COV being 92.3 μm and 0.24, respectively. It was seen that no significant difference was found for sediments diameters between dry-weather and wet-weather pumping discharge under long antecedent dry-weather period. The range of measured diameter exhibited low dispersion with COV less than 0.3, showing that sediments erosion occurred over the whole course of pumping discharge. This demonstrated that for the duration of pumping discharge, especially under long antecedent dry-weather days, antecedent sediments deposition and the following sediments flush plays an important role in weakening first flush effect, so that the first flush could not be claimed.

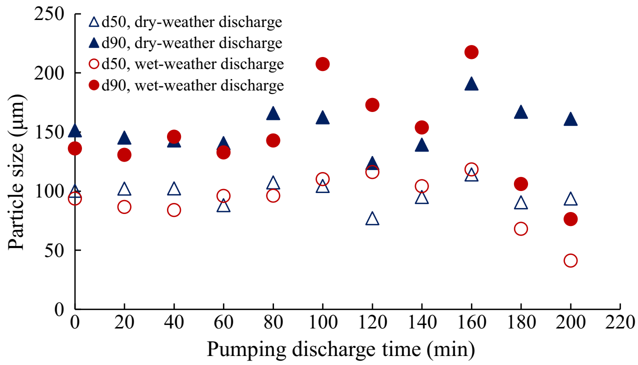


Fig. 5 Measured time-series sediments diameters (d50 and d90) for the dry-weather and wet-weather pumping discharge flows

Mass first flush ratio

The mass first flush ratio (MFF) was also employed to quantify and understand the magnitude of a first flush. MFF describes the fractional mass of pollutants emitted as a function of the pumping discharge process ranging from 0 to 100% (Ma et al. 2011; Barco et al. 2008), which can be represented as follows:

$$MFF_n = \frac{\dfrac{\int_0^{T_1} C(t)Q(t)dt}{M}}{\dfrac{\int_0^{T_1} Q(t)dt}{V}} \qquad (3)$$

where *n* is the percentage of the pumping discharge flow volume, T_1 is the period of pumping discharge, *M* is the total discharged pollutant mass, and *V* is the total discharged flow volume. By definition, MFF is equal to zero at the storm beginning and always equals 1.0 at the end of the storm. Values greater than 1 indicate first flush. For example, an MFF_{30} equal to 2.0 means that 60% of the pollutant mass is contained in the first 30% of the pumping discharge volume. For the pumping discharge on wet weather days, range of MFF_{30} and MFF_{50} is shown in Fig. 6.

Figure 6 shows that the range of MFF_{30} was 1.0~2.0, 0.7~1.4, and 0.5~1.2, respectively, and the range of MFF_{50} was 1.0~1.5, 0.8~1.2, and 0.7~1.1, respectively, for the scenario of heavy rain, medium rain, and light rain. The largest MFF_{30} was 2.0 on June 17, 2011, with a rainfall of 156.6 mm, maximum rainfall intensity of 34.4 mm/h, and maximum pumping discharge of 13.8 m^3/s. This was related to high wash-off of accumulated contaminants on the surface roads and high mobility of in-pipe sediments at the former stage of rainstorm. However, the mass first flush ratio under this event was less as compared to the reported case study (e.g., Barco et al. 2008). In this reported study site drained by a combined sewer system located in northern Italy, for the rainfall event with precipitation depth of 16.4 mm (i.e., medium rain event), the MFF_{30} was 1.7~2.2 for the measured parameters of SS, COD, BOD, and TN; by contrast, in our case, the MFF_{30} was 0.7~1.4 for the medium rain events.

In the reported catchment (i.e., Barco et al. 2008), they are typical of designed drainage system characterizing relatively high slopes that do not allow sediments to accumulate; therefore, a strong first flush may occur predominantly associated with road surface wash-off under high rainfall intensity events. By comparison, our study site exhibits flat topography where design of urban drainage system with high slope is difficult. In this case, the average slopes of storm pipes are low that do not reduce sediment deposition by maintaining higher velocity, and severe sediment deposition within the storm drains would occur on dry-weather days.

Overall pollution characteristics

Principal component analysis (PCA) was further conducted, concerning the overall pumping discharge scenarios and the resulting pollution characteristics. As one of the most applied approaches to study data structures, PCA aims at finding and interpreting hidden relationship between dataset features,

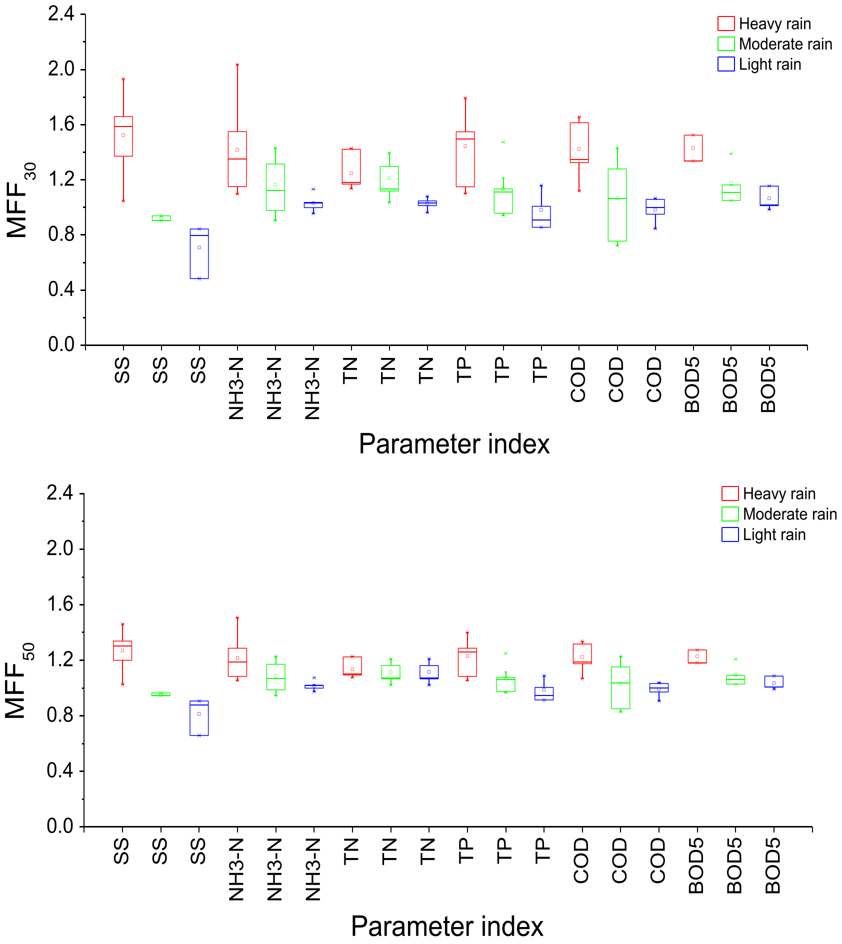


Fig. 6 Mass first flush ratio (MFF_{30} and MFF_{50}) for the wet-weather pumping events

which is accomplished by studying the data structure in a reduced dimension while retaining the maximum amount of variability in the data. In PCA, the number of components is equal to the number of variables. A component, however, is comprised not only of a single variable but all of the variables used in the study.

In this case, the input variables included rainfall duration (min), rainfall depth (mm), maximum rainfall intensity (mm/h), pumping flow duration (min), pumping discharge volume (m^3), maximum pumping flow (m^3/s), and antecedent dry weather period (day). All of the pumping discharge events listed in Tables 1 and 2 were selected for the PCA analysis. Usually, the variables are increasingly well represented by a component as the corresponding value of the square cosine approaches the unit. It showed that of the seven components, the first component (F1) accounted for 67.6% of the total variance, and the second component (F2) accounted for 14.8% of the total variance. Our discussion, therefore, focused principally on the two principal components that together explained 82.4% of the total variance of the dataset (see Fig. 7). This reduced the dimensionality of the total data from 7 to 2 (a 71.4% reduction) and resulted in only 17.6% loss of information contained in the dimensions. However, it was found that with the increase of input parameters (e.g., the overflow concentrations of different pollution indicators), the total variance of the dataset represented by F1 and F2 would be less than 80% and correspondingly result in larger loss of information contained in the reduced dimensions.

Figure 7 revealed that the observations from the PCA could be grouped into two distinct clusters, allowing the previous conclusions to be confirmed. As discussed above, for the storm drains with serious sewage entry, dry-weather overflow concentration is determined by sewage as well as sediment erosion within the storm pipes. Considering that the first cluster of PCA results included the monitored pumping events of dry-weather, light and medium rain, it was presented that overflow concentration under light rain and medium rain was also predominantly decided by sewage and sediments erosion within the storm pipes. Under the two rainfall scenarios, no mass first flush or only weak first flush mostly occurred. Another cluster of PCA results was of the monitoring events of heavy rain. This indicates that mass flush process under heavy rain is relatively slightly influenced by sewage and sediments erosion within the storm pipes. Under this rainfall scenario, especially for the rainstorm with early rainfall peak, the significantly increased pumping flow as well as surface road wash-off in the incipient rainfall could trigger the mass first flush to some extent.

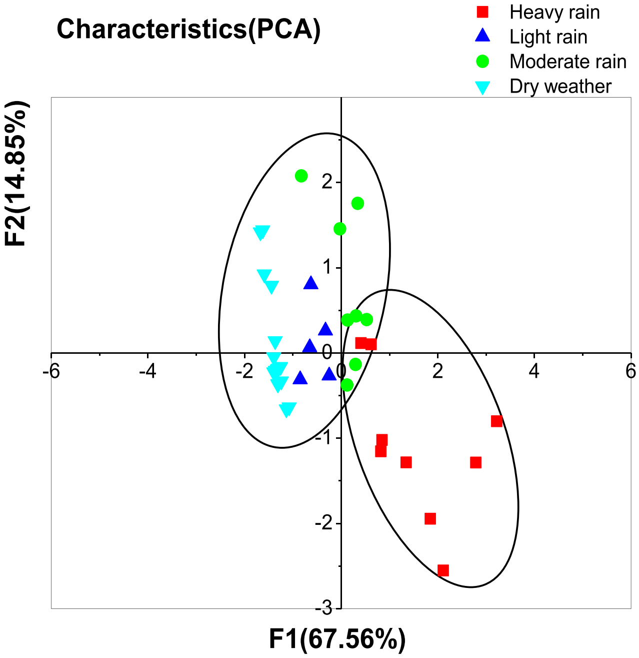
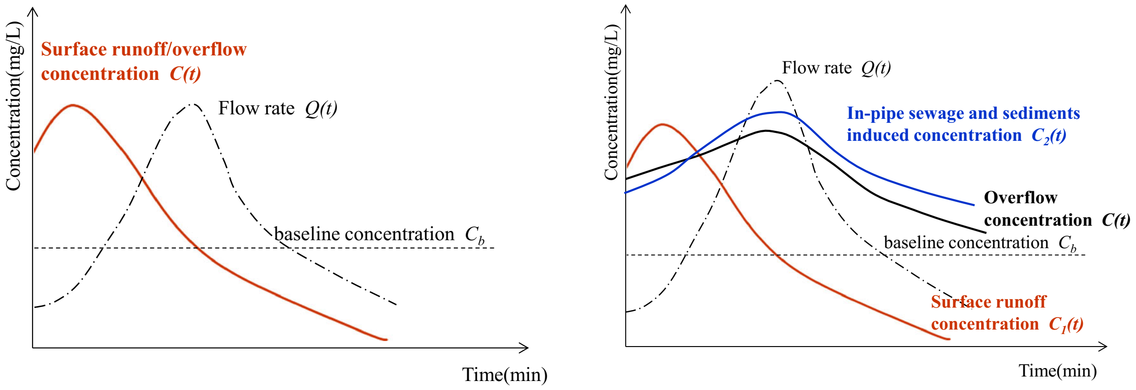


Fig. 7 PCA for the sampling events associated with pumping discharge

Finally, our discussion concerning first flush effect is clarified in Fig. 8, where the baseline concentration C_b represents the dry-weather outflow concentration under gravity discharge. Figure 8a shows time-series concentration exhibiting the potential strong first-flush effect, where C(t) and Q(t) represent the road surface runoff concentration and outflow concentration as a function of time, respectively; this could be the case for separate storm drains without inappropriate sewage entry that carry storm water from wet-weather runoff only. Under this circumstance, the degree of first flush depends on the percentage of impervious area and its spatial distribution, and the catchment size (Kang et al. 2006; Ma et al. 2011). By contrast, Fig. 8b shows the pumping discharge induced outflow concentration as a function of time (C(t)), as a result of the surface runoff concentration combining in-pipe sewage and sediment flush related concentration. This was the case in our study. In our study site, an array of separate flush conditions aroused by the operation of storm pumps may occur but reach the downstream location and terminal wet well at staggered intervals that substantially attenuate the first-flush effects. Therefore, in this case, the mass first flush effect is insignificant, and the mass flush effect may occur throughout the overflow event, except for the heavy rainfall with early precipitation intensity peak.

Implications for treatment

The basic principle to control overflows from an urban drainage system is that the overflow concentration should be lower than the baseline concentration, e.g., a specified water pollutant discharge standard. For example, in the design of a storm water detention basin, discharge can be designed to start when the overflow facility influent concentrations rise above the baseline level and to continue until the concentrations return to the baseline level. The volume of a storm water detention



(a) Overflow with potential high first-flush effect (b) Overflow without high first-flush effect

Fig. 8 Schematic diagram for flush effect under storm pumps discharge. **a** Overflow with potential high first-flush effect. **b** Overflow without high first-flush effect

basin is then estimated by plotting the flow on the same axis as the pollutant concentration (US EPA 1993).

Theoretically, if the first flush effect is significant, some control units may have smaller design sizes for a given level of removal performance. By contrast, for storm drains in this site that feature serious inappropriate sewage entry across the catchment, design of treatment-type units cannot be related to the first flush in practical manner, and the measures to abate overflow pollution of the storm drains with inappropriate sewage entries are suggested as follows.

1. Correct that the situation of sewage that illicitly enters the storm drains. It is necessary to mention that, for widespread sewage connections to storm drains (e.g., in this case), point-by-point corrections may not be feasible in very busy downtown areas. Point-by-point correction may also concern the widespread correction of old communities where separate storm pipes and sewers need to be constructed. This is time-consuming and requires significant investment. Therefore, a practical alternative is to disconnect several key entries featuring relatively large amount of wastewater discharge each from the storm pipes and reconnect them to the sewer pipes, while having large number of sewage entries with relatively small amount of wastewater discharge each, intercepted into the wastewater treatment plant by end-of-storm pipe interception sewer. In this study site, besides the existed end-of-storm pipe interception sewer that connects the storm drains with separate sewer system (see Fig. 1b), two largest sewage outfalls connecting to the storm drains that covered 24.3% of the total illicit dry-weather discharge, i.e., the semiconductor enterprise outfall with wastewater discharge of 1959 m^3/day on the HC road and the one sanitary sewerline tying into a storm drain with wastewater discharge of 2422 m^3/day on the GH road (see Fig. 1a), had been reconnected to the separate sewer system in the second half year of 2012, as the actions undertaken by local governments. This action would alleviate the dry-weather sediments deposition within the storm pipes and therefore abate overflow pollutant masses to some extent.
2. Dredge the in-pipe sediments on dry-weather days regularly. Equipment such as winch, suction sewage truck can be used to dredge the in-pipe sediments regularly; in this way, the overflow pollutants associated with sediment flush during storm pumps operation can also be alleviated. Traditionally, the dredged sediments are disposed with the drying and direct landfill method, which can cause some problems such as soil pollution and waste of land resources. Recently, the new combined process of pretreatment and recycling to the dredged sludge has been presented in Shanghai (Ma et al. 2015). For example, bulk materials within the dredged sediments can be preliminarily separated, and then the sludge is washed out by separation device, among which the separated particles with diameter of 0.2 to 10 mm can be reused as construction materials. The outflow of the separation device containing organic matter will be transported into the wastewater treatment plant through the sewers. By this means, the dredged sediments could be treated more environment friendly as compared to the traditional disposal method.
3. Develop treatment-type units to abate the overflow pollution. On-line treatment-type units may be more effective to treat overflow pollutants compared with the off-line treatment units. Especially, as a kind of on-line treatment type unit, vortex separators are compact flow throttling and solids separation devices that provide flow regulation and solids and floatable removal from the overflows continuously. Common technologies are swirl concentration of US Environmental Protection Agency (EPA swirl concentrator), the Fluidsep vortex separator, the Storm King hydrodynamic separator, and so on (US EPA 1993). For

example, the EPA swirl concentrator is most effective at removing solids with characteristics similar to grit (200-μm diameter), and Storm King separator can prevent grit of 106 μm and larger from reaching the environment. In our case, d90 diameters of sediments lie 92.3~97.8 μm on average (see Fig. 5), which approximately accords the range of solids to be removed using the apparatus such as Storm King separator. Recently, studies by the authors demonstrated that the coagulation-flocculation process (e.g., the use of poly-aluminum ferric chloride sulfate (PAFCS) as coagulant) could assist in improving the removal efficiency of sediments in urban drainage overflow (Wang et al. 2016); therefore, flocculation-enhanced vortex separation, whether standing alone or with storage tank, may play a more important role in controlling the overflow pollution.

Conclusions

Based on above discussions, we draw the following conclusions.

1. For the separate storm drains with inappropriate dry-weather flow entry, overflow events may occur under wet-weather days as well dry-weather days, due to storm pumping operation. The concentrations of dry-weather overflow could be higher than those of wet-weather overflow. Under wet-weather discharge, the overflow concentrations of storm drains could be close to or even higher than those of combined sewers. Therefore, the malfunctioned separate storm drains cannot play their intended role, and separate storm drains with inappropriate sewage entry may be worse than the combined sewers in controlling the overflow pollution.
2. Relatively strong first flush was mostly found under heavy rainfall (i.e., $0.185 < b < 0.862$ and $MFF_{30} = 2.0$ at maximum), which was related to critical rainfall, maximum rainfall intensity, and maximum pumping discharge. For the other events (i.e., pumping discharge under dry-weather, light rain and medium rain), basically, no first flush effect or only weak first flush effect was found, and the overflow concentrations of SS and SS associated pollutants could be still higher than the concentration of the inappropriately entered dry-weather sewage, until the end of pumping discharge event. Such phenomenon may be common in the study sites, where the average slope of storm pipes is low that cannot reduce sediment deposition by maintaining higher gravity flowing velocity on dry-weather days.
3. For such kind of system, attentions should be paid to correct the situation of key sewage entries into the storm drains, while constructing end-of-storm pipe interception sewers to let large number of illicit entries with low wastewater discharge be intercepted into the separate sewer system as a whole. The design of treatment-type units is also an option; however, priority should be given to develop online treatment-type units instead of offline treatment units, considering that the treatment may not be related to the first flush in practical manner. In the future, monitoring action plans should also be conducted in this place so as to assess the overflow pollutants abatements after a series of engineering schemes put into effect.

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