Article

First Flush Characteristics in Separate Sewer Stormwater and Implications for Treatment

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Abstract: The characteristics of stormwater need focus due to climate change. Paved areas and recipients receiving more stormwater have an enhanced need for treatment before discharge to remove suspended solids, nutrients and xenobiotics. To handle and treat stormwater efficiently, knowledge concerning first flush patterns is crucial. Therefore, we have studied 12 entire rain events and correlated water volume, suspended solids, and dissolved and particulate phosphorus to catchment characteristics and precipitation characteristics. We have mainly studied smaller rain events (average 12.6 mm), as nearly 90% of the events in the studied catchment are <10 mm. We revealed first flush tendencies in 50% of the rain events, concerning both suspended solids and phosphorus. We also found significant correlations between catchment size and discharged masses, and most importantly between precipitation patterns and discharged mass per volume. A long dry period and low amount of rain during the previous event, as well as high rain intensity, gives a high chance of first flush. We conclude that stormwater treatment should focus on the initial part of the event, especially in areas with a lack of space and/or economy to handle and treat the entire event.

Keywords: urban runoff; climate adaptation; pollution; retention

1. Introduction

Climate change is among the many other effects causing more extreme weather, including cloud bursts, storms and droughts [1,2]. For the northern part of Europe, an increased amount of precipitation with more and heavier rain events is expected [3]. As an example, it is predicted that the number of 10 year events in Denmark will increase by 30% within the next 100 years [4].

Stormwater runoff from separate sewers is most often either discharged directly into the recipient or discharged after retention, e.g., in a wet stormwater pond [5]. Especially the first stormwater discharged will often have a larger content of particles and dissolved substances compared to the remaining part, as the first discharge contains all the accumulated particulate material from surfaces and the pipe systems [6,7]. This phenomenon is referred to as ‘first flush’, and is defined as a disproportionally high load of either concentration or mass in the first stormwater load during a rain event [7,8]. First flush depends on the dry period before the actual event, the intensity and duration of the rain event, the catchment type, and the transport distance of the discharge before the outlet (pipe length) [9]. Historically, different methods have been used to describe first flush events.

A commonly used method is to express the percentage of mass transported along with a certain percentage of the volume [9], presented as normalized accumulated mass (L') for each time as a function of normalized accumulated volume (V') at each time [9]. A 45° bisector will then represent a proportional transport of mass and volume, see example in Figure 1. If the curve is above the bisector, a relatively larger mass is transported in the discharge compared to the transported volume, whereas

the opposite is the case if the curve is below the bisector; in that case, the runoff is diluted. So, if first flush is occurring, the curve will be above the 45° line [9,10].

Figure 1. Schematic L'/V' curve—redrawn after [9]. L' is the mass load and V' is the volume. Both are expressed as normalized accumulated values.

The numerical definition of the first flush varies. Some have suggested that first flush is characterized by an 80% mass transport during the first 30% of the volume—a 30/80 first flush [10,11]. Others have argued for an even stronger characterization, where 80% of the mass should be transported during the first 20% of the volume—a 20/80 first flush [7]. Finally, some studies have suggested a less strict definition with first flush at 20/40 or 25/50 as first volume/mass [9]. In general, first flush is most common in smaller catchments (<10 ha) [11].

A well-known method to store stormwater and avoid hydraulic effects on the recipient, as well as to remove primarily particulate substances, is wet stormwater ponds [12,13]. In Denmark, wet ponds are often designed with a controlled outlet intensity of 1–2 L/s/ha catchment, a permanent wet volume of 150–250 m³/reduced hectare and a storage volume, if properly designed [5]. The reduced area is the impermeable proportion of the catchment. Many of the wet stormwater ponds are designed with an overflow facility placed near the pond outlet, which is activated if the pond's storage capacity is exceeded. The result is that it will most likely be the discharge that entered the pond first that will be discharged first during overflow. Put another way, the first flush holding the most polluted water might be discharged through the overflow if the storage capacity of the pond is exceeded, and the cleaner water coming after the first flush is kept in the pond and treated. That is an undesirable, and environmentally and economically inefficient way of handling stormwater.

Therefore, a greater knowledge of the first flush phenomenon will support the knowledge platform so that the design of stormwater ponds can be optimized and make it possible to retain and treat first flush, without making the ponds inappropriately big. Barbosa and Hvitved-Jacobsen have suggested that the treatment efficiency could be enhanced by placing the overflow facility at the inlet instead, so that the more diluted, cleaner stormwater coming after first flush is bypassed instead of the most polluted first flush [6]. This will not change the hydraulic load, but it will entail that if overflow occurs, it will be the cleanest water that overflows. A model study in progress made on Danish ponds has revealed that this change in design can effectively increase the treatment efficiency.

The important question is what proportion of the first flush should be kept in the stormwater pond and treated. To provide more information about that, we have examined the runoff from 12 rain events in three different catchments with varying intensity, duration and dry weather periods since last rain event. The aims were (1) to characterize to what extent first flush was observed with respect to

suspended solid (SS), dissolved phosphorus (DP) and particulate phosphorus (PP), and (2) to evaluate which catchment and precipitation patterns the first flush was dependent on.

2. Materials and Methods

In the period 2012–2017, we examined the runoff from 12 different rain events at 3 different stations (Table 1). All stations are in the southern part of Denmark, and were named Graasten 1–6, Aabenraa 1–2 and Padborg 1–4, respectively; first the city name, then the rain event number. In Graasten, the catchment is a mixed urban area with roads and houses. The total catchment area is 4.2 ha, and the reduced catchment is 1.5 ha. In Aabenraa, the catchment area consists of light industry and it is nearly 5 times larger (23.1 ha, 5.8 red. ha) compared to the Graasten area. In between the two is Padborg, with a total catchment area of 15.5 ha and 10.1 red. ha. In contrast to the two others, this catchment only consists of roads and parking lots. The maximum pipe length, equal to the maximum length that the water is transported before discharge, varies from 600–1400 m. The investigated rain events covered a wide range of rain amounts, 6–24.4 mm (median 12.3, average 12.6), and the events lasted 6–52 h (median 13, average 22). The intensity of the rain ranged 0.2–2 mm/hour, along with the number of days since last rain event (1–8 days). Finally, the amount of rain during the previous event varied 1.4–18.6 mm. In Graasten, all precipitation data were measured by an on-site Netatmo rain measure with tipping function, measuring the precipitation with a precision of 0.2 mm. In Aabenraa and Padborg, a Global Water RG200 Rain Gauge, 6 inches (Tipping bucket), was used, also with a precision of 0.2 mm.

Table 1. Descriptive data of the 12 studied outlets, including catchment characteristics and precipitation patterns.

Location	Date	Catchment			Precipitation				
		Catchment Type	Catchment Size (Total/Red ha)	Max Distance Catchment (m)	Rain (mm)	Duration (h)	Mean Intensity (mm/h)	Dry Period (Days)	Rain in Last Event (mm)
Graasten 1	11/01/17	Urban	4.2/1.5	600	8.9	5.6	1.6	1	1.0
Graasten 2	22/02/17	Urban	4.2/1.5	600	13.7	7.0	2.0	2	4.5
Graasten 3	23/02/17	Urban	4.2/1.5	600	12	6.6	1.8	1	13.9
Graasten 4	17-18/03/17	Urban	4.2/1.5	600	15.9	19.4	0.8	8	6.0
Graasten 5	19/03/17	Urban	4.2/1.5	600	10.3	11.6	0.9	1	9.2
Graasten 6	20/03/17	Urban	4.2/1.5	600	11.5	10.1	1.1	1	11.1
Aabenraa 1	10/04/13	Industry	23.1/5.8	900	12.6	70	0.2	3	2.6
Aabenraa 2	14-15/09/13	Industry	23.1/5.8	900	12.6	18.3	0.7	2	18.6
Padborg 1	04-05/11/12	Road/P	15.5/10.1	1400	9.8	12.3	0.8	1	1.8
Padborg 2	09-10/11/13	Road/P	15.5/10.1	1400	24.4	35	0.7	2	3
Padborg 3	11-14/11/13	Road/P	15.5/10.1	1400	6	52	0.1	2	24.4
Padborg 4	29-30/11/13	Road/P	15.5/10.1	1400	12.8	18	0.7	2	1.4

During all events, flow SS, DP and PP were measured. In Padborg and Aabenraa, the water level in the inlets was measured by Onset Compute HOBO U20 water level loggers, with a temporal resolution of 5 min. The water level was converted to flow by the Manning equation for not-full running pipes, and these flows were verified by manual flow measurements with a Kleinflügel Ott propeller Instrument. In Graasten, the flow was measured by an optic automatic flow recorder every minute. All water samples were sampled by a Teledyne ISCO model 6712 Portable Automatic Sampler. The water samples were taken with varying frequency. Before the rain event started, the frequency was 1–3 h depending on the station, and occasion, whereas during the first part of the event, the frequency was typically 15, 30 or 60 min, and then an hour frequency in the last part of the event and after the event. Known volumes of all water samples were filtered in duplicate on pre-washed and pre-dried Whatman GF/C filters. DP was measured on the filtrate by the molybdenum-blue method [14]. The filters were dried for 24 h at 105 °C, or until constant weight, and the dry weight and filtered volume were used to calculate SS. After the ignition of the filters (520 °C, 5 h) PP was measured by boiling the combusted filters in 1 M HCl (1 h), followed by the determination of the DP in the extract [15].

Sigmaplot 12.0 was used for statistical analyses. $p < 0.05$ was chosen as the level of significance, and linear regressions were performed after a normality test (Shapiro-Wilk) and constant variance.

3. Results

All 12 rain events were examined before, during and after the precipitation. Figure 2 presents the Aabenraa 2 rain event as an example. The flow regime follows the precipitation patterns, with an immediate increase in runoff when it starts raining and, simultaneously, a rapid decrease in the runoff when the rain stops. In this example, the concentrations of SS, DP and PP start to increase before the runoff, which indicates that the first water of this event contains a proportionally higher content of substances. Later in the event, the concentrations follow the flow patterns to a higher extent. The concentrations of SS, PP and DP declined rapidly when the rain stopped and the flow decreased. These tendencies were general for all 12 events. In the Aabenraa 2 case, the concentration of DP is higher than PP in the beginning of the event, and more equal in the later part of the event, but this varied between events.

Figure 2. Aabenraa 2 as an example showing precipitation (primary y-axis), flow, and concentration of PP and DP (secondary y-axis) over time during the rain event.

Table 2 presents an overview of volumes and masses during the examined events. The total water volumes and masses for the specific events vary based on the catchment size and characteristics of the precipitation. In Graasten, the total volume per event ranged from 6–125 m³, whereas the corresponding volumes varied from 659–702 m³ in Aabenraa and 606–2424 m³ in Padborg. The total mass transport during the events varied according to the volumes. Regarding SS, 0.4–7 kg was discharged in Graasten, 44–90 kg in Aabenraa and 6–157 kg in Padborg. The corresponding discharge amounts for DP and PP were 1–39 and 2–18 g, respectively, for Graasten, 37–42 and 56–159 g for Aabenraa, and 85–408 and 25–260 g in Padborg.

In Figure 3, the L/V' curves are given for all 12 events, and Table 2 shows the accumulated mass transport of SS, DP and PP at 20 and 30% of the volume. Overall, there are clear first flush tendencies for some of the events, but there are also some without any tendency, and it varies among SS and DP/PP. Concerning SS, >20% of the mass was transported with the first 20% of the water in half of the events (two in Graasten (26–27%), one in Aabenraa (30%), and three in Padborg (23–28%)). The picture was similar at 30% of the volume with 32–64% of SS transported (Table 2, Figure 3). Also, DP and PP were showing first flush tendencies in some of the events, where >20% DP mass was transported with the first 20% of the water in half of the events (three in Graasten (28–31%), two in Aabenraa (33–34%), and one in Padborg (23%)), and five events had DP mass >30% at 30% of the volume corresponding to 34–52% of the DP mass. Finally, >20% of the PP mass was transported with the first 20% of the water in four of the events (two in Graasten (30–38%), one in Aabenraa (24%), and one in Padborg (24%)), whereas five events had PP mass >30% at 30% of the volume equal to 34–44% of the PP mass. Both Padborg and Aabenraa expressed first flush tendencies in most cases, whereas the Graasten

events varied between events with very clear first flush tendencies towards events completely without tendencies (Figure 3). Finally, there are also differences in the L'/V' curves. Some are above the 45 degrees bisector during the whole event, whereas others are only above it during part of the event, indicating that a lower percentage than the corresponding volume of water is transported.

Table 2. Total discharged volume of water and mass transport of SS, DP and PP during the 12 events. Also, the percentage (%) of SS, DP and PP discharged at 20 and 30% discharged volume, respectively, is given. G = Graasten, A = Aabenraa and P = Padborg. Values in bold indicate that a larger fraction of substances have been discharged relative to the discharged volume.

Location	G1	G2	G3	G4	G5	G6	A1	A2	P1	P2	P3	P4
Total volume (m ³)	29	125	6	31	29	25	702	659	1103	2414	606	1242
Total mass SS (kg)	3	7	0.4	3	1	1	44	90	6	82	25	157
Total mass DP (g)	1	39	0.2	1	1	2	37	42	100	205	85	408
Total mass PP (g)	6	18	0.8	6	2	3	56	159	25	260	63	177
%SS at 20% Vol	19	26	27	12	6	20	30	9	26	28	8	23
%SS at 30% Vol	27	32	35	15	9	30	37	17	64	36	16	38
%DP at 20% Vol	31	17	28	17	7	30	33	34	11	20	8	23
%DP at 30% Vol	44	26	36	30	9	30	52	42	21	29	14	34
%PP at 20% Vol	19	30	38	17	16	20	24	15	24	21	11	15
%PP at 30% Vol	27	38	44	25	23	29	34	24	44	34	23	30

Figure 3. L'/V' curves for the 12 events. L' is the mass load and V' is the volume, with both expressed as normalized accumulated values.

A regression analysis performed on all the studied parameters described above revealed several significant correlations (Figure 4a–i, Table 3). There was a significant positive correlation between the total discharged mass of total SS and PP versus the total catchment area (Figure 4a, $p = 0.027$

for both). The same was the case for SS ($p = 0.028$), PP ($p = 0.012$) and DP ($p = 0.007$) versus the reduced catchment area (Figure 4b). The longer the maximum distance in the catchment, the more SS and P were transported and discharged. That was also significance for total SS ($p = 0.039$), total PP ($p = 0.017$) and total DP ($p = 0.005$) (Figure 4c). Knowledge about event characteristics can also give information about expected discharge of SS and P (Figure 4d–f), as we found a significant positive correlation for total discharged PP versus total precipitation during the event ($p = 0.030$), a significant positive correlation for % total discharged PP at 20% of the volume versus the rain intensity ($p = 0.017$) and a negative correlation for the corresponding SS % at 20% volume versus the amount of precipitation during the previous rain event ($p = 0.035$). Finally, significant correlations among the measured parameters were found (Figure 4g–i). Total discharged SS, PP and DP correlated positively and significantly with the total discharged volume ($p = 0.021$, <0.001 and 0.010 , respectively). Among SS and P, there was a positive and significant relationship between the total discharged amounts of PP and DP versus SS ($p < 0.001$ for both), and total DP versus total PP ($p = 0.007$).

Figure 4. Significant correlations between the studied parameters, including data from all measured events (a–i). $n = 12$.

Table 3. Regression parameters (r and r^2) concerning the significant correlations presented in Figure 4a–i (values in bold), plus the coefficients for the nonsignificant correlations. $N = 12$. (–) not relevant.

Figure	4a	4b	4c	4d	4e	4f	4g	4h	4i
	r/r^2								
Total SS	0.63/ 0.40	0.63/ 0.40	0.60/ 0.36	0.34/ 0.12	–	0.61/ 0.37	0.65/ 0.43	–	–
Total DP	0.41/ 0.17	0.73/ 0.53	0.75/ 0.56	0.29/ 0.09	–	–	0.71/ 0.51	0.86/ 0.74	0.73/ 0.53
Total PP	0.63/ 0.40	0.69/ 0.48	0.67/ 0.45	0.62/ 0.39	0.67/ 0.45	–	0.88/ 0.77	0.86/ 0.73	–

4. Discussion

This study does not include intense rain events, where first flush most likely occurs, but only regular smaller rain events, which covers nearly 90% of all rain events in the study area [12]. Even so, the study still demonstrates that the amount, intensity and pollution patterns of stormwater discharge

varies both during a single precipitation event and among different events, as the dynamic of the discharged stormwater can be dependent on many parameters. This study also clearly demonstrated that the 12 studied events do not express either a 20/80 or a 30/80 first flush pattern, but we still see first flush tendencies close to the 20/40 and 25/50 scenarios. This is most likely due to the relatively small catchment areas, as first flush is a phenomenon most often seen in smaller catchments [11], and in this study the reduced catchments are below 10.1 ha. Therefore, it is beneficial to ensure treatment of the first part of a rain event, e.g., if the available area for stormwater pond establishment is restricted. Finally, this study finds very clear and significant relationships between catchment characteristics, precipitation characteristics and the quality of the discharged stormwater.

In all events, the runoff starts immediately after the onset of precipitation, due to the limited retention possibilities in the paved areas. It is also characteristic that the SS and P concentrations peak before the flow peak indicating first flush, as the first stormwater that is discharged has flushed the paved surfaces for substances accumulated since the last rain event, as seen in other studies [16,17]. The total discharged volume, SS and P were naturally dependent on catchment size and maximum pipe distance in the catchment, as a larger area accumulates a larger amount of both water and substances. The ratio between PP and DP is often stated to be 50:50 [16], which is also the case in many of the studied events. However, some of the Graasten and Padborg events had a higher proportion of DP, which is problematic, as the methods used to treat stormwater very often rely on sedimentation processes [6], which are only effective for PP. On the other hand, the events from Aabenraa had a higher proportion of PP. Methods that remove DP effectively from the stormwater, and are at the same time easy to manage and cost-effective, are still lacking. Constructed wetlands with a high nutrient uptake/cycling due to biomass production, followed by biomass removal could be an option. Part of the DP measured in Graasten and Padborg might be particulates bound to small particles/colloids, that have passed the filter used for separating the two fractions, but if that is the case, these small particles are still very difficult to retain in, for example, sedimentation ponds, as the required retention time is long. The significant relationships between SS and DP/PP, as well as PP and DP, indicate that a fraction of DP might be either particulate bound or loosely adsorbed P.

The L/V' curves show a first flush tendency for 50% of the events concerning both SS and P. The initial discharged mass is though not to be high enough to fulfill the 30/80 or 20/80 requirement suggested by other studies [7,10,11]. Our findings are closer to the 20/40 suggestion [9]. A reason for why we are not seeing a more pronounced first flush tendency is probably that all our investigated rain events are rather small; on average 12.6 mm. More intense events are of course expected to give clearer first flush tendencies, but we decided to study the smaller and more common event sizes, as the events <10 mm in the studied area cover 86% of the early precipitation patterns [12], and this majority of events also carry the largest part of the discharged mass. Other reasons for why we do not always see first flush tendencies, as also seen in this study, could be: (1) recent rain events had cleaned the surfaces, and therefore no new accumulation of material occurred; (2) calm rain intensities removed material from the surfaces over a longer period of the event; and (3) stormwater retention mechanisms in the catchments slowed down the discharge velocity.

It was primarily the particulate fractions (SS and PP) that were dependent on the rain characteristics (amount, intensity and previous rain amount), because these substances accumulate and stay on the surfaces to a larger extent than the dissolved fractions. The significant negative relationship between rain depth and the discharged amount of PP during the first 20% of the volume, and the number of days since last event and the discharged amount of SS during the first 20% of the volume, clearly expresses how important the rain history is for determining first flush. The partial importance of rain depth and intensity was found in [18], where these two factors were the first and second most important variable for first flush. We have only studied SS and P, but it would be highly relevant to perform a similar study for metals, as performed by others [19]. This is important, as many metals are bound just as often to particles as P [20]. The treatment of P, metals and other xenobiotics in discharged stormwater can be improved if event characteristics, like those reported in this paper, can be used to target the treatment

methods towards the volume of water with the highest mass content. It is, however, often difficult to obtain samples from full rain events, like those in this study, as it should either be done manually with a good prediction of when the rain starts, not to lose the initial part of the event, or have automatic sample equipment coupled to information from a rain gauge. Therefore, many stormwater samples are instead either point samples or flow-weighted average samples, which do not give the kind of information needed to study first flush characteristics. We have studied 12 whole events, and they are representative for Danish conditions and many other northern European catchments, and even though there might be local difference, we have a solid basis for the conclusions below.

5. Conclusions

In conclusion, the 12 studied events clearly demonstrate that:

- In approximately 50% of the events, a larger part of SS and P was transported and discharged in the first part of the event, indicating a first flush tendency.
- The transport of particulate matter and particulate P is significantly dependent on catchment characteristics, but also on rain amount, rain intensity and rain during the previous event. These findings are important for management and treatment of stormwater before discharge.
- First flush discharge can be minimized by designing wet ponds with the overflow facility at the inlet instead of the outlet, to ensure the treatment of the first flush volume in the pond.
- A considerable part of the P content is DP, which can't be handled through traditional sedimentation methods, but can be removed, for example, by uptake in biomass or biofilm in properly designed ponds with a sufficiently long retention time.

Therefore, we suggest that future treatment systems should be designed to ensure the treatment of the first part of the rain event, in order to optimize both retention efficiencies and the cost-effectiveness of the pond.

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