First flush assumptions in pollution management for separate stormwater systems: debunking a classical urban (drainage) myth

Ditte Marie Reinholdt Jensen, Santiago Sandoval, Jean-Luc Bertrand-Krajewski, Peter Steen Mikkelsen, Luca Vezzaro

First flush assumptions in pollution management for separate stormwater systems: debunking a classical urban (drainage) myth

D.M.R Jensen[1,2,3], S. Sandoval[4,5], J.-L. Bertrand-Krajewski[4], P.S. Mikkelsen[1] and L. Vezzaro[1*]

[1]*Technical University of Denmark (DTU), Kgs. Lyngby, Denmark*
[2]*Chinese Academy of Sciences (CAS), Beijing, China*
[3]*Sino-Danish Center for Education and Research (SDC), Aarhus, Denmark and Beijing, China*
[4]*Institut National des Sciences Appliquées (INSA Lyon), Lyon, France*
[5]*University of applied Sciences of Western Switzerland (HES-SO), Fribourg, Switzerland*

**Corresponding author email: luve@dtu.dk*

Highlights

- We reviewed the various definitions of First Flush (FF) investigated in the last half century.
- We applied the different FF definitions to a high-resolution dataset of 363 events.
- We showed that First Flush is observed in only a minor fraction of the observed events, highlighting the environmental risks using the FF concept for pollution control.

Introduction

The concept of First Flush (FF) in pollution management of separate storm sewers has been utilized for over half a century. Initially introduced by Sartor and Boyd (1972), the idea that the greater fraction of pollutants discharged during a rain event is concentrated in the initial part has been investigated by several studies during the last decades (Mamun et al., 2020).

Regulations around the world widely adopted the FF concept to mitigate the pollution originating from separate storm systems, by specifically requiring treatment of only the FF fraction, assuming that this will avoid the discharge of the greatest fraction of the stormwater pollutants.

However, the presence of FF in separated stormwater is still debated, with different FF definitions being adopted by various authors (see an overview in Table 1). Similarly, regulations in different countries show a great variety in definitions of the stormwater fraction to be treated, often lacking a strong data evidence to support the enforced criteria (see for example the overview in Jensen, 2022).

Our work firstly reviewed the international scientific literature dealing with FF, to establish a common understanding in the ongoing scientific debate. Then, we applied these FF definitions to the events monitored by Métadier and Bertrand-Krajewski (2012), one of the major sets of high-resolution turbidity data collected so far. These data were integrated by using a second dataset based on a 10-year simulation. Our results show an inconsistency in the use of the FF concept when applied to a large dataset of measurements, highlighting that the effect of FF is often overrated and that usage of FF in regulation of stormwater pollution thus poses a risk to the natural water environment.

Results and discussion

The review of the international scientific literature dealing with FF identified 14 different definitions (Table 1). These can be further grouped into four main categories, defining the presence of FF based on (a) the timing of pollution peaks, (b) the dynamics of the pollutant concentration during an event, (c) the volume of runoff that is expected to contain the major pollutant mass, and (d) different ratios between the cumulative pollutant mass and the event volume (often exemplified by MV curves). Several definitions are then expanded by using different parametrization, resulting in an increasing variability of FF classifications and thus in different conclusions. For example, the definition of Mass First Flush Ratios (MFFR) used to identify FF in literature ranged from 80/30, i.e. 80% of the event mass in the first 30% of event volume (Bertrand-Krajewski et al., 1998), to 50/25, 40/20 (Hathaway et al., 2012), or 80/20 (Sansalone and Cristina, 2004).

Table 1. Categorization of the over 14 different definitions of First Flush found in literature

Category	#	First flush Definition	Criterion/Parametrization used in this study	Source/examples of application
Timing based	1	Hydrograph vs pollutograph	FF if pollutograph peak coming before hydrograph peak	(Kang et al., 2008; Lee and Bang, 2000)
	2	Runoff zones	FF correspond to mass transported by the runoff volume between 0.5% and 10% of the total cumulative runoff	(Peter et al., 2020)
	3*	Rinsing time	Time needed to resuspend sediments in the catchment (often assumed proportional to concentration time)	(Bertrand-Krajewski et al., 1998)
	4*	Baseline concentration	FF corresponds to pollutant discharged when concentration exceeds a fixed threshold (applied for combined systems)	(US Environmental Protection Agency, 1993)
Concentration based	5	Slice approach	Runoff slices for several events are identified. FF is present if there a significant difference in distribution between concentrations of initial slices and averaged mean concentration	(Bach et al., 2010)
	6	Partial EMC (PEMC)	Mean concentration after 1 hr (PEMC) is compared against all EMC. FF if PEMC/EMC>1	(Kang et al., 2008)¤
V based	7	V finite	FF correspond to the first half inch of runoff	(Schueler, 2000)
MV curve based	8	Specific M	FF correspond to the first 80% of the cumulative mass	(Chow and Yusop, 2014)
	9	Specific V	FF correspond to the first 25% of the cumulative mass	(Qin et al., 2016)
	10	Dynamic V	FF correspond to fraction of event where derivative of cumulative mass is greater than cumulative volume	(Perera et al., 2021)
	11	Mass first flush ratio (MFFR)	FF if 50% if the event mass is discharged by the first 25% of the volume	(Hathaway et al., 2012)
	12	Cumulative curve ratio (CCR)	Classification of MV curves based on $y=x^b$ polynomial approximation. FF if b>.925	(Lee et al., 2002)
	13	Bisector gap	FF if deviation between MV curve and bisector line is greater than .2	(Geiger, 1984)
	14	MV gap	FF if cumulative mass curve is above cumulative volume curve for more than 90% of the event	(Helsel et al., 1979)

* *Not applied in this study*

The definitions and parametrization from Table 1 were then applied to two large dataset: the measured turbidity dataset from the Chassieu catchment (Métadier and Bertrand-Krajewski, 2012) and the simulated TSS data from Albertlund catchment (Vezzaro et al., 2015). Site-specific FF definitions (as definition #3) or definitions mainly used for combined systems (definition #4) were not included in the analysis. When different parametrization were possible, the values listed in Table 1 were adopted. The Chassieu dataset includes 363 events, with turbidity data collected at 2 minutes resolution from a 185 ha separate catchment in the outskirts of Lyon, France.

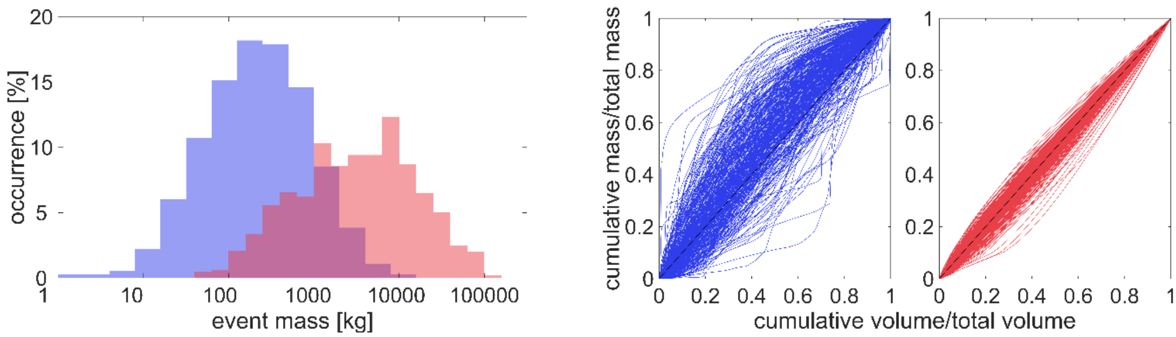

Figure 1. Overview of the analysed event characteristics for the measured Chassieu data (red) and the simulated Albertslund data (blue). Left: distribution of event TSS mass. Right: MV curves.

The measurements from Chassieu were integrated with the modelled data from the Albertslund catchment. This simulated dataset includes results from a 10-year simulation (1,094 events) obtained by using an uncertainty-calibrated stormwater quality model, based on the accumulation-washoff model. The median TSS concentration of 1,000 simulations was used in the analysis. Figure 1 shows a comparison among the dataset. The structural limitation of the accumulation-washoff model compared to the complex reality of measured stormwater quality are exemplified by a smaller variability in the MV curves, which are generally closed to the 1:1 curve (i.e. the results of the accumulation-washoff model showed a smaller FF signal).

Figure 2 shows the inconsistency of the different definitions proposed in the literature, with only a minor fraction of the events consistently showing FF according to at least 3 different definitions: 22% of the measured events (left) and 8.1% of the simulated events (right), respectively. Figure 2 also shows that according to definitions #12, only 8.8% of the measured events showed FF. According to other definitions, the fraction of events showing FF ranged from 10 to 38% of the 363 measured events.

For the simulated data, the smaller variability and the vicinity to the 1:1 line resulted in a smaller fraction of events classified showing FF, with the exception of definition #6 and #14. Indeed, the assumption behind the accumulation-washoff model structure results in a higher TSS concentration at the beginning of the event, then decreasing during the event. This affects the variables used by definition #6 and 14. Overall, this analysis stresses the structural limitations of existing stormwater quality models in reproducing the high variability observed in measured stormwater discharges.

Figure 3 shows the fraction of total event TSS mass belonging to FF for the analysed events, according to different definitions. Clearly, the assumption that the greatest fraction of an event pollutant mass (>75%) is transported in the FF runoff volume is not observed in the Chassieu data, for the different definitions that were explored, except for a few events (1%-5% of all events – except for definition #7 with a 27% of the events).

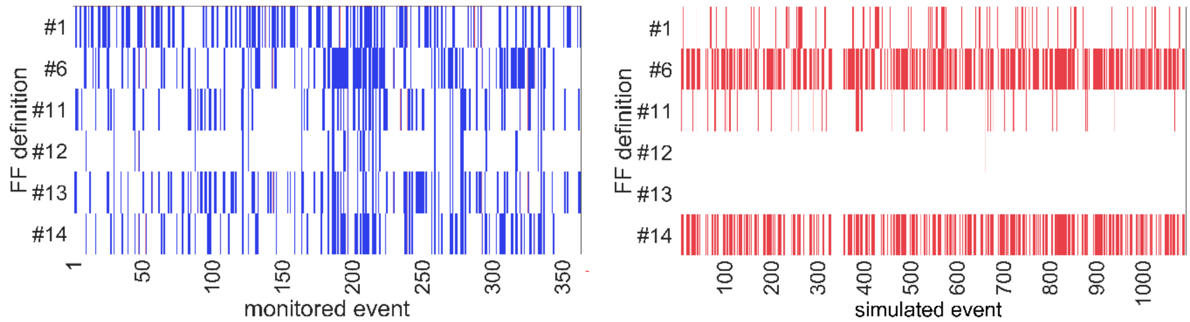

Figure 2. Presence of FF in the analysed datasets according to FF definitions #1, 6, and 11-14 from Table 1. Left: 363 monitored events from Chassieu (blue). Right: 1,094 simulated events from Albertslund (red).

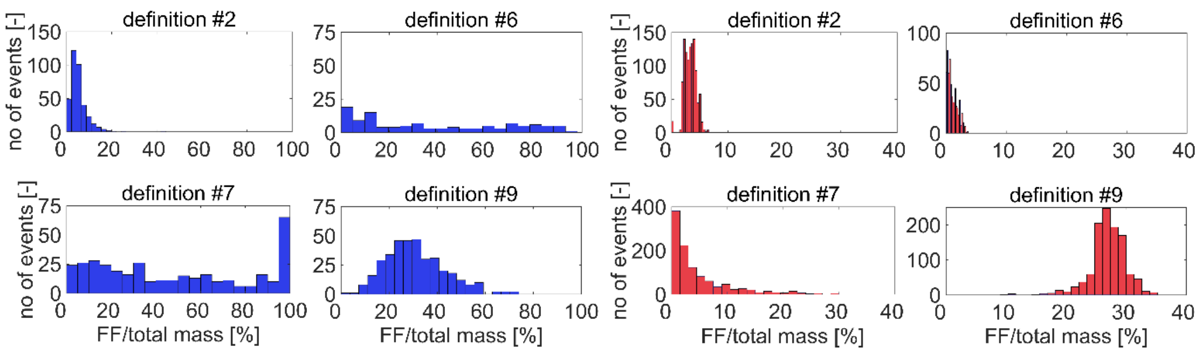

Figure 3. Fraction of total event TSS mass included in FF for the analysed events which were classified as having FF, exemplified for definitions #2, 6,7 and 9 from Table 1. Left: measured events (363 events, with exclusion of definition #6, where 116 events where classified as having FF). Right: simulated events (1,094 events, with exclusion of definition #6, where 623 events where classified as having FF)

When looking at all the 363 measured events (thus assessing the effect of a stormwater control measure designed to only treat the FF fraction), the intercepted mass ranged from 6% to 35% of the total TSS load discharged from the catchment. Similar conclusions can be drawn when looking at the modelled data. These results underline the environmental risks posed to the natural water environment when applying design guidelines and regulations based on static assumptions, not adapted to the dynamic and variable behaviour of stormwater pollutants

Future Outlook

Although the Chassieu dataset is one of the largest available in literature, the analysis should be extended with measured data from a greater number of sites. The structural limitations of accumulation-washoff models limits the usage of simulated data. The authors are thus seeking for collaboration with other researcher to analyse the results from other monitoring sites.

Nevertheless, our results call for new and more effective approaches to regulate pollution based on flexible, site specific methods, rather than relying on the half-century debated and often misunderstood concept of First Flush.

References

Bach, P. M., McCarthy, D. T., and Deletic, A. (2010a) Redefining the stormwater first flush phenomenon. Water Research, 44(8), 2487–2498.

Bertrand-Krajewski, J. L., Chebbo, G., and Saget, A. (1998) Distribution of pollutant mass vs volume in stormwater discharges and the first flush phenomenon. Water Research, 32(8), 2341–2356.

Chow, M. F. and Yusop, Z. (2014) Sizing first flush pollutant loading of stormwater runoff in tropical urban catchments. Environmental Earth Sciences, 72(10), 4047–4058.

Geiger WF (1984) Characteristics of combine drainage runoff. In: Proceedings of the 3rd international conference on urban storm drainage. Goteborg, Sweden, pp 851–860

Hathaway, J. M., Tucker, R. S., Spooner, J. M., and Hunt, W. F. (2012) A traditional analysis of the first flush effect for nutrients in stormwater runoff from two small urban catchments. Water, Air, and Soil Pollution, 223(9), 5903–5915.

Helsel, D. R., Kim, J. I., Grizzard, T. J., Randall, C. W., and Hoehn, R. C. (1979) Land use influences on metals in storm drainage. Journal of the Water Pollution Control Federation, 51(4), 709–717.

Jensen, D. M. R. (2022). Challenging current practices for management of pollution in separate stormwater discharges. PhD thesis. DTU Environment.

Kang, J. H., Kayhanian, M., and Stenstrom, M. K. (2008) Predicting the existence of stormwater first flush from the time of concentration. Water Research, 42(1–2), 220–228.

Lee, J. H. and Bang, K. W. (2000) Characterization of urban stormwater runoff. Water Research, 34(6), 1773–1780.

Lee, J. H., Bang, K. W., Ketchum, J. H., Choe, J. S., and Yu, M. J. (2002) First flush analysis of urban storm runoff. Science of the Total Environment, 293(1–3), 163–175.

Mamun, A. Al, Shams, S., and Nuruzzaman, M. (2020) Review on uncertainty of the first-flush phenomenon in diffuse pollution control. Applied Water Science, 10(1), 53.

Métadier, M. and Bertrand-Krajewski, J. L. (2012) The use of long-term on-line turbidity measurements for the calculation of urban stormwater pollutant concentrations, loads, pollutographs and intra-event fluxes. Water Research, 46(20), 6836–6856.

Perera, T., McGree, J., Egodawatta, P., Jinadasa, K. B. S. N., and Goonetilleke, A. (2021) New conceptualisation of first flush phenomena in urban catchments. Journal of Environmental Management, 281, 111820.

Peter, K. T., Hou, F., Tian, Z., Wu, C., Goehring, M., Liu, F., and Kolodziej, E. P. (2020) More Than a First Flush: Urban Creek Storm Hydrographs Demonstrate Broad Contaminant Pollutographs. Environmental Science and Technology, 54(10), 6152–6165.

Qin, H.-P., He, K.-M., and Fu, G. (2016) Modeling middle and final flush effects of urban runoff pollution in an urbanizing catchment. Journal of Hydrology, 534, 638–647.

Sartor, J. D. Boyd, G. B. (1972) Water pollution aspects of street surface contaminants, Rep. No. EPA R2-72-081

Sansalone, J. J. and Cristina, C. M. (2004) First Flush Concepts for Suspended and Dissolved Solids in Small Impervious Watersheds. Journal of Environmental Engineering, 130(11), 1301–1314.

Schueler, T. (2000) First Flush of Stormwater Pollutants Investigated in Texas. Watershed Protection Techniques, 1(2), 88–89.

US Environmental Protection Agency (1993) Manual - Combined Sewer Overflow Control, Rep. No. EPA/625/R-93/007

Vezzaro, L., Sharma, A. K., Ledin, A., and Mikkelsen, P. S. (2015) Evaluation of stormwater micropollutant source control and end-of-pipe control strategies using an uncertainty-calibrated integrated dynamic simulation model. Journal of Environmental Management, 151.