engineering proceedings

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Proceeding Paper

Design Storms for First Flush Modelling at Sewer Inlets †

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† Presented at the 3rd International Joint Conference on Water Distribution Systems Analysis & Computing and Control for the Water Industry (WDSA/CCWI 2024), Ferrara, Italy, 1–4 July 2024.

Abstract: First flush is one of the key phenomena in the dynamics of pollutants in urban drainage. It is affected by a number of factors, like the characteristics of urban surfaces and drainage systems, the rainfall patterns, the street sweeping frequency and efficiency, and the gully pot features. This paper discusses how a storm event can maximize pollution mass and concentration in first flush runoff. It turns out that the critical events derive from particular combinations of factors and not necessarily from the maximum values of rainfall depths or intensities.

Keywords: first flush; design storm; urban drainage; build-up; wash-off

1. Introduction

First flush is one of the key phenomena in the dynamics of pollutants in urban drainage. In fact, the amount of pollution mass and concentration at the sewer inlets depend both on the build-up process on the catchment surface during dry weather and on the wash-off during rainfall events. These processes are affected by a number of factors, like the characteristics of the urban surfaces and the drainage system, the rainfall patterns, the street sweeping frequency and efficiency, and the gully pot features [1–4]. Although the basic features of both build-up and wash-off are known, the effect of rainfall variability is often underrated, and first flush modelling is reduced to just a standard quantification of rainfall depth thresholds. To reduce urban areas' impact on receiving water bodies through a more sustainable urban drainage system, however, it is necessary to improve the modelling of pollutants at the sewer inlets. The aim of this paper is to identify the storm event characteristics maximizing pollution mass and concentration in first flush runoff. Herein, general results are tested and discussed by means of the continuous simulation of build-up and wash-off processes in a simple catchment. Two real rainfall series with very different characteristics are considered: a 21-year series from Milan (Italy) and a 33-year-long series from Odense (Denmark). The results show the influence of some characteristics of the rainfall process, such as the interval between the rainfall events and the maximum and average rainfall intensities for the considered duration. In particular, it is found that the most critical events, which are also the most significant for design purposes, derive mainly from particular combinations of factors and not necessarily from the maximum values of rainfall depths.

2. Materials and Methods

2.1. Build-Up

The accumulation models normally recommended in the literature to simulate the build-up of the pollutants on urban surfaces respond to exponential empirical laws such as the classic equation [5]:

$$Ma(t) = \frac{Accu}{Disp} \cdot \left(1 - e^{-Disp \cdot ts}\right) \quad (1)$$

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Citation: Becciu, G.; Raimondi, A.; Sanfilippo, U. Design Storms for First Flush Modelling at Sewer Inlets. *Eng. Proc.* **2024**, *69*, 200. https://doi.org/10.3390/engproc2024069200

Academic Editors: Stefano Alvisi, Marco Franchini, Valentina Marsili and Filippo Mazzoni

Published: 21 October 2024

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where $Ma(t)$ is the accumulated mass on the basin at time t [kg/ha], *Accu* is the build-up coefficient [kg/(ha·d)], *Disp* is the decay coefficient [d^{-1}], and t_s is the duration of the antecedent dry period [d].

The *Accu*/*Disp* ratio represents the maximum value towards which the mass that can accumulate in the basin tends, in the hypothesis that the accumulation itself is asymptotically limited by the erosive action exerted by wind, traffic, and biochemical degradation.

The calibration of the parameters is of fundamental importance, since even in the literature, there are rather generic indications on the possible values to be referred to the basin under examination; for example, some experimental investigations [6] have established that the accumulation coefficient *Accu* is a function of the type of urbanization: highly populated residential areas 10 ÷ 25 kg/(ha·d), sparsely inhabited residential areas 5 ÷ 6 kg/(ha·d), commercial areas 15 kg/(ha·d), and industrial zones 35 kg/(ha·d).

Regarding the decay coefficient *Disp*, it has been estimated [7] that in some American basins, it varies between 0.2 d^{-1} and 0.4 d^{-1}, while from some French experiments, this coefficient was estimated to be 0.08 d^{-1} [8].

2.2. Wash-Off

The runoff caused by meteoric events is usually represented with empirical exponential laws. However, in the following paragraphs, the results will be reported in terms of what can be obtained through the most recent formulation of the SWMM model [9], which is of more general validity by virtue of its two calibration parameters compared to the only one present in other models and in the original formulation of the same SWMM model. This two-parameter model has a differential form, which is as follows:

$$\frac{dMd(t)}{dt} = -\frac{dMa(t)}{dt} = Ma(t) \cdot Arra \cdot i(t)^{wash} \tag{2}$$

This becomes, after integrationin terms of finite differences, the following:

$$Md(t + \Delta t) - Md(t) = Ma(t) \cdot (1 - e^{-Arra \cdot i(t)^{wash} \cdot \Delta t}) \tag{3}$$

where $Md(t + \Delta t)$ is the cumulated washed-off mass at time $t + \Delta t$ [kg/ha]; $Md(t)$ is the cumulated washed-off mass at time t [kg/ha]; $Ma(t)$ is the built up mass present at t [kg/ha]; *Arra* is the wash-off coefficient [length^{-wash} · time$^{(wash-1)}$]; *wash* is a numerical parameter; Δt is the time step [hours] (i.e., 5 min is equal to 1/12 h); and $i(t)$ is the average precipitation intensity in the calculation time step Δt [length · hour^{-1}].

In general, the calibration values for *Arra* and *wash* depend on the type of washed substance, the characteristics of the basin, and, indeed, the rainfall. As regards *Arra* in particular, values between 2.9 and 9.3 inch^{-wash} · hour$^{(wash-1)}$ are suggested in the literature for rainfall ranging from 0.2 to 0.8 inch/hour and sedimentable materials, but much lower values are suggested for dissolved substances. Even for *wash*, a certain variability is found in the literature, where values are reported to be between both 1 and 3, in relation to sedimentable substances [9], and between 0 and 1, in relation to soluble substances [10].

2.3. Equivalent Dry Time

From (1), it is possible to calculate the "virtual" dry time t_{sv} corresponding to the residual *Mar* mass remaining in the basin at the end of a rainfall event:

$$t_{sv} = \frac{1}{Disp} \cdot \ln\left(\frac{Accu}{Accu - Disp \cdot Ma_r}\right) \tag{4}$$

So, it is possible to define the "equivalent" dry time $t_{se} = t_{sr} + t_{sv}$, which, for a generic n-th event, is the sum of the previous real dry time t_{sr} and the virtual dry time t_{sv} corresponding to the residual mass Ma_r left at the end of the previous $n - 1$-th event [4].

3. Results

For this study, two series of historical rainfall were used, namely that of Milan—via Monviso—pertaining to the years 1971–1991, and that of the Danish city of Odense, pertaining to the years 1936–1941 and 1952–1979, which are very different from a climatic point of view.

The results of the numerical simulations are presented in Figures 1 and 2.

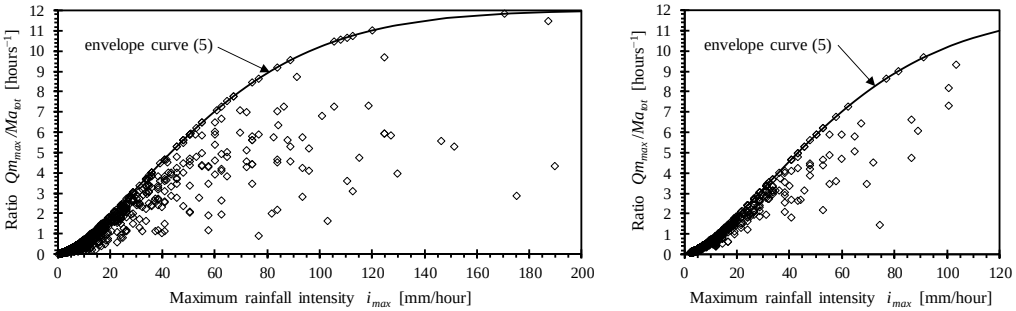

Figure 1. Envelope curves of the Qm_{max}/Ma_{tot} ratio as a function of i_{max}. The simulations were carried out with the following parameters: $Accu$ = 32 kg/(ha·d), $Disp$ = 0.4 d^{-1}, $Arra$ = 2.9 inches^{-wash} · hour$^{(wash-1)}$, and $wash$ = 1.5.

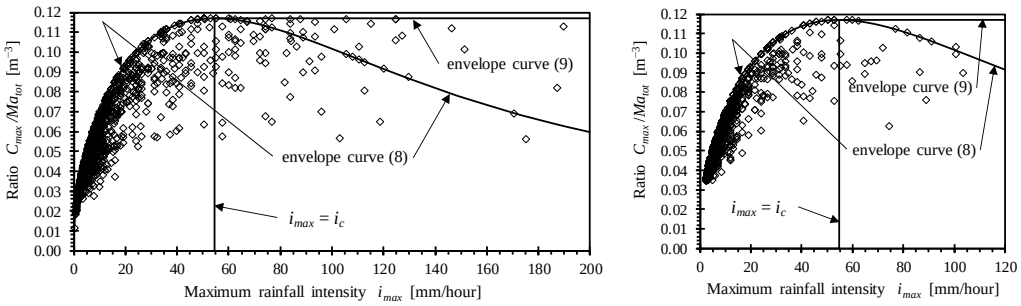

Figure 2. Envelope curves of the C_{max}/Ma_{tot} ratio as a function of i_{max}. The simulations were carried out with the following parameters: $Accu$ = 32 kg/(ha·d), $Disp$ = 0.4 d^{-1}, $Arra$ = 2.9 inches^{-wash} · hour$^{(wash-1)}$, and $wash$ = 1.5.

4. Discussion

It can be demonstrated that the envelope curve for Figure 1 is given by the following:

$$\frac{Qm_{max}}{Ma_{tot}} = \frac{Md_{max}/\Delta t}{Ma_{tot}} = \frac{Ma_{tot}\cdot\left(1-e^{-Arra\cdot(i_{max})^{wash}\cdot\Delta t}\right)}{Ma_{tot}\cdot\Delta t} = \frac{\left(1-e^{-Arra\cdot(i_{max})^{wash}\cdot\Delta t}\right)}{\Delta t} \quad (5)$$

For i_{max} tending to infinity, envelope (5) tends to the asymptote $Qm_{max}/Ma_{tot} = 1/\Delta t$, which is 12 h^{-1} in the case under consideration, having adopted Δt = 5 min.

Regarding Figure 2, while the occurrence of the maximum intensity of the i_{max} event in the first Δt certainly leads to the maximum Qm_{max}/Ma_{tot} ratio, this does not necessarily happen for the C_{max}/Ma_{tot} ratio. In fact, keeping in mind that the concentration $C(t)$ is given by $Qm(t)/(i(t)\cdot S)$, where S is the catchment area, then the maximum concentration C_{max} occurs for the maximum value of the multiplication between the two functions $Ma(t)$ and $(1-e^{-Arra\cdot i(t) wash\cdot\Delta t})/(i(t)\cdot S\cdot\Delta t)$; the first of these two functions, as observed above, is, of course, at the maximum at the beginning of the event, while the second is maximal for a value i_c of rainfall intensity such that

$$e^{-Arra\cdot i_c{}^{wash}\cdot\Delta t}\cdot(wash\cdot Arra\cdot i_c{}^{wash}\cdot\Delta t+1)-1=0 \quad (6)$$

So, dividing (2) by $i(t) \cdot S$, it can be found that the concentration of the washed-off pollutant is as follows:

$$C(t) = Ma(t) \cdot Arra \cdot i(t)^{wash-1} / S \quad (7)$$

Now, focusing on the cases in which $wash > 1$ (the range for sedimentable substances), if the maximum intensity i_{max} of an event is less than the intensity i_c given by (6), then the maximum value of the C_{max}/Ma_{tot} ratio occurs when the i_{max} occurs in the first Δt, a situation that corresponds to the increasing branch of the equation curve:

$$\frac{C_{max}}{Ma_{tot}} = \frac{Ma_{tot} \cdot (1 - e^{-Arra \cdot (i_{max})^{wash} \cdot \Delta t})}{Ma_{tot} \cdot i_{max} \cdot S \cdot \Delta t} = \frac{(1 - e^{-Arra \cdot (i_{max})^{wash} \cdot \Delta t})}{i_{max} \cdot S \cdot \Delta t} \quad (8)$$

If, however, the maximum intensity of the event, i_{max}, is higher than the intensity i_c, then the maximum value of the C_{max}/Ma_{tot} ratio occurs when the i_c occurs in the first Δt; in this case, it results in the following:

$$\frac{C_{max}}{Ma_{tot}} = \frac{Ma_{tot} \cdot (1 - e^{-Arra \cdot {i_c}^{wash} \cdot \Delta t})}{Ma_{tot} \cdot i_c \cdot S \cdot \Delta t} = \frac{(1 - e^{-Arra \cdot {i_c}^{wash} \cdot \Delta t})}{i_c \cdot S \cdot \Delta t} \quad (9)$$

In other words, the increase in the intensities i_{max} beyond the value i_c, even assuming that these intensities occur at the beginning of the event (i.e., when $Ma(t) = Ma_{tot}$), causes a progressive reduction in the C_{max}/Ma_{tot} value given by (7) due to the superior influence of the dilution effect over the leaching effect.

In practice, a rainfall event can be classified as critical from the point of view of the quality of the water entering a drain if it determines a washed-off mass Md_{tot} higher than a pre-established percentage of the maximum possible value, which asymptotically tends to the saturation mass $Accu/Disp$, or a maximum pollutant mass flow Qm_{max} higher than a similarly pre-established percentage of the threshold value $Ma_{tot} \cdot (1 - e^{-Arra \cdot {i_{max}}^{wash} \cdot \Delta t})/\Delta t$.

Author Contributions: Conceptualization, G.B. and U.S.; methodology, G.B. and U.S.; validation, G.B., A.R. and U.S.; formal analysis, G.B., A.R. and U.S.; investigation, G.B. and U.S.; data curation, G.B., A.R. and U.S.; writing—original draft preparation, G.B. and U.S.; writing—review and editing, G.B., A.R. and U.S.; visualization, G.B.; supervision, G.B.; project administration, G.B.; funding acquisition, G.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Italian Ministry of University and Research (MIUR) in the framework of the national research program PRIN2020 via the "Floods in cities: new INSights for integrating Pluvial floodIng into flood Risk maNaGement plans (INSPIRING)" project.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declare no conflicts of interest.

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